Industrial Revolution

Every home that is built is a representation of compromises made between different and often competing goals: comfort, convenience, durability, energy consumption, maintenance, construction costs, appearance, strength, community acceptance, and resale value. Consumers and developers tend to make tradeoffs among these goals with incomplete information which increases risks and slows the process of innovation in the housing industry. The slowing of innovation, in turn, negatively affects productivity, quality, performance, and value. This department piece features a few promising improvements to the U.S. housing stock, illustrating how advancements in housing technologies can play a vital role in transforming the industry in important ways.

How Can Construction Process Simulation Modeling Aid the Integration of Lean Principles in the Factory-Built Housing Industry?

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Abstract

New and existing factories that produce and deliver factory-built housing can benefit from construction process simulation modeling to explore the integration of Lean principles in their operations. Construction process simulation modeling provides digital or virtual recreations of the real-world factory environments to visualize, quantify, analyze, and optimize their underlying behavior, including factory productivity, material flow, labor dynamics, bottlenecks, and work scope. One of the key benefits of process simulation modeling is the ability to create and compare "what-if" scenarios, including integrating Lean principles such as reducing waste (for example, transportation, waiting), line balancing, and just-in-time concepts.

In general, three process simulation methods are widely used: discrete event simulation (DES), agent-based modeling (ABM), and system dynamics (SD). Myriad process simulation software also is available, but depending on the industry, complexity of the system, and purposes of the simulation, some software might be more appropriate. Similar to how computer-aided design (CAD) software such as AutoCAD™ and Rhinoceros™ enable building design of modular or factory-built housing, process simulation modeling software such as jStrobe™, ProModel™, and AnyLogic™ can enable factory design of new and existing factories to deliver modular affordable housing at scale, as opposed to traditional site-built construction. Software with DES capabilities can help generate a process model that is a logical representation of resources and activities in a factory. Software with CAD-DES integration can leverage product-process data integration to help spatially visualize a DES model of the factory in the CAD environment. Software with multimethod simulation capabilities, widely used in the manufacturing industry, brings together DES, ABM, and SD in a single platform that allows visualization, quantification, analyses, and optimization at varying data fidelities. Near-real-time data from an existing factory can be directly plugged into multimethod simulation software so that the construction process simulation model is a near-accurate representation of the real-world factory conditions. This report provides insights into the use of simulation as an aid to integrate Lean concepts in factories, including guidelines for selecting the appropriate process simulation modeling method and software. These insights have been developed as part of ongoing process simulation modeling research, development, and demonstration projects at the U.S. Department of Housing and Urban Development, the U.S. Department of Energy, and the National Renewable Energy Laboratory focused on how process simulation models can enable better integration of resilience, energy efficiency, and low-carbon design strategies.

Introduction

Lean manufacturing supports production optimization strategy. It originated at the Ford Motor Company in the early 1900s and was later modernized by the Toyota Motor Corporation. Lean approaches focus on the elimination of waste in all forms, including defects, unnecessary processing steps, unnecessary movement of materials or people, waiting time, excess inventory, and overproduction. In 2007, a unique large-scale study on the introduction of Lean production strategies in the factory-built housing industry uncovered existing levels of efficiency and highlighted opportunities for improvement. Participating production departments in nine plants experienced productivity improvements ranging from 10 percent to more than 100 percent (MHRA, 2007). Factory-built housing's production strategies should therefore include production optimization, and Lean principles can support the objective of increasing production and lowering cost.

The foundation of Lean production is stability and standardization, achieved through streamlining operations while reducing waste. It involves identifying and eliminating nonvalue-added activities throughout the entire value chain to achieve faster customer response, reduced inventories, higher quality, and better human resources. In a Lean production strategy, all improvements and system design are focused on reducing the seven wastes related to transportation, inventory, motion, waiting, overproduction, overprocessing, and defects (Mullens, 2011).

Process simulation modeling complements widely practiced Lean principles and provides better support to decisionmakers in system design and improvement initiatives. A recent study revealed an increasing interest in the link between Lean and process simulation modeling, especially specific methods such as discrete event simulation (DES) (Uriarte, Ng, and Moris, 2020). Furthermore, the study highlighted gaps and future research opportunities, including (1) lack of reviews on the combination of Lean and simulation focused on the application domain, Lean tools, or specific types of simulation; (2) lack of comprehensive frameworks in the combination of Lean and simulation; (3) lack of framework performance and usability evaluations; (4) lack of the combined use of Lean and simulation for educational purposes; (5) lack of the combination of Lean and simulation in the entire lifecycle of the system; and (6) not taking into account Lean principles in the simulation process (Uriarte, Ng, and Moris, 2020).

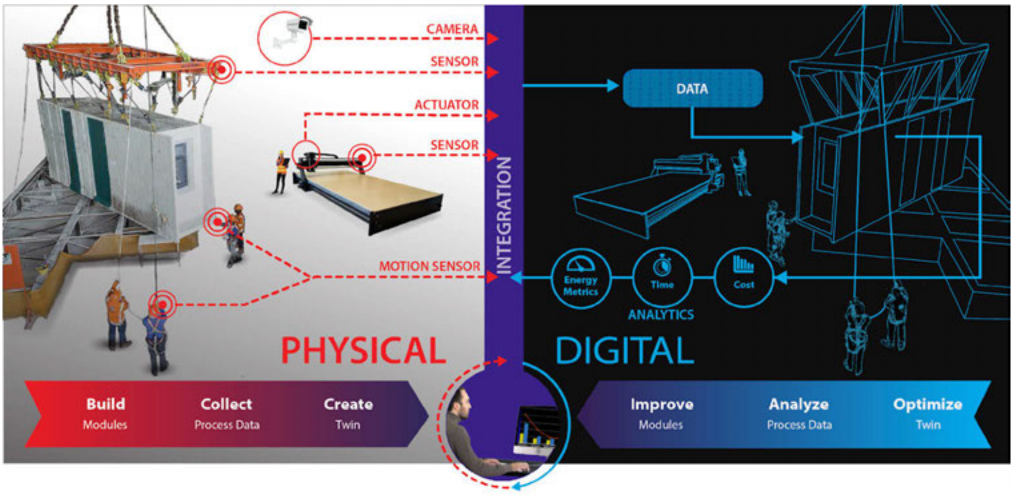
This report provides insights into the use of simulation as an aid to integrate Lean concepts in factories, including guidelines for selecting the appropriate process simulation modeling method and software. These insights have been developed as part of ongoing process simulation modeling research, development, and demonstration projects at the U.S. Department of Housing and Urban Development, the U.S. Department of Energy, and the National Renewable Energy Laboratory focused on how process simulation models can enable better integration of resilience, energy efficiency, and low-carbon design strategies.

Process Simulation Modeling

The authors envision that to modernize factories producing and delivering factory-built housing, builders operating existing factories or gearing up to deploy new factories would take decisions on factory planning and explore opportunities to improve productivity—first, in process simulation models, followed by real-world implementation (exhibit 1). Once a construction process simulation model has been created for a particular factory using data from cameras and sensors, the modular builder can readily inspect the performance of the factory under an endless number of what-if scenarios by changing various spatial and functional aspects of its stations or bays. Because of the high integration between the simulated factory layout, the resources, and the process, the result of any of those changes will be considered in the final performance metric provided by the factory.

Exhibit 1

Conceptual Representation of Construction Process Simulation Modeling



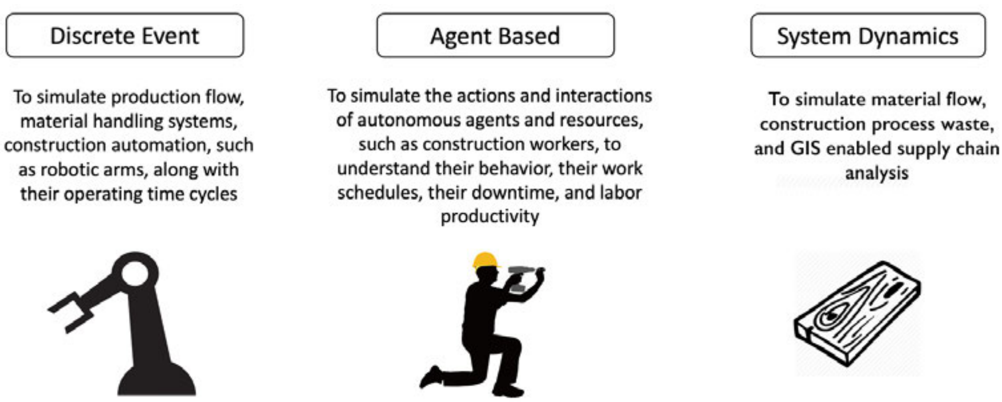
Source: National Renewable Energy Laboratory (NREL)

Process Simulation Modeling Methods

This section expands on widely used process simulation modeling methods that are well suited to the construction processes and can be leveraged by the factory-built housing industry. In general, this section highlights three process simulation modeling methods: discrete event, agent-based, and system dynamics. Each approach can be used as a standalone method for specific processes (exhibit 2). The three methods can also be used as one integrated methodological framework to simulate a complex system, such as a modular construction factory.

Exhibit 2

Three Process Simulation Modeling Methods: Discrete Event, Agent-Based, and System Dynamics



GIS = Geographic Information System.
Source: National Renewable Energy Laboratory (NREL)

Discrete Event Simulation

DES is used for simulation of real-world systems that could be divided into separate processes (events) or sequences of events progressing through time (Barrett et al., 2008). Each of the events happens at a particular instant in time, and the outcome affects the consecutive events. The DES method is based on queuing theory and has been used historically for job allocation and to evaluate telephone scheduling. The overall model simulates how processes respond to random events (such as a completion of a job requested or customer arrival) happening in time—for example, how a production line responds to delayed subprocesses. The DES model is represented as a process flowchart in which individual blocks represent real processes (The AnyLogic Company, 2019). The model can then help with system evaluation, finding "worst-case" scenarios and bottlenecks of the process, and modeling possible what-if scenarios for finding the form of solution. Today, the DES method is widely used in the manufacturing and healthcare industries.

Agent-Based Modeling

Agent-based modeling (ABM) is used to model a system as a collection of agents, which are autonomous decisionmaking entities interacting with each other (Bonabeau, 2002). Using a set of rules, each agent evaluates its situation and makes decisions. The decisionmaking by agents can evolve over time, making their behavior not completely predictable. Models can be very detailed (agents are basically physical objects) or abstract (agents are competing projects). This type of modeling continues to be used in epidemiology, road traffic, population, supply chain, or logistics modeling, specifically when the focus must be on individual objects and their interaction.

System Dynamics

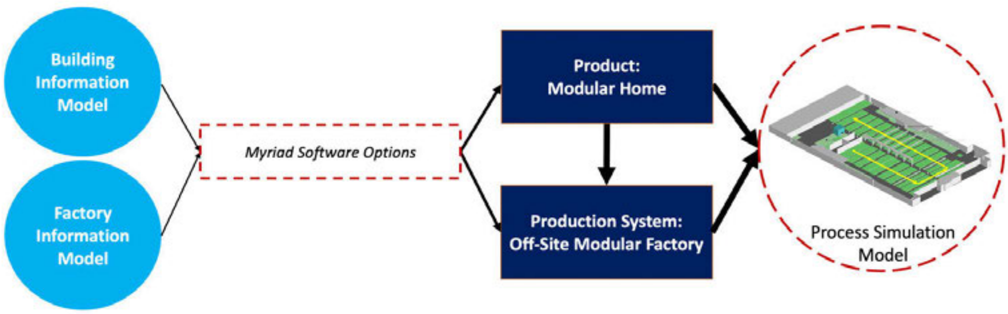
System dynamics (SD) is the oldest simulation process. It focuses on the behavior of very complex systems over time, described with nonlinear behavior, usually in the form of differential equations (System Dynamics Society, 2021). Processes are modeled as a flow between stocks, with loops and time-delayed relationships between the individual parts. System dynamics focuses on the system as a whole when the behavior of the system cannot be described by the behavior of the individual parts. SD modeling has many applications in population, agriculture, economic systems, or modeling behavior of mechanical parts, such as pistons, valve systems, or suspension systems, which all interact with and depend on each other.

Process Simulation Modeling Software

This section expands on recommended software that is available today for builders. To the best of the authors' knowledge, no commercially available software exists that was purpose-built to create process simulation models of factories representing all the activities in new construction at high fidelity. Today, myriad commercially available software options exist to support the creation of building information models (BIMs) and factory information models (FIMs). A FIM can be defined as a fly-through virtual representation of the factory, enabling direct interaction with a wide range of assessments, results, and metrics (Podder et al., 2020). Together, BIM and FIM help create high-fidelity process simulation models of factories through an end-to-end digital workflow, as shown in exhibit 3.

Exhibit 3

End-to-End Digital Workflow



Source: National Renewable Energy Laboratory (NREL)

DES Software

Open-source DES software, such as jStrobe™, can be used for modeling operations that involve uncertainty in durations, require complex activity startup conditions, and involve interdependence of resources (Louis and Dunston, 2017). Such DES software can provide a simple interface and the ability to create a quick DES model that functionally represents the factory. DES software such as jStrobe™ is being actively developed to have seamless data interoperability with game development environments, such as Unity™, to make the DES model run a 3D spatial visualization of the factories (Podder, Louis, and Swanson, 2020). DES software is being specifically used to create DES models of new and existing factories through collaboration with builders across the United States as part of the U.S. Department of Energy-funded project, "Integrating Energy Efficiency in Permanent Modular Construction" (Podder et al., 2020).

Software with CAD-DES Integration

Software with computer-aided design (CAD)-DES integration can leverage product-process data integration to help spatially visualize a DES model of the factory in the CAD environment. An example of such software that is commercially available is ProModel™. It provides reusable predictive analytic solutions with proprietary technologies in all facets of manufacturing and could be applied to the factory-built housing industry. The factory building plan layout and its process model can be created within the same CAD software. CAD-DES integration can also provide several built-in distribution functions, which, in conjunction with process streams, return random values according to a statistical distribution. Such software has proven to minimize the learning curve and maximize the efficiency for modifying large and complex models (Harrell and Price, 2000), which lends itself to builders who may not be familiar with the software and would need to be trained to use it effectively on a daily basis.

Multimethod Simulation Modeling Software

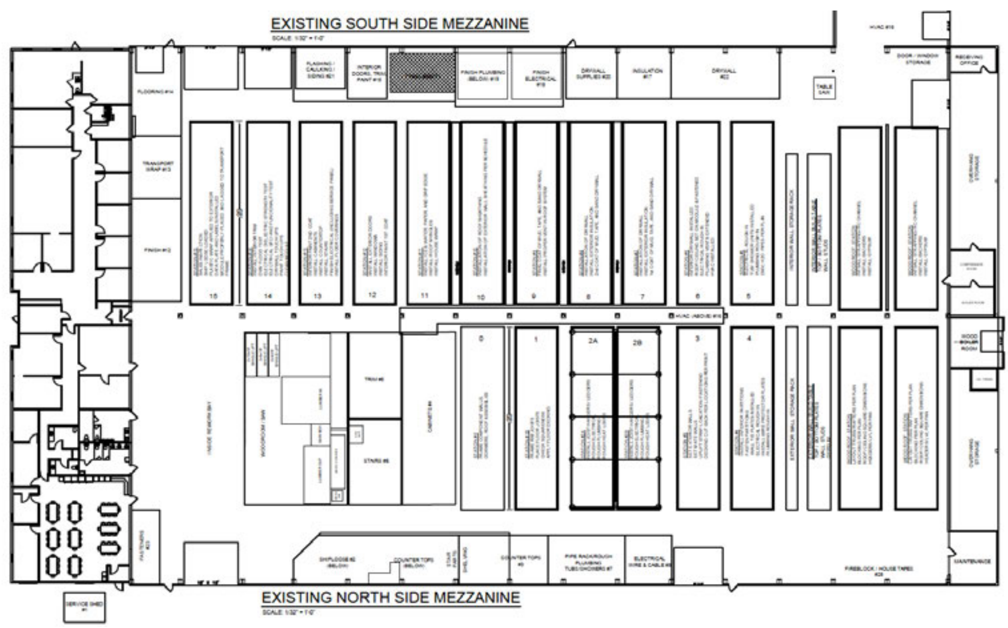
To create the ideal factory, generate what-if scenarios, and understand what governs the integration of cost-effective resilience, energy efficiency, and low-carbon design strategies, builders in the factory-built housing industry need to adopt multimethod simulation modeling. To that end, multiple methods—including DES, ABM, and SD—can be brought together to assist the builders. Multimethod simulation modeling software such as AnyLogic™ has been traditionally used for optimizing manufacturing processes and supply chains of macro-industries.[1] Such software can be used to perform time and cost studies using data from real-world factories, productivity analysis, scaling analysis with supply chain optimization, and waste stream reduction input/output modeling and to create what-if scenarios with solar-plus-storage systems to be integrated during the factory-built process.

Integrating Lean Strategies via Process Simulation Modeling

This section addresses how a real-world Lean improvement project was supported by the approach explained in exhibit 2. Exhibit 4 shows a high-level layout of the U-shaped production line under study for an ongoing simulation development effort, which is housed in a 70,000-square-foot (sq.-ft.) facility with 19 main workstations; all workstations are listed in exhibit 5 in the order of the workflow, from 0 to 15. The last four workstations on the main production line are outside the facility due to limited space. The main production line is supported by six feeder stations (wall framing, etc.).

Exhibit 4

Existing Factory Layout



Source: KBS Builders (case study factory partners with the project team)

The production capacity of this facility, before Lean implementation, is about eight modules per week. On average, units spend 6 hours at each workstation, with a minimum of 3.54 hours and a maximum of 7.57 hours. This time is also known as the "time per move." The time variation is

[1] AnyLogicTM capabilities are explained in this video: https://www.youtube.com/watch?v=9e0F4VtgoaQ.

due to the scope of work completed and the number of workers at each station. This production is supported by 90 workers divided into 23 departments (electrical, carpentry, etc.). One of the indirect labor departments, quality control, is integrated at every workstation to ensure that the modules are built in accordance with the plans and the company's quality standards.

Exhibit 5

Baseline Production Times

Workstations	Major Component	Working Time (hrs)	Percentage of Uptime During Module Moves (%)
0	Walls, Dormers, Roof	5.8	100
1	Floor Framing and Decking	3.54	61
2A & 2B	Raised Plumbing/Electrical Jig	5.80	100
3	Exterior and Mate Wall Set	5.28	91
4	Interior Partition Set	5.23	90
5	Rough Electrical and Plumbing	6.52	112
6	Rough Electrical and Plumbing, Drywall, and Roof Set	6.17	106
7	Exterior Insulation and Drywall	7.57	131
8	Exterior Insulation and Drywall Finish and Sanding	7.54	130
9	Roof Sheathing, Drywall Finish, and Sanding	6.19	107
10	Roof Sheathing and Exterior Wall Sheathing	5.95	103
11	Roofing and House Wrap	7.33	126
12	Windows and Exterior Doors, Siding, and Interior Paint	6.69	115
13	Cabinets, Flooring, Electrical Hookups, Interior Trim	6.86	118
14	Interior Trim, Electrical Tests, Plumbing Tests	5.60	97
15	Touch-up, Exterior Wrap, Ship-Loose, and Labels	3.88	67

Source: Data from case study factory as evaluated by the project team

During the Lean evaluation of the current production layout, the team identified material handling and storage as areas for improvement. In general, the facility has limited storage areas, aisles are crowded, and outside areas are used for temporary storage. Storing material outside the factory not only increases the travel distance to the point of use on the production line but also increases the probability of damage due to exposure to the elements and unnecessary handling. Adding mezzanine space along the North and South sides of the factory would add 4,105 sq. ft. of additional storage inside the factory. That space could be used to store exterior doors, windows, interior doors, bathtubs, and showers, decreasing the travel distance to the point of use. In addition, organizing the existing warehouses and building a new warehouse on the west side of the facility would improve factory operations and allow the outside area to be used for staging completed modules. An additional warehouse (200 sq. ft. x 40 sq. ft.) at the west side of the current factory would add another 3,650 sq. ft. of inside storage. The proposed new warehouse on the west side could store sheet goods and dimensional lumber, which would bring them closer to the mill room and house the receiving department.

The staging and storage areas ideally should be aligned with a designated workstation or point of use to limit the travel distance and material handling. Currently, those areas are too far away from each other, and the staging area must be replenished very often, which slows down the production line. The project team identified several opportunities to reduce distances for more than one-half of the workstations. The team estimated a reduction of about 4,000 ft. of distance if storage areas were relocated closer to the point of use on the production line, decreasing cycle times of major tasks. Opportunities are also available to move feeder stations closer to related workstations. More Lean principles are being continuously implemented via process simulation modeling to improve material handling and streamline operations, with the goal of increasing the estimated production capacity from 8 modules per week to 11 modules per week on average.

Solar-Plus-Storage Evaluation

Once the optimal factory setup was achieved by integrating Lean principles via process simulation modeling, the team evaluated the scope of work to better integrate resilience, energy efficiency, and low-carbon design strategies. The focus of this simulation development effort is the implementation of a solar power array and residential battery storage system installation—"solar-plus-storage." The incremental cost from solar-plus-storage systems installation is composed of subcosts, including factory labor, onsite labor, materials, and prefabricated components related to solar-plus-storage systems; relevant factory construction and material-handling equipment; subcontractors, including solar-plus-storage systems experts; design; and overhead. The cost of labor is typically the component with the greatest variability, and it is determined by a combination of factors, including the scope of work, material and component quantities, inspections, design, factory and site installer composition, hourly installer costs, installer productivity, and factory process efficiency. Focusing on the Lean principle of improving productivity, this simulation development effort intends to leverage process simulation modeling to define key variables that help quantify productivity, as shown in exhibit 6.

Exhibit 6

An Early Version of Mapping Solar-plus-Storage Systems to Relevant Key Metrics to Measure and Verify Its Productivity

Activity	Input (in factory)	Output (in factory)	Baseline to Compare
Installation of rooftop solar PV	Time (in labor hours)	Number of installed solar PV panels	Productivity in site-installed rooftop solar PV
Installation of home battery or storage	Time (in labor hours)	Number of installed units	Productivity in site-installed batteries or storage
Installation of electrical infrastructure	Time (in labor hours)	Number of installed apartment-level conduits and inverters to integrate solar PV and home battery	Productivity in site-installed electrical infrastructure
Distances (e.g., between storage of equipment and work/installation areas or stations/bays)	Time taken to cover the distance	Distance between A and B	Previous distance

PV = photovoltaics

Source: Data from case study factory as evaluated by the project team

A what-if analysis is a data-intensive simulation with a goal is to inspect the behavior of a complex system (Golfarelli, Rizzi, and Proli, 2006), which in this case is a factory construction and installation process. What-if scenarios are the standard way of using process simulation modeling to analyze cause and effect. Behavior can be presented through various output objects for the end user to study. The end user may give input variables new values, thus influencing the process simulation model behavior. As shown in exhibit 7, input and output variables change the behavior of the process models in the simulation. The primary source of input variables is worker schedules, and the primary source of output variables is the production plan.

Exhibit 7

Construction Process Simulation Model

Note: Shown are process models, worker schedules, worker allocation to each station or bay, planned state changes of the volumetric modular products across different stations or bays in production queue, and a dynamic 3D visualization.

Source: Screengrab of baseline process simulation model in AnyLogic™ by National Renewable Energy Laboratory (NREL)

Conclusion

The insights presented and discussed in this paper have been developed as part of ongoing process simulation modeling research, development, and demonstration projects at the U.S. Department of Housing and Urban Development, the U.S. Department of Energy, and the National Renewable Energy Laboratory focused on how process simulation models can better integrate resilience, energy efficiency, and low-carbon design strategies. The primary stakeholders and beneficiaries of using process simulation modeling and integrating Lean principles are the builders. A modular builder, in this case, is the entity that owns or operates factories and builds a wide range of subassemblies of components, pods, panels, and volumetric modules to deliver residential projects at scale.

Pros and Cons—How Can Process Simulation Models Assist Builders in the Factory-Built Housing Industry?

The following benefits apply directly to the modular builder:

- Simulation models specific to real-world conditions of factories that represent schedules of workforces would benefit the modular builder in effective project management and construction scheduling using a user-friendly interface.
- Although the modular builder benefits the most from the value proposition of using simulation modeling, benefits trickle throughout the value chain to designers, developers, and tenants or homeowners. Trickle-down benefits include saved time, reduced cost, and improved living.

The following technical and market challenges need to be addressed to ensure wider adoption of simulation models by builders:

- Builders must be incentivized, trained, and supported to adopt simulation modeling and Lean principles. Also important is addressing the skills gap in the construction industry workforce by encouraging simulation experts from the computer science industry to actively explore developing simulation models for factories producing and delivering factory-built housing.
- Inputting data from real-world factories sourced from cameras and sensors should be possible to continuously update the simulation models. A major market penetration challenge, therefore, is the development of low-cost and easy-to-deploy data collection packages, including cameras and sensors, to be used by builders to retrofit their existing factories.

Guidelines—Takeaways for Builders on Best Practices when Interacting with Process Simulation Models

While existing literature such as *Factory Design for Modular Homebuilding* (Mullens, 2011) has disseminated frameworks on productivity improvement and waste reduction, it has not necessarily led to pathways where process simulation models can be used to improve the products and the processes. High-performing builders who are actively engaged in implementing a wide range of Lean principles in their new and existing factories often face challenges in realizing effective interventions in the factory. Using process simulation models will enhance the workflow of builders and will empower them to make more informed decisions, furthering continuous improvement of the factory process to reduce cost and time. The following is a step-by-step description of the guidelines for builders on the workflow when interacting with process simulation models:

1. The modular builder or design team hands off the BIM model of the modular building to its process engineer or factory construction manager.
2. The process engineer or factory construction manager uses the process simulation model on a computer or device to create a digital factory floor plan layout (in 2D).
3. The outputs from the process simulation model are process efficiency (time, cost) and product efficiency (resilience, energy efficiency, low-carbon design strategies), which are of direct interest to the process engineer or factory construction manager.
4. The process engineer or factory construction manager uses the process simulation model to optimize time, cost, and final product quality in a de-risking environment and to create what-if scenarios based on the modular home builder's plans and development stages.
5. The process engineer or factory construction manager looks at those outputs as feedback from process simulation models to inform decisions to implement process changes in the real-world factory.
6. Factory performance is monitored to measure and verify the performance of process changes before and after implementation. The process simulation model is continuously updated and provides continuous feedback on improvements in the real-world factory.

Acknowledgments

The authors would like to thank KBS Builders for continued engagement to ensure success of factory data collection and case study. The authors would also like to thank the U.S. Department of Housing and Urban Development and the U.S. Department of Energy for funding support.

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