

CS4691000

Process-Based Digital Twin for Industrialized Construction Efficiencies

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Learning Objectives

- Explain how discrete event simulation measures and optimizes baseline performance of an industrialized construction factory.
- Recognize the importance of visualizing factory processes in 3D to enable a greater level of interaction by stakeholders.
- Describe how a process-based digital twin can be leveraged to improve existing and upcoming factories and products.
- Differentiate how BIM, IFC, VDC, and machine learning integrate energy efficiency tech with little/no extra lead time/first cost.

Description

Industrialized construction is becoming more important than ever given current housing shortages and a decline in skilled labor. Optimizing factory processes is thus essential for productivity, however, changes to lines can be both expensive and disruptive. In this presentation we will demonstrate how a process-based digital twin can help analyze and optimize a factory. First, a Factory Information Model is created using discrete event simulation and virtual reality. This model is then updated using a variety of sensors that can measure baseline performance. Together, the model and sensors produce a digital twin of a factory that serves as a virtual test-bed for evaluating the manufacturing process, and optimizing factory layout and resource allocation to mitigate any adverse effects. We'll share preliminary results from an ongoing project to integrate energy efficiency technologies into modular buildings with little or no additional lead time and first cost.

Speaker(s)



Colby Swanson is a Serial Entrepreneur, Innovation Strategist and Construction Technologist who has spent over 20 years in the building industry gaining a 360 degree understanding of the construction space. He is currently the Managing Partner at Momentum Innovation Group (MIG), an innovation consulting firm helping clients drive transformation in their business and find unseen areas of opportunity and growth and also serves as the Director of the Modular Mobilization Coalition - 15+ modular construction companies with a nationwide network of two dozen factories.



Dr. Joseph Louis's research interest lies at the intersection of simulation, visualization, and automation within the context of construction operations. He draws upon concepts in these areas to provide construction managers with better means of planning, monitoring, and controlling their operations to improve safety, maximize productivities, and minimize equipment idle times. Dr. Louis is passionate about engaging with the broader community and has organized university-level TEDx talks.



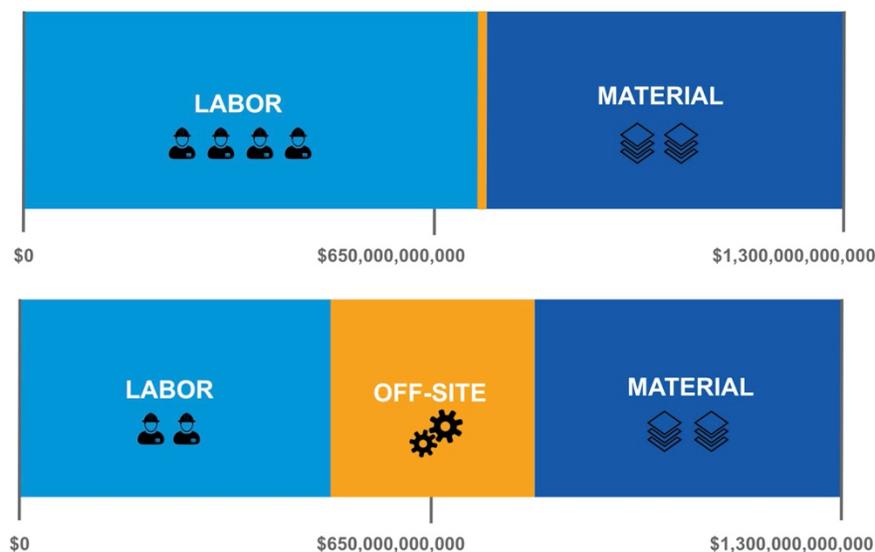
Ankur Podder joined the Industrialized Construction Innovation (ICI) team at NREL in 2019 with a focus on advanced manufacturing of buildings and integration science. His research work aims to facilitate the integration of a wide range of energy efficiency strategies and distributed energy resources during factory production of permanent modular buildings. His work involves strategizing the blending of factory information modeling and building information modeling into NREL's building energy modeling capabilities as well as accelerating whole-building systems integration in upcoming modular net-zero energy buildings.

Introduction

Construction in the U.S. has long been a profitable industry with little meaningful innovation over the last 100 years with the intention to increase the speed, and lower the cost to build. Growing labor and supply chain challenges, as well as the overwhelming need to build better buildings has provided an opportunity for industrialized construction to gain a greater portion of the market share. Optimizing factory processes and material improvements to increase productivity through the use of digital twins will be crucial for enabling stakeholders to analyze potential expenses and disruptions in a factory line. This talk will discuss the process and tools used to create a modular construction factory digital twin and how it can be used to improve overall factory production. In this presentation you'll also hear about preliminary results from an ongoing project using a digital twin to integrate energy efficiency technologies into modular buildings with little or no additional lead time and first cost.

The Need for Industrialized Construction

While the U.S. struggles to keep up with the necessary speed of construction, projects are being offshored to companies in other countries who are able to complete jobs on a faster time frame. Modernizing the U.S. construction industry has never been more important for keeping local jobs and billions of dollars in the states. In 2019 off-site construction represented only \$50 billion of the \$1.3 trillion value of U.S. total construction put-in-place (with materials and labor representing the rest). There is obvious room for improvement, however, the construction industry is consistently risk averse with little-to-no R&D investment.



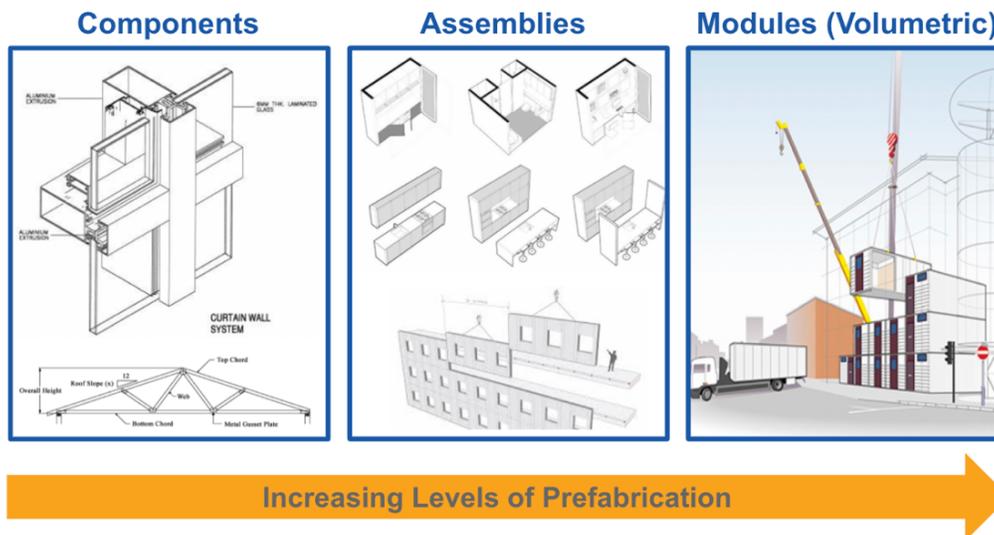
Off-site Advantage: Twice the Speed / Half the Cost

The U.S. construction process is still largely a manual one, including inside of modular factories. Many modular units are still stick-framed very much like the on-site process. This is not to say that modular is not more efficient, but many of the 200+ modular factories in the U.S. need to

consider new processes and products in order to move away from their current on-site mentality to a more controlled, standardized, and repeatable manufacturing mentality.

Typically, one or more of the following elements would be found in off-site construction:

- Components: Elements that can be combined together to comprise full systems and/or assemblies such as trusses or mullions.
- Assemblies: Large building elements that require minimal finishes after installation such as flooring or façade panels.
- Modules: Complete building modules requiring little to no additional finishes after on-site installation. This can include, but is not limited to, hotels, hospital rooms, multifamily buildings, and dormitories.



Manufacturing Centricity: Embracing Productization and Prefabrication

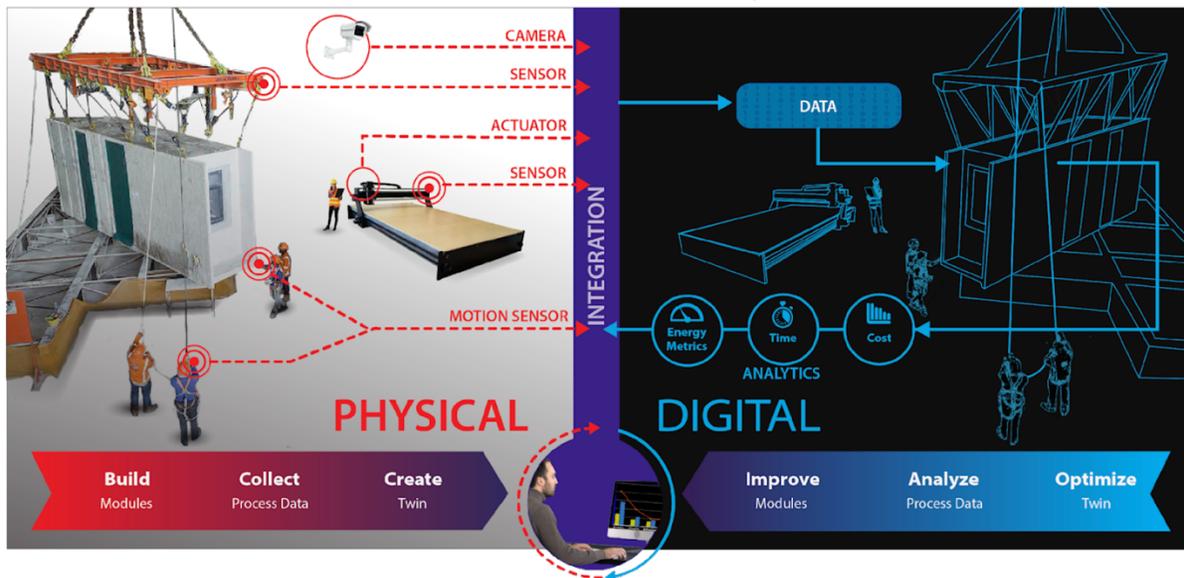
The goal of any factory is to continuously optimize production in order to increase throughput, while managing cost and quality. There is very little factory data collected related to the production process on the manufacturing floor making it very difficult to know where to begin the optimization process. This gap, The Invisible Factory Dilemma, is where a virtual digital twin, along with sensors, can start to inform better decision making and remove bottlenecks.

Digital Twin

A digital twin is simply a virtual model of a process, product or service that enables the pairing of virtual and physical worlds. It is useful in the analysis of data and the monitoring of systems to mitigate costly expenses or disruptions before they occur. Digital twins are used to develop future processes or new opportunities by using simulations and have been used in many industries including space, energy, automotive, oil and gas, healthcare, farming, and even city planning (there's a digital twin of Singapore).

Current usage of digital twins in AEC are primarily surrounding building operation and

maintenance¹ and construction schedules for project management² and focus mainly on the built product. We are focused on the building process.



Novel Capabilities of Advanced Time-and-Motion Study and Process-Based Digital Twin

The figure above shows a high level concept for collecting various types of data from a factory, its resources, and the module that is ultimately built. That information is used to update a digital twin of the entire factory process. All of this is done with the goal of improving the construction of modules by analyzing data from the real-world and performing various optimizations within the digital twin.

Until recently there was no real way to analyze how the various elements of a factory come together and work to create the modules. In order to develop a process digital twin for a modular factory, 4 elements need to be taken into consideration: the space in the factory; the equipment available; the labor or human workers; and the materials involved.

The result is discrete event simulation (DES) - a method for simulating processes as discrete activities that are dependent on the availability of resources. DES is a highly detailed and faithful virtual representation of what happens on the factory floor (image below) depicting how human workers handle materials and interact with the equipment in the factory. With the basic virtual model factory managers can change the number of workers or stations and receive real data on how the change would affect both the build time, as well as the usage of space and resources.

¹ Qiuchen, et al. 2020

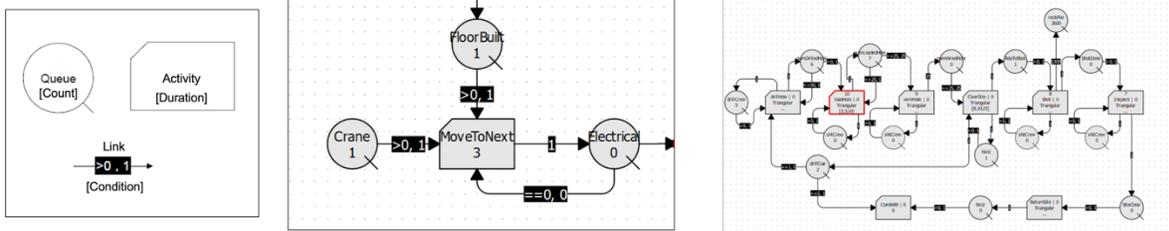
² Yusen et al. 2018



Screenshot of detailed modeling of work processes

Steps to Measuring & Optimizing Baseline Performance With Discrete Event Simulation

1. A Factory Information Model is first created using discrete event simulation and virtual reality.
2. A library of physical activities commonly performed in the factory must be produced and cataloged and would include activities such as:
 - a. Human laborers hammering, using nail guns, walking, carrying loads
 - b. Cranes lifting, moving, and lowering loads
 - c. Forklifts loading, moving, and unloading material
3. A station library is created of every clearly marked physical workspace on the factory floor that is reserved for the performance of a specific set of activities in the construction of a modular unit. Computer vision is being tested to track the presence of modular units in different stations. This allows a high level of insight into the allocation of resources and process performance in a factory, and provides data that can be input directly into the factory models to enable further analysis and forecasting.
4. The model can be updated using a variety of sensors that can automatically measure and report performance to the digital model to provide insights and forecasts. We are currently testing inertial measurement units (IMUs) to detect the vibrations and movements of modules. The obtained data was trained with machine learning methods to determine if the current station and state (idle/ busy/ moving) of the units could be determined. This enables the calculation of time of each box at each station and could be directly used as input for the overview model to forecast factory performance (94% prediction accuracy using test data).



Left: Primary elements for DES model; Middle: Small portion of a DES model using available resources; Right: Activities and resources can be added to build up larger operations. In live mode the simulation would demonstrate how activities start, how they are interdependent on previous activities ending, as well as the availability of resources.



Computer Vision being employed to track modules and provide data for the DES.

Leveraging Process-Based Digital Twin to Improve Factories and Products

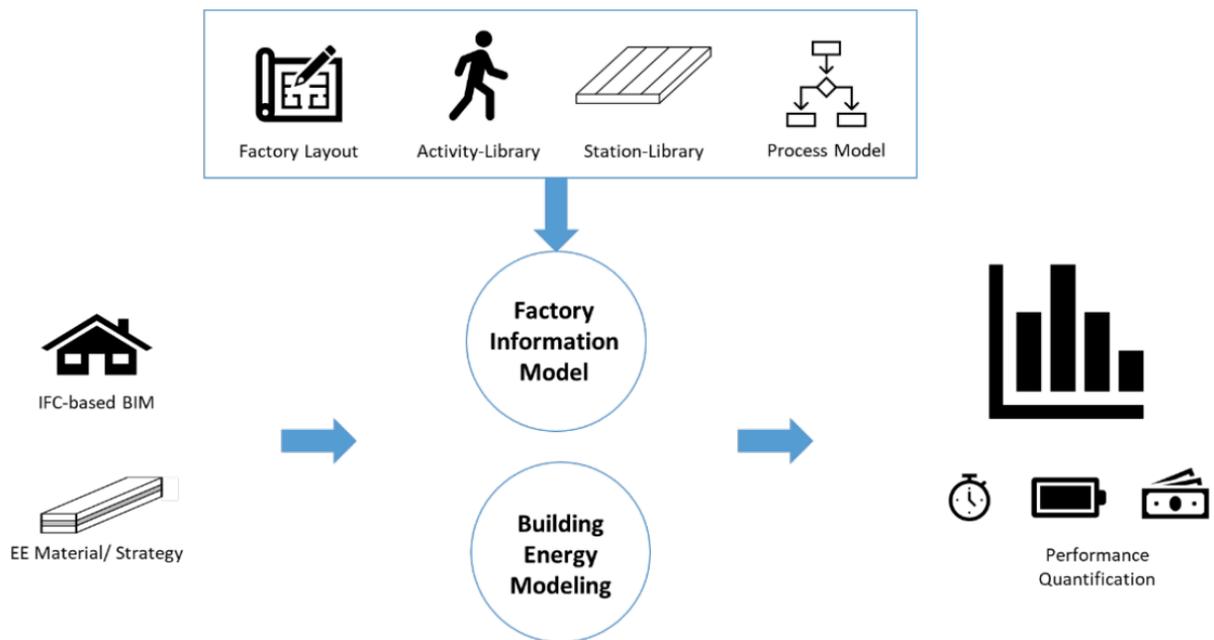
Visualizing factory processes in a digital twin will enable all stakeholders to interact on a greater level with the decision-making process. Whether a material change, a factory process, or automation implementation they will have the ability to virtually see the benefits or consequences in a real-time scenario and make performance improvements to the factory.

Integrating Energy Efficiency into Industrialized Construction

We are not only developing approaches to benefit the industrialization of construction to increase productivity. In addition to advanced manufacturing tools and process efficiency strategies, we are also looking at integrating energy efficiency strategies into our research. This novel, integrated workflow can be leveraged across the industry to ensure wider adoption of energy efficiency integration during permanent modular construction.

Roadmap for Process Analysis

The envisioned workflow for the holistic analysis of modular construction factories is presented in the figure below. The goal is to quantify performance of the production line in terms of time and cost for producing modules, along with the energy benefits provided by the energy efficiency (EE) strategy. The Factory Information Model³ (FIM) will work alongside the existing Building Energy Models (BEM) to provide analysis of the process performance. The FIM will be preloaded with a library of common activities, stations, and underlying processes, along with the layout of the factory itself.



Overview of envisioned workflow for holistic analysis of EE strategy intro to modular factory

The FIM will then take as input the Industry Foundation Classes⁴ (IFC)-based Building Information Model⁵ (BIM) of the modular units to be constructed, along with the EE strategy under consideration. The results of the FIM will be provided in terms of cost and time implications for the manufacturer when they introduce the EE strategy into the assembly line. The following subsections will describe the role of each component of the FIM in producing the desired results for analysis.

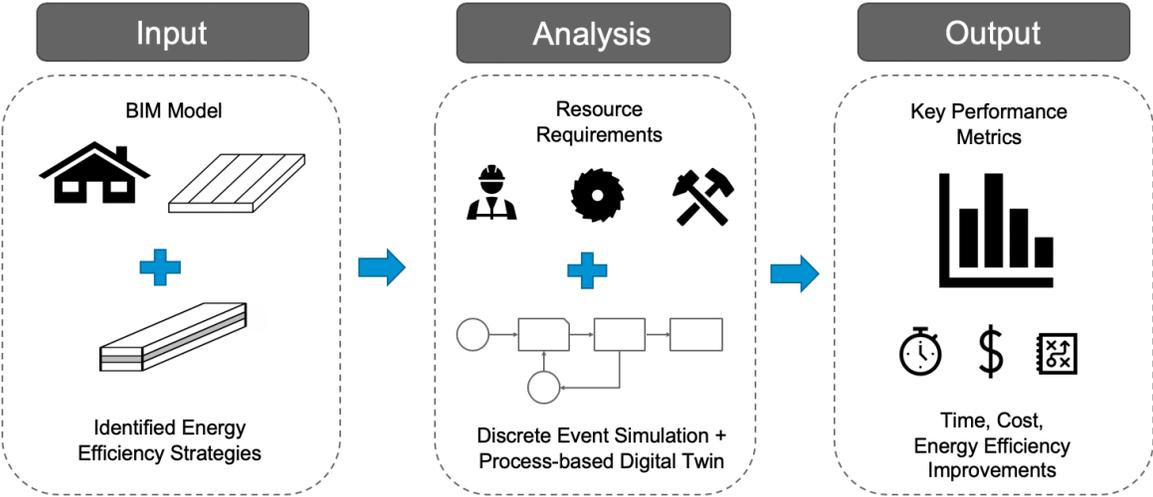
³A FIM is a digital representation of a modular construction factory that integrates information regarding its physical layout, interaction between multiple heterogeneous resources, and underlying process maps. More precisely, it is a dynamic virtual model of the factory that is more than the sum of its individual components including static 3D CAD models of the IC factory floor and equipment, and non-visual schematics of process flows.

⁴IFC facilitates the sharing and exchange of information among IFC-compatible software applications such as ability to import BIM directly to other tools such as Unity3D® and EnergyPlus®

⁵BIM technology allows users to create a digital representation of a physical building. Virtual Design and Construction (VDC) is a similar technology but differs in purpose as it allows companies to analyze construction plans from start to finish before breaking ground.

An Integrated Workflow to Deliver Efficient Buildings

Inputs from designed BIM models including geometric and non-geometric data of energy efficiency strategies and building components can be effectively analyzed using discrete event simulation modeling. The key performance metrics of cost, time, and energy efficiency improvements are outputs specific to each strategy.



The selected strategies currently under study leveraging a Process-Based Digital Twin are easy to integrate in an off-site modular construction factory. These strategies include advanced envelope techniques, smart apartment controls platform, integrated mechanical pods, and factory assembled building solar systems. As part of this research project, led by the National Renewable Energy Laboratory, we are analyzing product-process improvements for each of these strategies.

<p>1- Advanced Envelope Strategies</p> <ul style="list-style-type: none"> - Off-Site Wall Framing with Thermally Broken Studs for Low-Cost Thermally Efficient Envelopes - Aerosol-Based Sealing Technology for improved Airtightness of modular units 	<p>2- Smart Apartment Controls Platform</p> <ul style="list-style-type: none"> - For Modular Grid-Interactive Efficient Buildings (modGEBs) - Occupant engagement platform 	<p>3- Integrated Mechanical Pod solution (Factory-Installed, In-Unit)</p> <ul style="list-style-type: none"> - For Space Conditioning, Energy Recovery, and Water Heating 	<p>4- Factory-Assembled Building Solar Systems (FABSS)</p> <ul style="list-style-type: none"> - For Solar PV, Building-integrated PV (BiPV), and In-Unit Battery Storage

In-Factory Aerosol-Based Sealing Process for Improved Air-Tightness of Built Product

Sensors and cameras are being utilized to perform time and motion studies during in-factory air sealing of modular units in partnership with Volumetric Building Companies. The in-factory data collection serves as inputs of time, cost, and final air-tightness to the discrete event simulation model. Using a baseline of on-site sealing the analysis showed a lower starting ACH than on-site as well as reduced prep and sealing time of 40%-60%. Due to significantly faster sealing time, off-site sealing brings costs down by 40%.

Such comparative analyses using data from in-factory pilot demonstrations, discrete event simulation modeling, and process-based digital twin are being performed for other identified strategies as well

In-Factory Wall Framing

Another envelope strategy being researched is adding insulation in-factory using thermally-broken studs as opposed to adding continuous insulation on-site. The key performance metrics remain the same given the strategy meets the same or better product efficiency versus the baseline envelope.

Centralized MEP System vs. In-Unit Integrated MEP Pods

In-unit integrated MEP pods would enable apartment compartmentalization, as opposed to centralized MEP systems. Unlike traditional construction, almost all MEP systems could be fabricated at a single off-site facility prior to in-unit installations on-site. We are moving towards data collection of this strategy through pilot demonstration and prototyping at the National Renewable Energy Laboratory campus.

Automation Integration and Continuous Improvement

As part of this research, we are developing an inherent capability with the process-based digital twin to provide guidance on introducing automation to a primarily manual construction process in the factory. Process Engineers of modular construction factories can phase-in increasing levels of automation by first understanding its implications to performance metrics in the digital twin environment. For example, the capability would allow the user to drag-drop-swap between a fully manual framing station and a human-supervised machine-mediated framing station for the same factory line.

The ongoing research project is an attempt to kick-off a shared development platform of process-product innovation within the building industry through which a broad range of stakeholders can engage and leverage learnings from digital twin-based optimized improvements. Through this, we aim to ensure wider adoption of such means, methods, and novel tools to deliver products that are healthier, more affordable, and energy efficient by ensuring improved productivity, quality, and affordability of building construction processes.

In conclusion, the U.S. construction industry is skewed towards on-site construction. A rebalancing towards more off-site practices is essential to dealing with the current industry

challenges. The off-site construction industry has the ability to more effectively perform highly repetitive construction activities at significant cost, labor and time savings but need powerful tools like the process-based digital twin to truly transform and industrialize our industry.