Development of Integrated Mechanical Pods

Presented at the 2021 ASHRAE Virtual Design & Construction Conference

08/29/2021

NREL/PR-5500-79948

Learning Objectives

- **Objective 1:** Attendees will learn about the vision of **national-scale shared development platform** for process-product innovation on integrated mechanical pod solutions and **how to get involved**.

- **Objective 2:** Attendees will gain an understanding of the components of an all-electric, high performance home, design characteristics and equipment included in an **all-electric mechanical pod**, **integration of mechanical systems within a modular factories' assembly line**, and the system's **commissioning, operation and maintenance**. The pre-planning and coordination with the factory and sub-contractors will also be highlighted.

- **Objective 3:** Attendees will gain insights on **design for manufacturing and assembly, rapid prototyping, and emulated testing** of various form factors across different climatic conditions. The need for such preliminary testing with open-source sharing of learnings will also be highlighted.

- **Objective 4:** Attendees will gain an understanding of using **process modeling tools** to quantify resource-constrained performance of operations (such as integration of energy efficiency strategies) to manufacture **pods and sub-assemblies** of varying design.

Acknowledgements

- Cedar Blazek, Buildings Technologies Office (BTO), US Department of Energy
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- Airia Brands Inc.
- Emerson Swan, Inc.
- GE Haier
- Mitsubishi Electric
- Blokable Inc.
- Factory_OS
- Volumetric Building Companies (VBC)
- Skender

Outline

1. **Introduction and NREL project:** NREL's ongoing project focused on integration of energy efficiency strategies, including Integrated Mechanical Pods and highlight the vision of a shared development platform and its need in order to stimulate and accelerate product-process innovation on Integrated Mechanical Pods for residential and commercial buildings
2. **A Case Study of Factory-Built Integrated Mechanical Pods for Zero-Energy Modular Homes**: Part 1 by VEIC on lessons from the field from projects that integrate an all-electric HVAC, solar PV, battery storage and hot water systems into affordable homes before they leave the modular factory
3. **Design for Manufacturing and Assembly (DfMA), Integration Logic, and Generative Variability:** Part 2 by NREL on how NREL is leveraging the DfMA approach leading to integration logic, rule-sets, and generative variability that inform DfMA of centralized mechanical systems into unitized integrated mechanical pods for commercial buildings (multi-family, hotels)
4. **Process Modeling for Factory-Built Optimization of Pods:** Part 3 by OSU on how digital twin and discrete event simulation is being leveraged to inform process optimization of pods during modular construction, including Mechanical Pods

Team Leads

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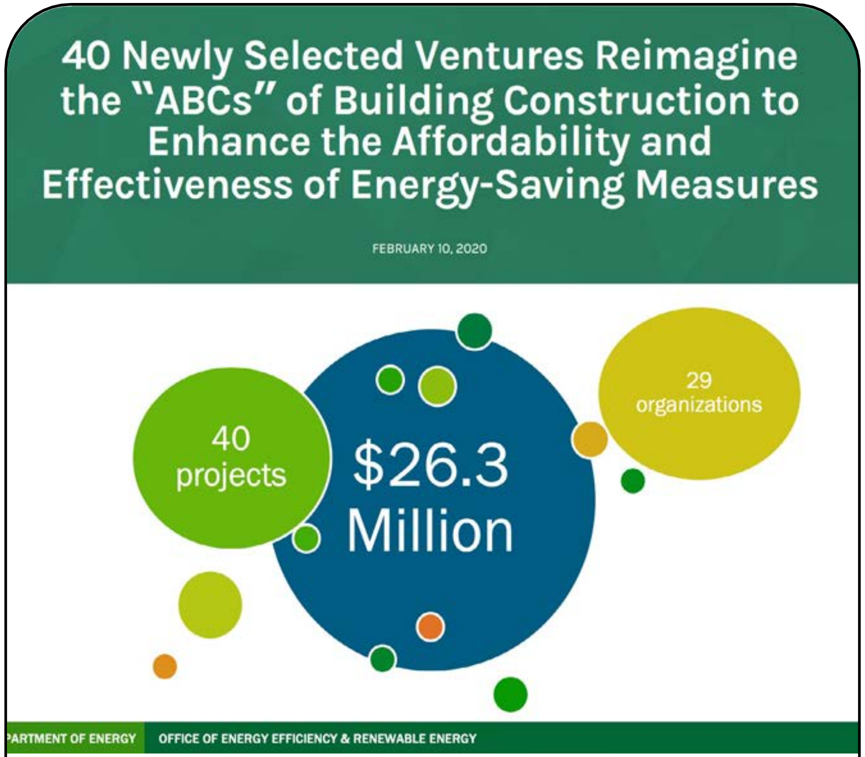
U.S. DOE "Advanced Building Construction"

Low Carbon | Affordable | Fast | Appealing

[Source: ABC Initiative webpage]



[Source: ABC Projects]

Permanent Volumetric Modular Construction

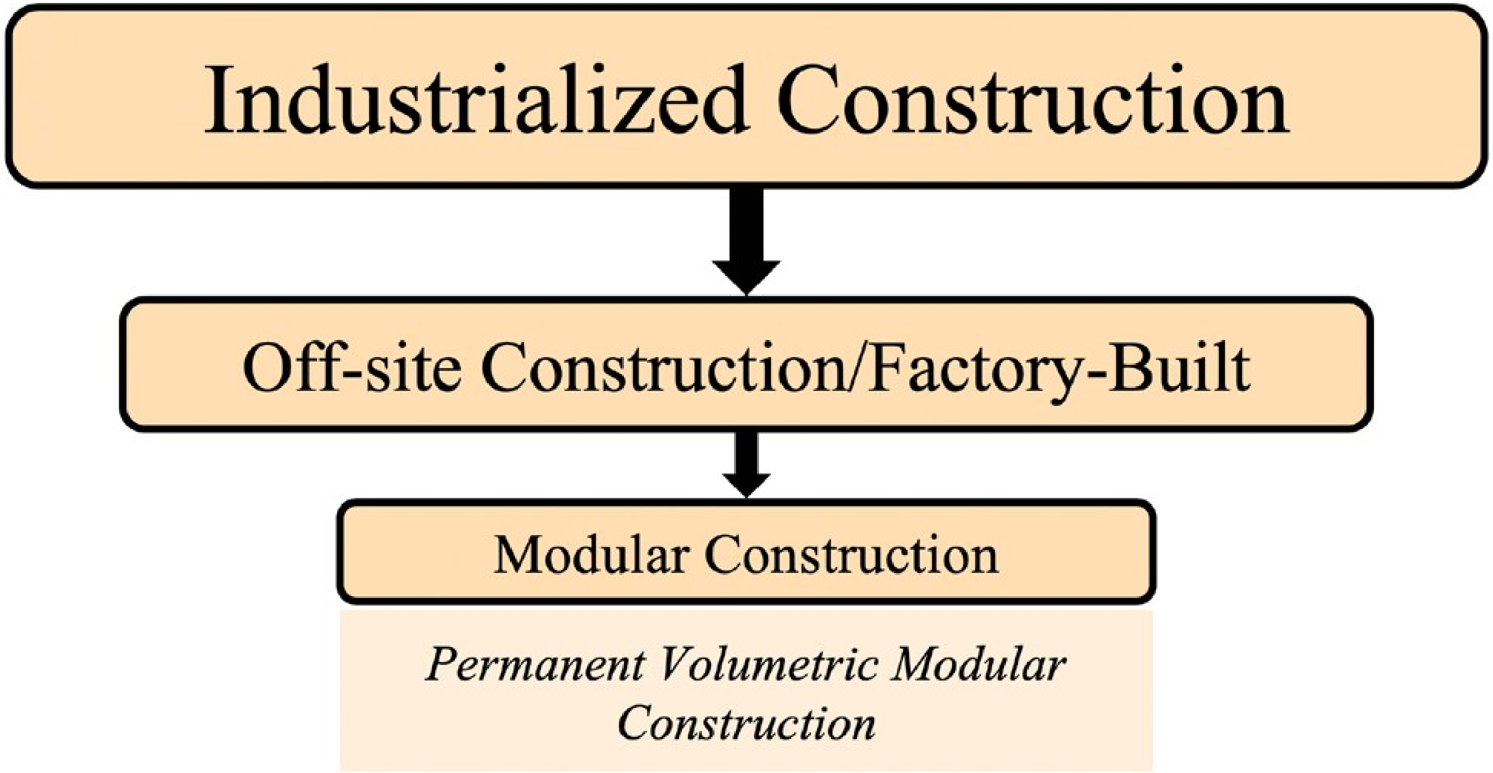


Figure created by NREL

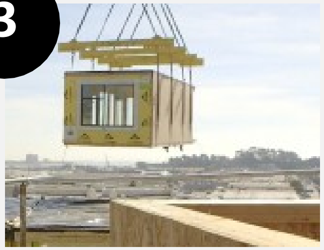
Are Modular Buildings more Energy Efficient?

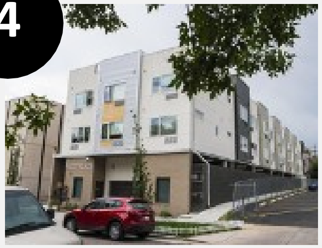
1

Manufacturing and Assembled in a factory

2

Transported to the site

3

Set on the site

4

Connect to the Grid

- **20%-40% faster** to build*
- **5%-95%** construction off-site in a factory* (Volumetric modular, wall panels, and so on)
- **3% of new construction** in 2017* (Multifamily and hotels)
- **Higher quality**
- **Can be cheaper to build**
- **Any program that can be modularized**
- **New investment from outside construction industry**

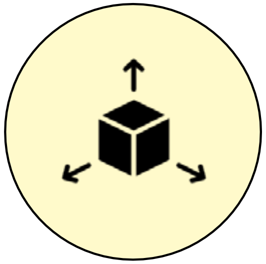
But does it result in **more energy efficient buildings**? Perhaps...

* Modular Advantage by Modular Building Institute (https://www.modular.org)

Approaches, Tools, and Strategies

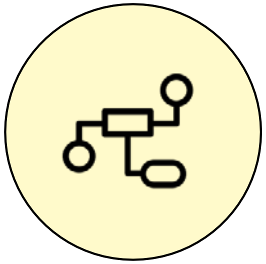
Develop industrialization **approaches**, advanced manufacturing **tools**, and process efficiency **strategies** to increase productivity in integrating energy efficiency and grid interactive controls into buildings.

Broadly, the advanced manufacturing approaches, tools, and strategies we are applying:



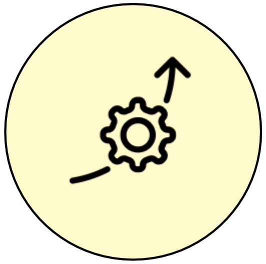
(1) Design for Manufacturing and Assembly

- Subassembly design to optimize manufacturing productivity
- Standardized catalogue of parts



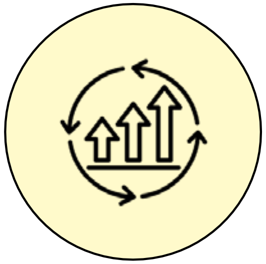
(2) Streamline workflows through integrated product design to mfg

- Virtual Design & Construction tools, Integrated BIM tools, Generative Design
- Automation in construction methods



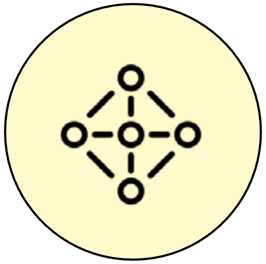
(3) Productivity modeling from design through manufacturing

- Time and Motion studies to optimize process efficiency
- Digital twin of processes to evaluate proposed improvements



(4) Process improvement prototyping

- Test new assembly methods of energy efficiency strategies near or on the factory line
- Continuous improvement, leverage Six Sigma strategies



(5) Distributed Manufacturing approaches

- Industry 4.0
- Digitization

Product-Process Innovation

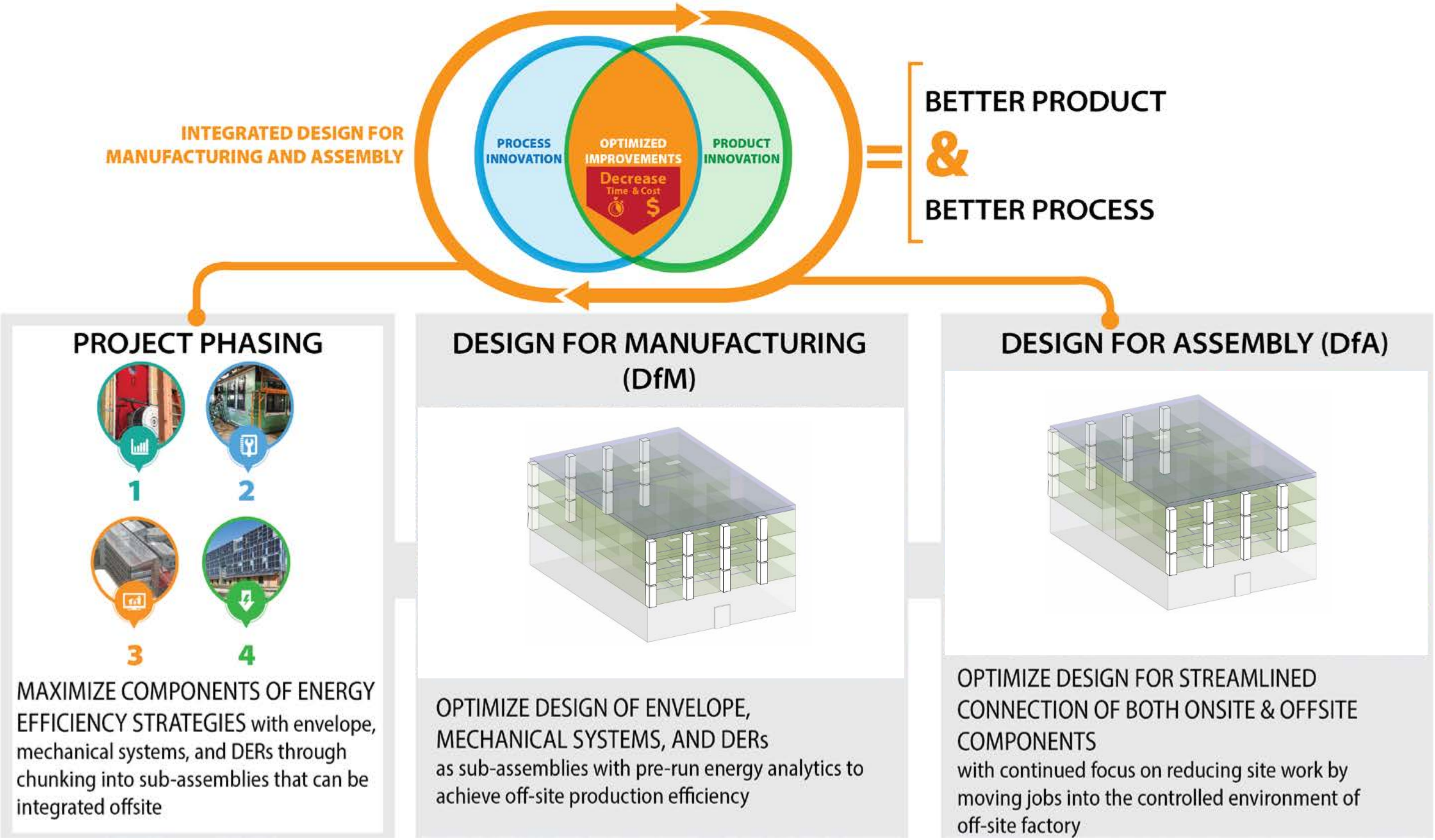
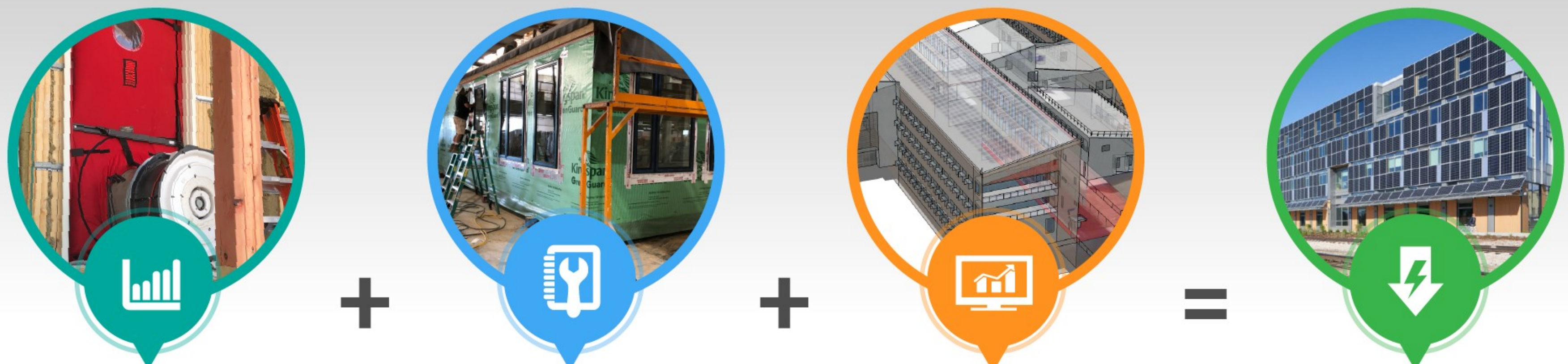


Figure created by NREL

Integrating Energy Efficiency Strategies

- 3-year DOE project, now into the last year
- Wood-framed and Steel-framed volumetric modular construction partners
- ***"How can optimal integration of Energy Efficiency strategies with Permanent Modular Construction be achieved with little or no additional cost, labor, or lead time?"***



Benchmark

- Code → High Performance
- Pilot technologies
- Baseline dataset from factory partners

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Recommendations and Factory Pilot

Develop initial set of energy solutions for factory partners to consider

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Discrete Event Model

- Modeling
- Simulation
- Baselining: code to high performance pilot technologies

=

Integration: Energy Savings/ Cost Effective

Document cost savings pathways for replication

Figure created by NREL

Design for Manufacturing and Assembly (DfMA) of Energy Efficiency (EE) Strategies

Explore strategies that maximize factory assembly scope

- Factory installed EE strategies can simplify installation, better control scope and scheduling, enhance quality, standardize means and methods, increase construction productivity, and reduce overall construction timelines

- Quantify trade-offs for strategies that increase cost of module but reduce construction cost/time/complexity and/or eliminate on-site scope

This allows modular solutions to maximize cost effectiveness of EE solutions and leverage industrial engineering and advanced manufacturing approaches to increase productivity and reduce first cost of construction

Overall DfMA for EE in Modular Recommendations

Compartmentalize (modularize) EE in HVAC, DHW, Controls, and Exterior insulation systems to maximize in-factory installed measures

- **In-unit Energy Recovery Ventilator (ERV)** - no vertical ductwork/chases with fire blocking and dampers or rooftop site work
- **Distributed Domestic Hot Water (DHW) tanks** - Single pipe domestic cold plumbing system with reduced hot water distribution, No site installed rooftop boiler with DHW circulation system
- **In-unit best in class efficiency Air Source Heat Pump (ASHP)** - Eliminate rooftop site installed equipment and on-site installed refrigerant lines
- **Smart apartment control hardware** installed and programmed in factory - Digital divide, access control, leak sensors, submetering, property management feedback and thermostat control
- Exceed code required **exterior wall insulation** levels within the wall structure - Eliminate exterior continuous insulation scope
- Factory quality control for **air tightness –** inherent air tightness from high quality factory envelope and opportunity to streamline application of modular apartment air sealing strategies

Strategy: Off-Site Wall Framing with ITSs

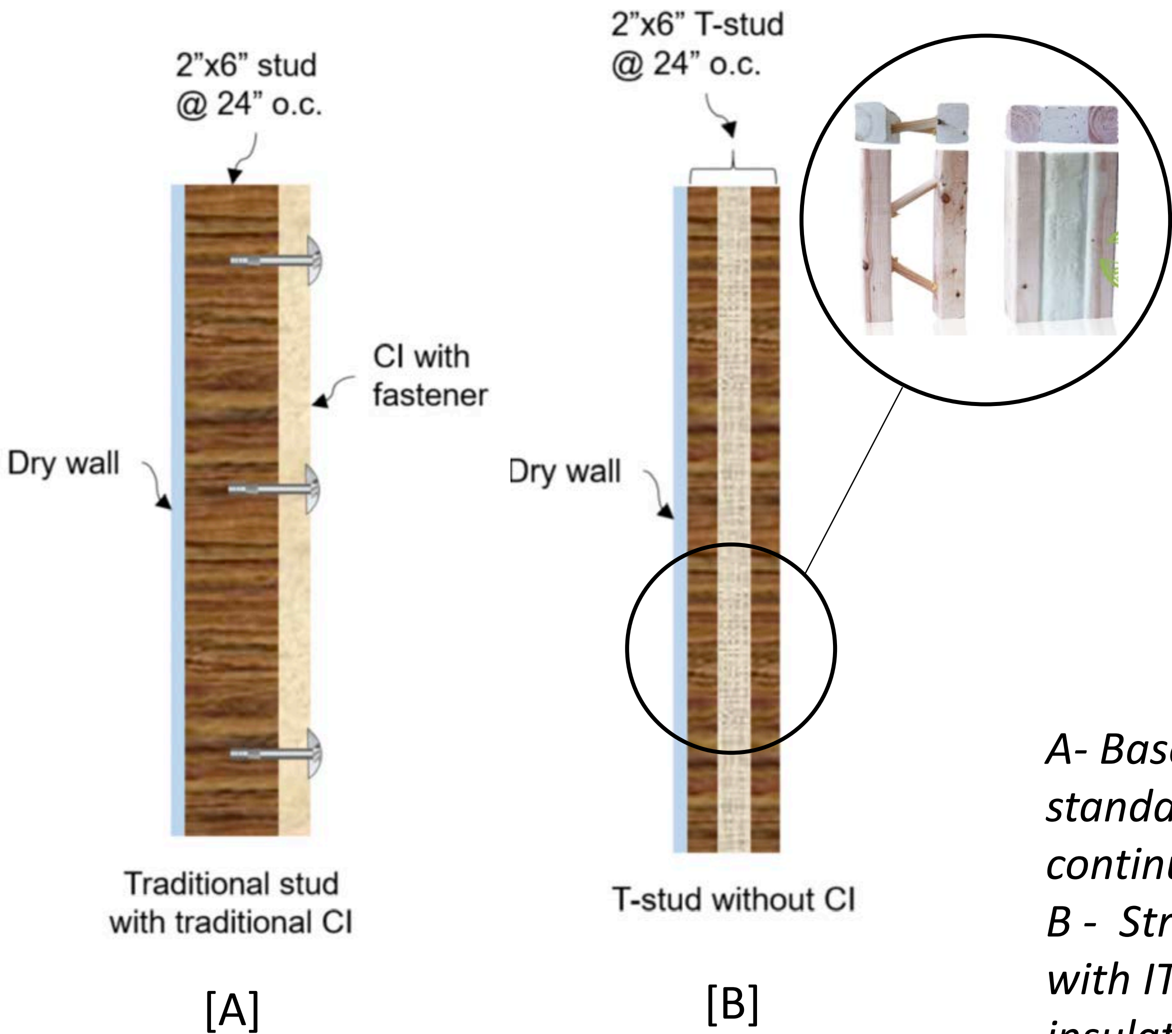


Figure created by NREL

Benefits from Off-site wall framing with Insulated Truss Studs (ITSs) [B]:

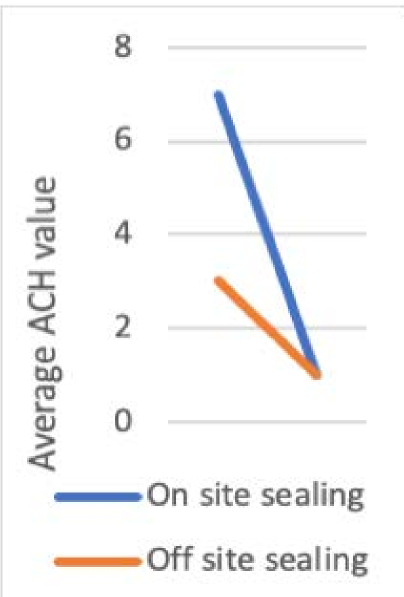
- Reduced labor-minutes by **63%** for framing
- Reduced total material used by **38%** for wall framing
- Reduced cost (material + labor) by **78%** for wall framing

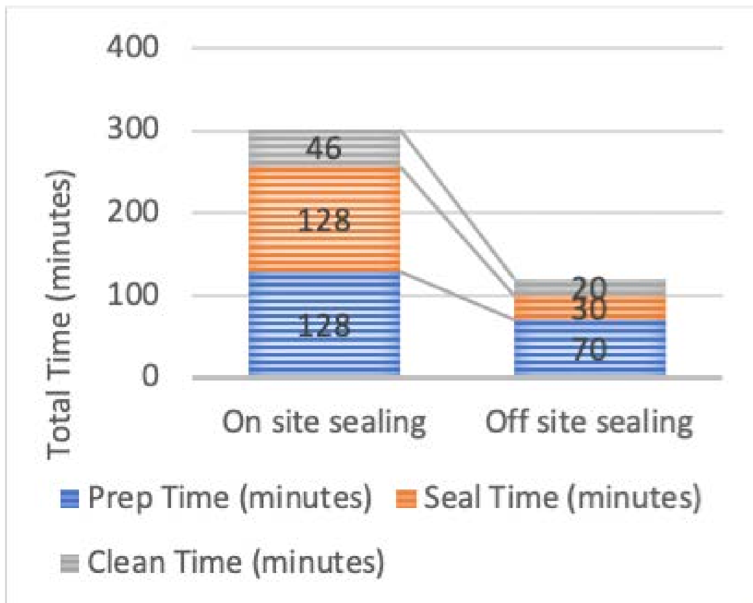
A- Baseline: Off-Site Wall framing with standard 2x6 studs followed by on-site continuous insulation

*B - Strategy: Off-Site Wall framing with ITSs and **no** on-site continuous insulation*

Strategy: In-Factory Atomized-Sealing of Envelope

Atomized-sealing of envelope in factory during industrialized construction of modular apartment or hotel guest room units (off-site sealing)





Starts in modules that are **60% more airtight**

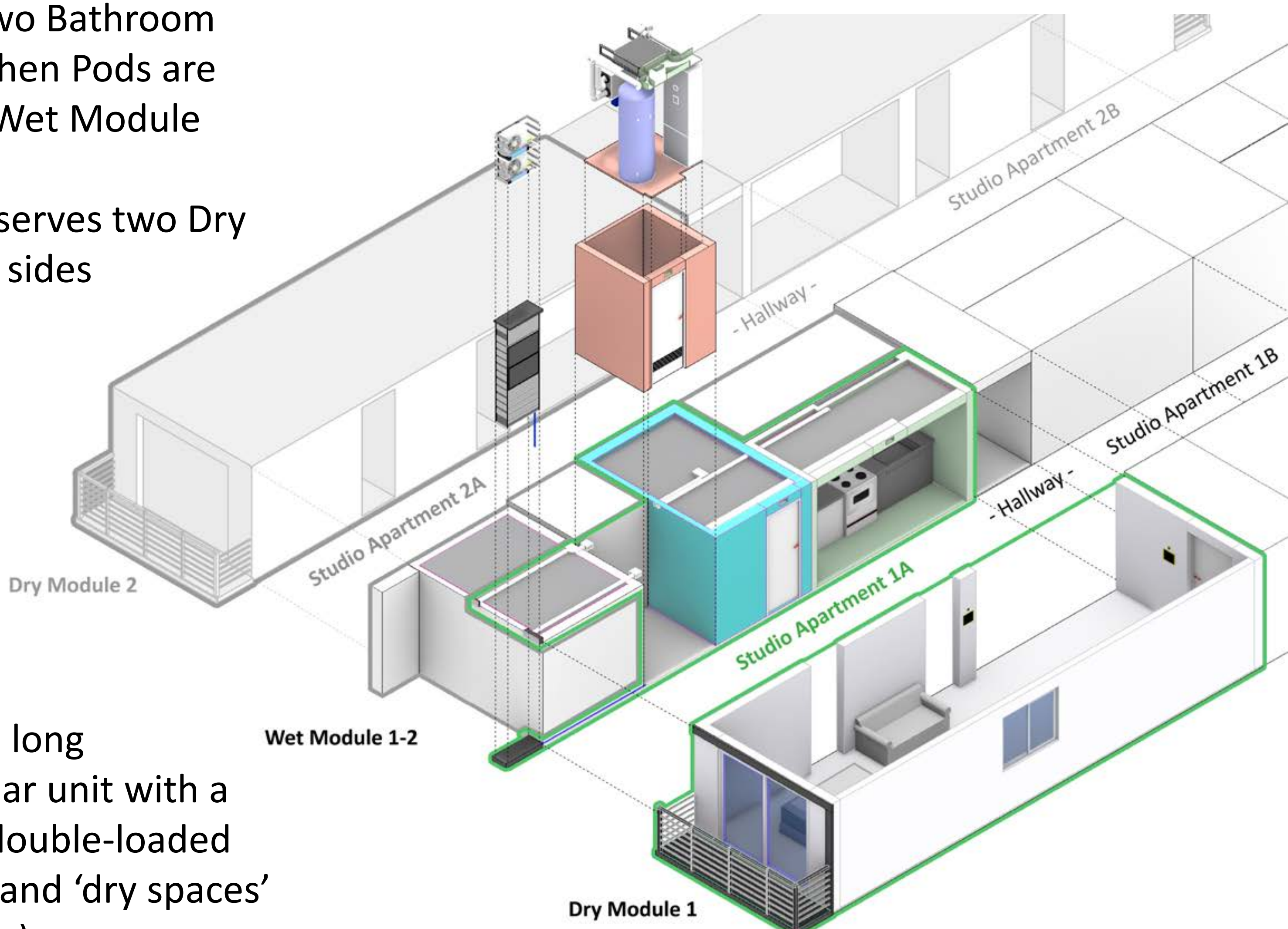
Takes 60% less total time to complete the three stages of **prep, seal, and clean**

Due to significantly **faster** sealing time, off-site sealing **brings down costs by 40%**

vs. Baseline: aerosol-based sealing on site during/after site construction of multi-family and hotels

Focus Strategy: Integrated Mechanical Pods

- Two Mech Pods, two Bathroom Pods, and two Kitchen Pods are chunked into one Wet Module
- Each Wet Module serves two Dry Modules on either sides



- A Dry Module is a long volumetric modular unit with a sliced section of double-loaded corridor (hallway and 'dry spaces' of two apartments)

Figure created by NREL

Precedents: Sub-assemblies and Pods

Can we imitate the bathroom pod approach for mechanical system?

BATH PODS → UTILITY CUPBOARDS

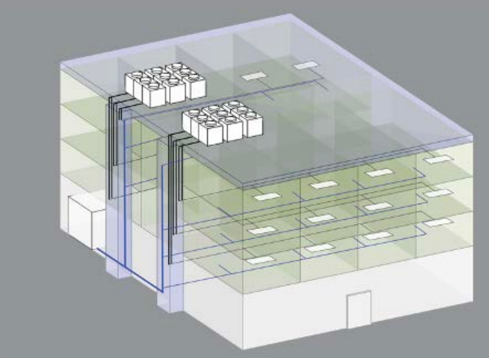
Bath pods are:

- Prefabricated
- Installed on-site or on factory line

- *Prefab 'Utility cupboards' in the UK* took 18 man-hours to build vs 42 hours for those constructed on-site
- 44% cheaper, including factory overheads; 73% fewer defects

From Centralized to Unitized

Centralized System

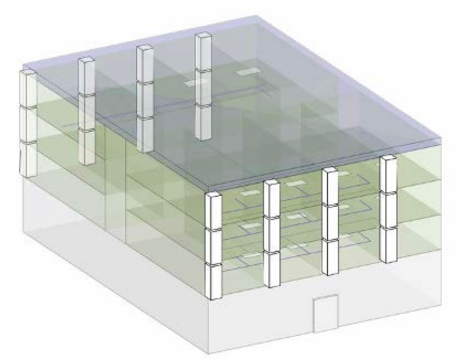


Almost entirely site work

Semi-Centralized Systems by Floor

Opportunity to move work to factory

Unitized Systems

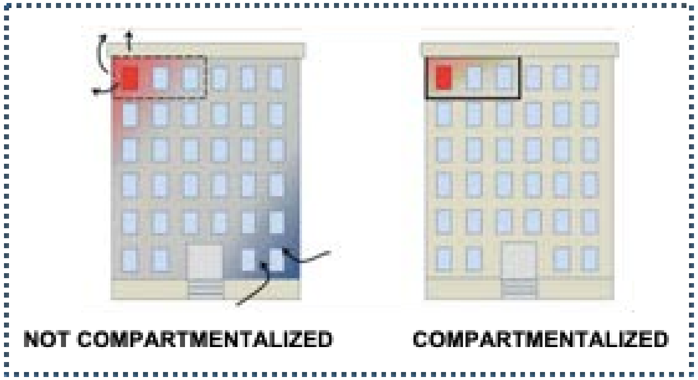


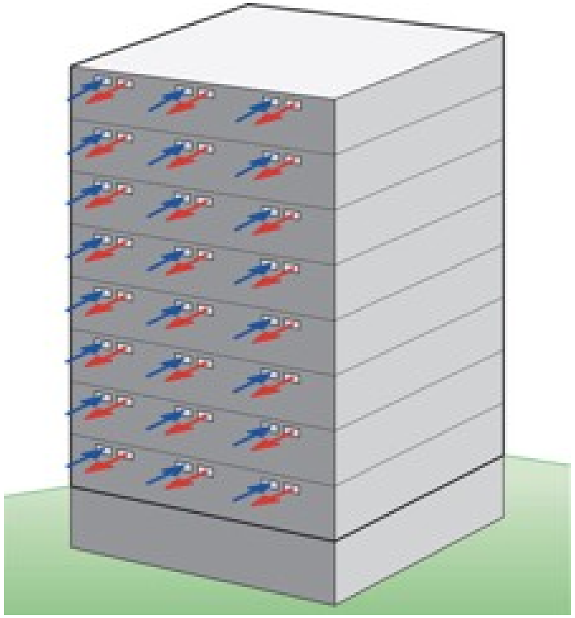
Fully factory installed as pod

Figure created by NREL

Benefits of Apartment “Compartmentalization”

- Air sealing to **control unwanted air movement** is one of the most cost-effective means of reducing building energy consumption
- **Reduces stack effect**, noise, and odors; improves fire stopping, comfort, and indoor air quality; and provides a first line defense against pests





All Strategies in one Modular Unit (Studio)

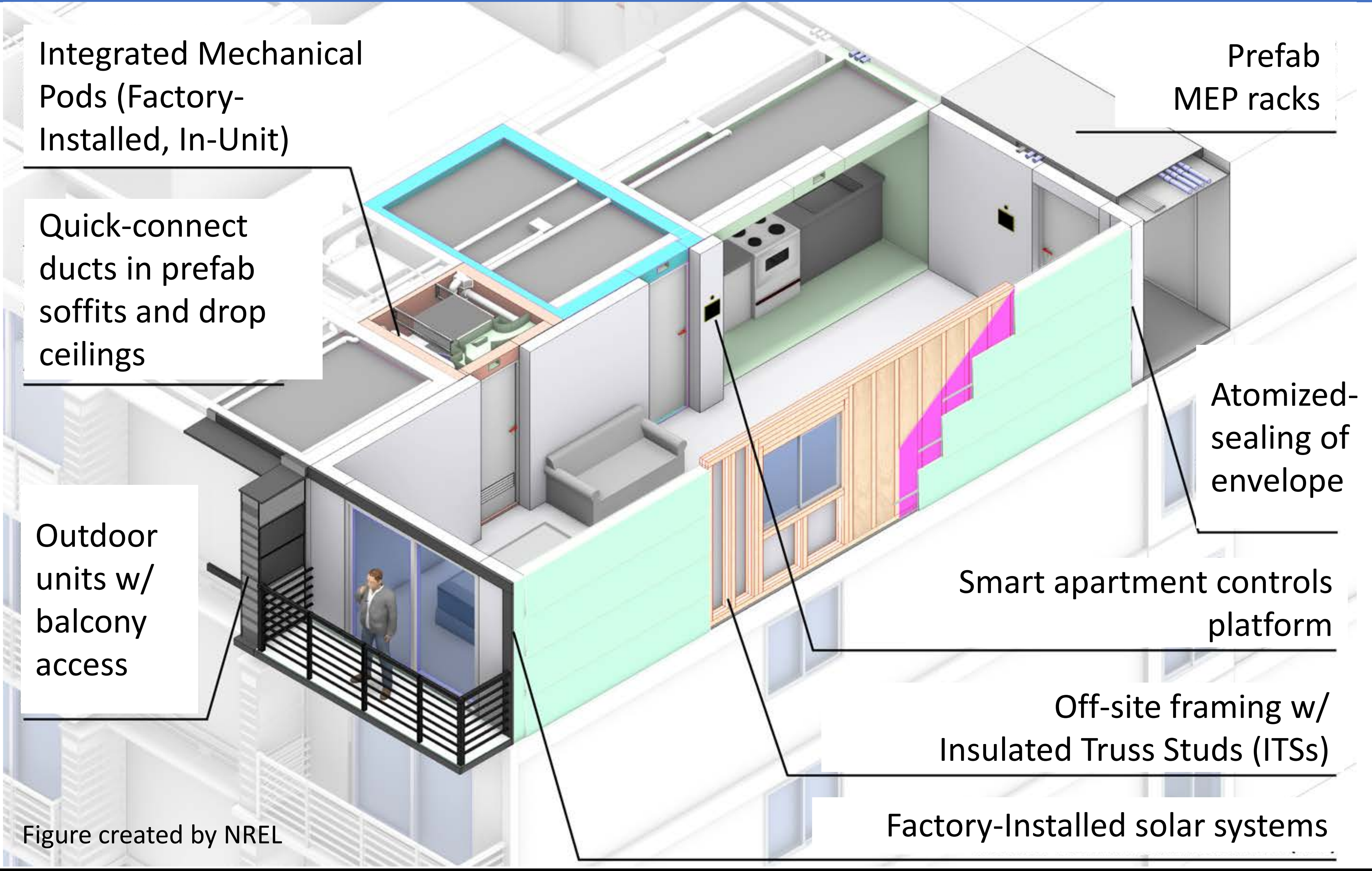


Figure created by NREL

Whole-Building Strategies Integration

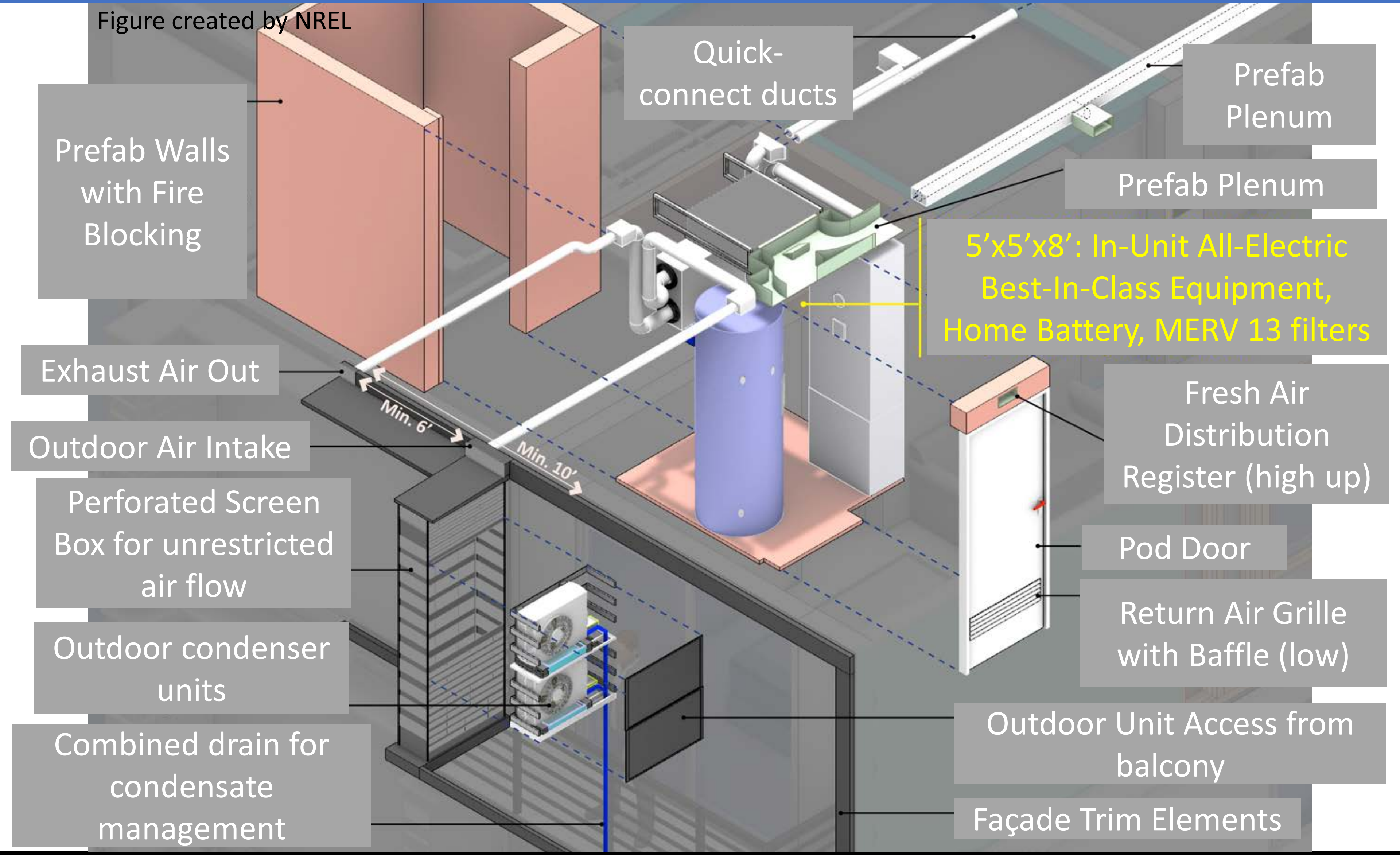
Figure created by NREL

Minimize Site-work

Integrate Mechanical system components such as outdoor air intake/exhaust air/outdoor units' screen boxes to Façade

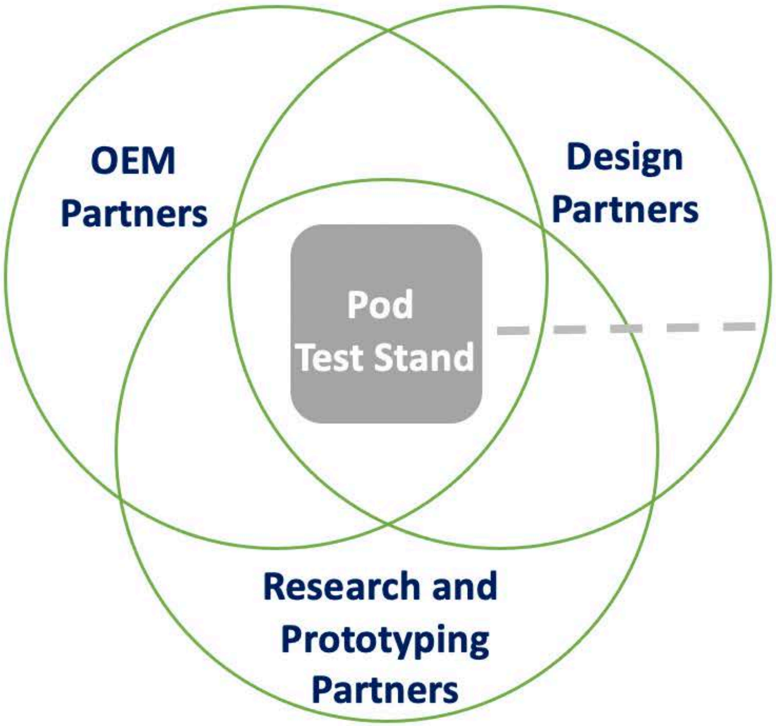
Consider Prefab balconies

Structural and Functional Components

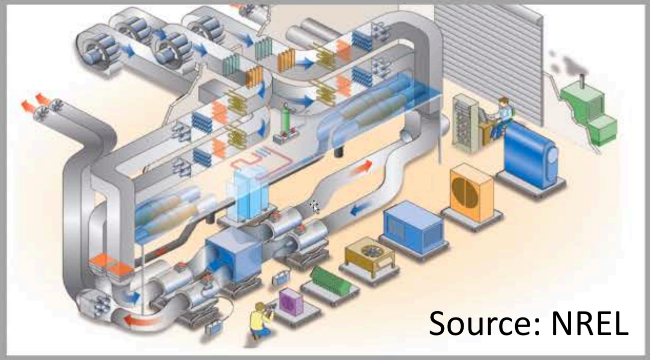


What is a ‘Shared Development Platform’?

We are building out a shared development prototype platform centered around Pod Test Stand at Golden CO campus for testing various pod configurations with various equipment and at various emulated outdoor and indoor conditions.

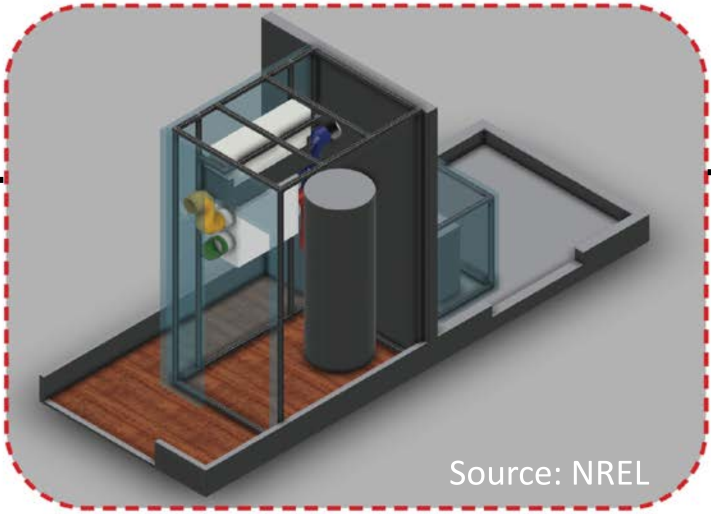


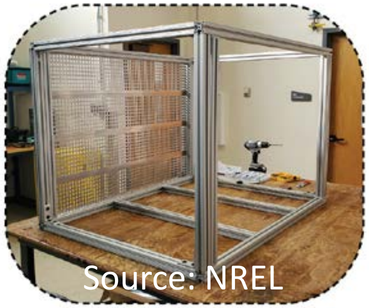
At HVAC Lab
in Thermal Test Facility (TTF)


Source: NREL


Source: NREL

Pod Test Stand: At the heart of the Platform





- To develop a set of standard site-installed conditions and recreating typical daily load profiles to define the baseline assessment
- To compare this baseline to various prefabricated configurations of pod and control integration scenarios for emulated outdoor air temperatures (middle winter and summer)
- Optimum size of the prepackaged solution
- Ease of replacing like-size components but of different functionalities
- Ease of access to the exterior grille/screen
- Ability to perform standardized summer/winter/swing season tests
- Integration of low-load, medium static ERV ductwork and controls

Need and Value: Shared Development Platform

- No one OEM offers all structural, functional components, and MEP equipment necessary to achieve **all three: space conditioning, energy recovery, and domestic hot water**

- Value in bringing together **off-the-shelf products**/equipment

- Collaboration **opens the opportunity to perform integration studies, pod product development, and validation** of the such an integrated 'productized' system

- Innovation lies in creating a **hardware-in-the-loop** platform, allowing industry to **easily adopt and implement** the pods for projects

Vision for Future Collaboration

- To ensure **open-access, widespread knowledge dissemination**, we invite a wide range of **original equipment manufacturers (OEMs), appliance manufacturers, MEP product development teams, MEP subcontractors, chassis builders, other industry stakeholders, and relevant consortiums** to be part of this project

- Contributed products towards this project would be integrated as part of the testing at Pod Test Stand through 2021

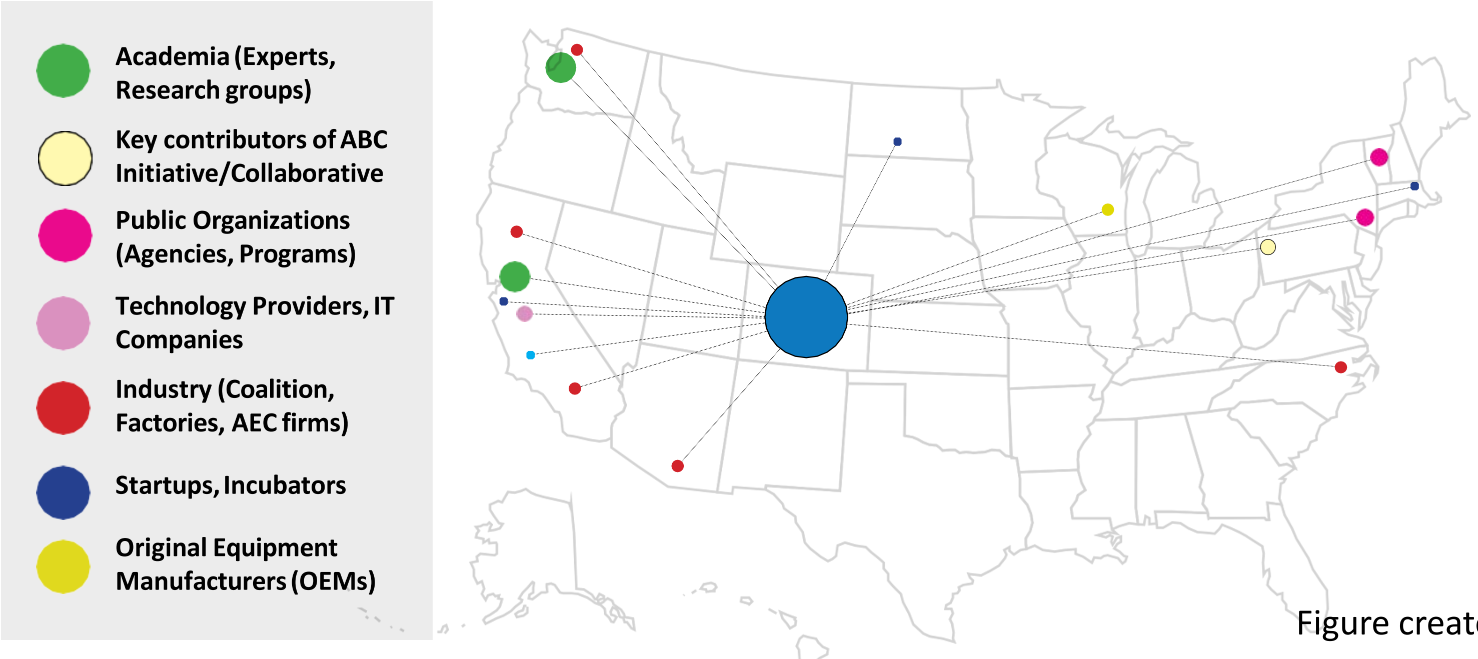


Figure created by NREL

Part 1

Factory-Built

Zero-Energy Modular Homes

Affordability

Peter Schneider
Senior Consultant, Engineering
VEIC

Zero Energy Modular HVAC Innovations

A Case Study of Factory-Built Energy Exchange Pods

About VEIC

VEIC is on a mission to generate the energy solutions the world needs.

- VEIC works with organizations across the energy landscape to create immediate and lasting change
- We serve as an objective partner for our clients as they navigate complex energy challenges
- Every challenge is different, but our commitment is the same: make an impact

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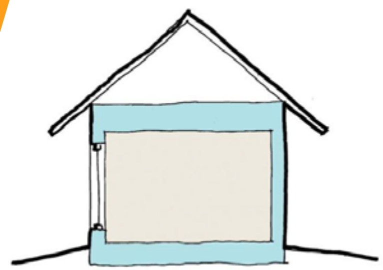
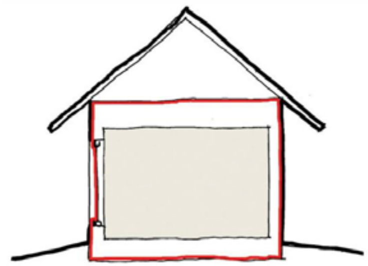
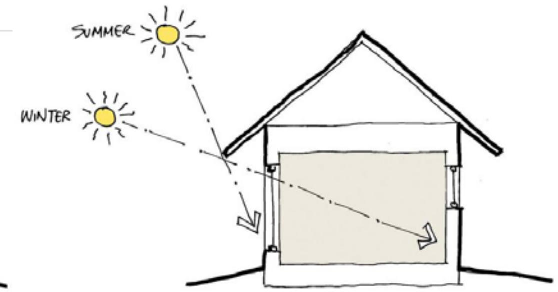
High Performance Standard



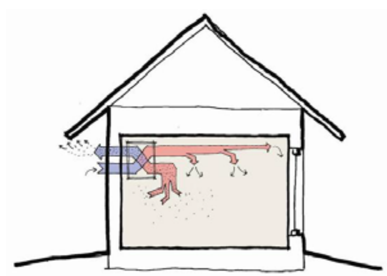
SUPER-INSULATED



AIRTIGHT



HIGH PERFORMANCE WINDOWS



FRESH AIR VENTILATION

ENERGY STAR

EPA INDOOR AIR PLUS

WATER SENSE

Why Zero Energy Modular (ZEM)?

- zero energy
- resilient
- healthy

AFFORDABLE

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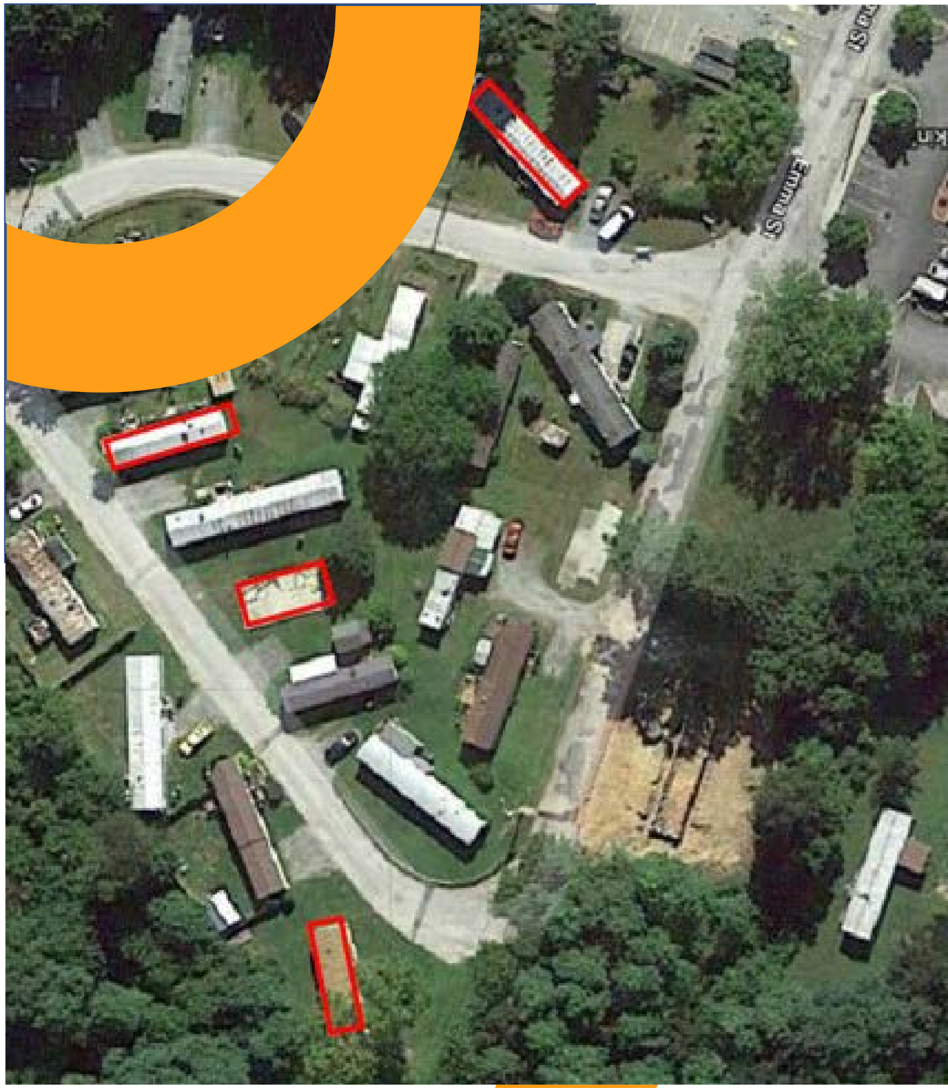
Mobile Home Replacement

Re-defining affordable housing

Delivering zero energy, high performance modular homes to vacant lots in existing, non-profit owned mobile home parks.

Each home is custom designed to optimize the site available. Homes are sold to income-qualified buyers and offered as low-income rental units, owned by park owner.

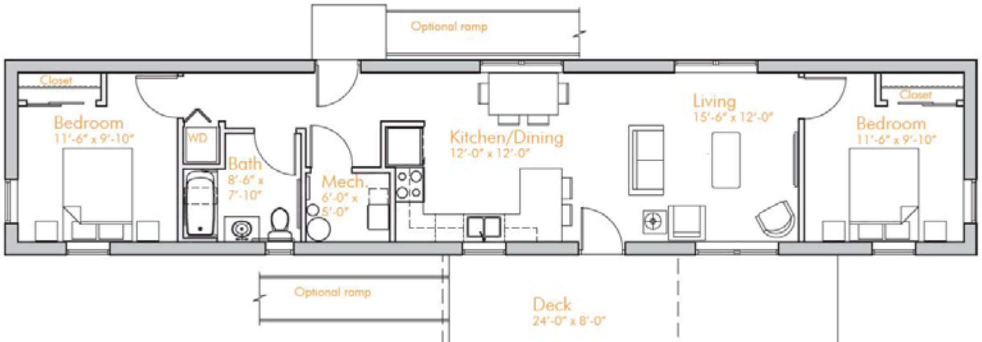


Simplifying HVAC Design & Installation

Typical ZEM home – 14’ x 70’

2-Bedroom, 1-Bathroom with open Kitchen, Living, & Dining Room.

5’ X 5’ Mechanical Room in Conditioned Living Space



2 bed / 1 bath home- Accessible unit
70′ x 14′

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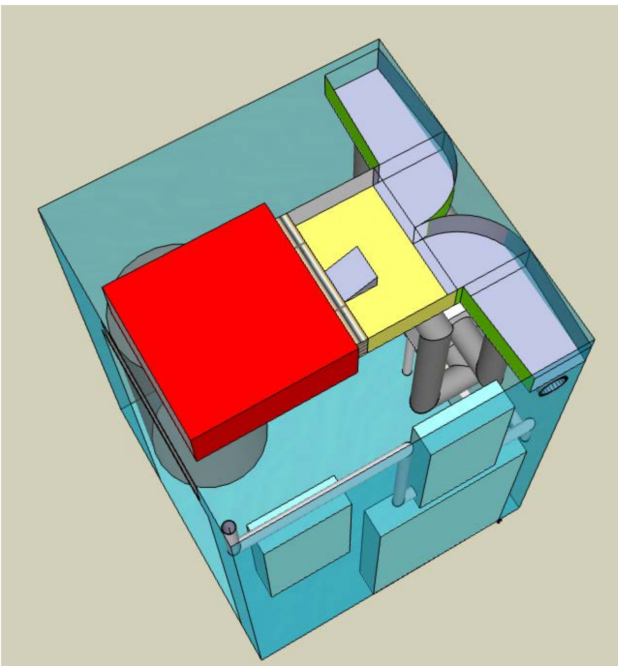
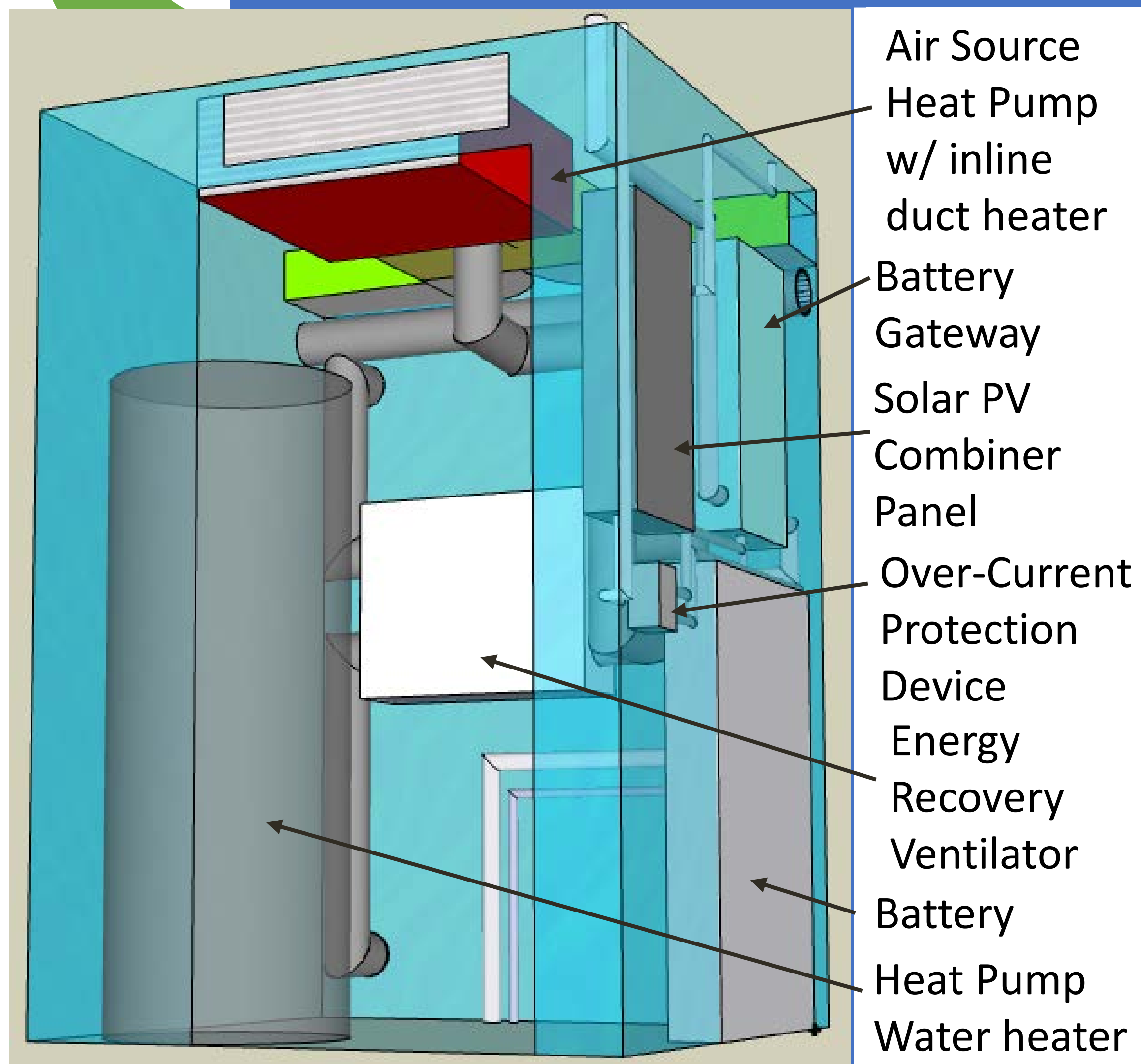
Energy Exchange Pod



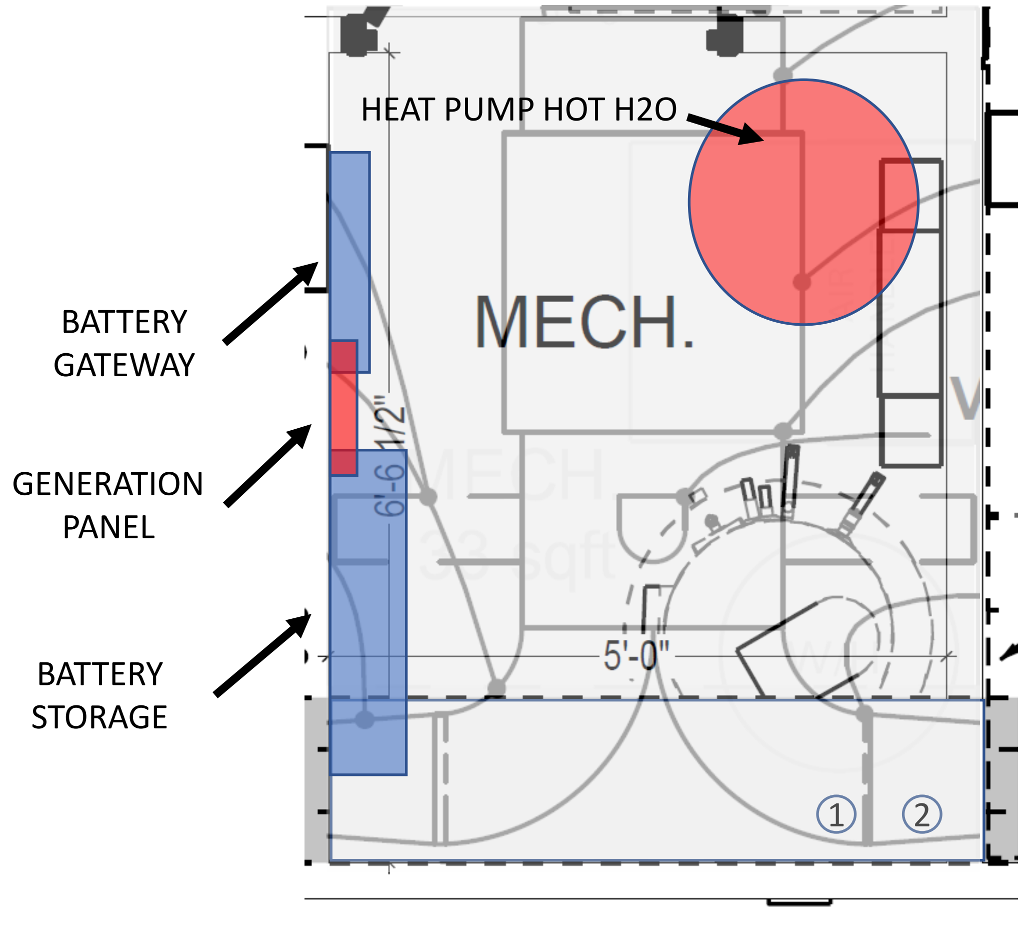


COMBINER BOX INTEGRATED INTO LIQUID APPLIED ROOF w/ TWO 10-3 WIRES FROM ROOF TO COMBINER PANEL (MECH RM)

- 8-3 wire from combiner panel to solar production meter at gable end
- 8-3 wire from production meter back to generation panel
- 2" and 1" conduit from battery gateway to main panel for service & non-load circuits
- ¾" Conduit from gateway to gable end for system emergency disconnect

Conduit to crawlspace:

1) Communication
2) Main water – sized larger to accommodate 2 layers of pipe insulation and heat tape



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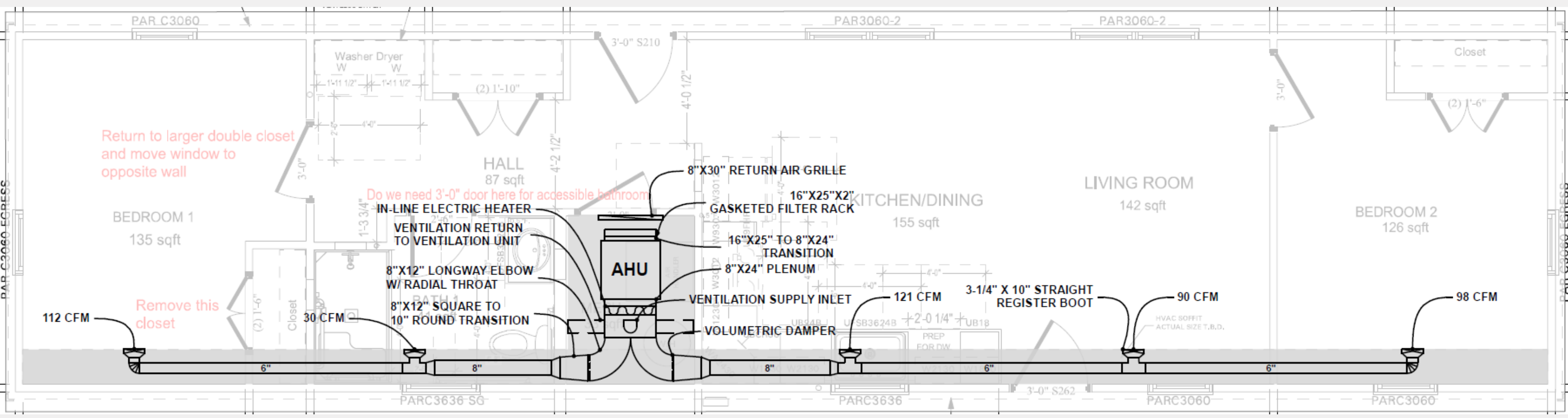
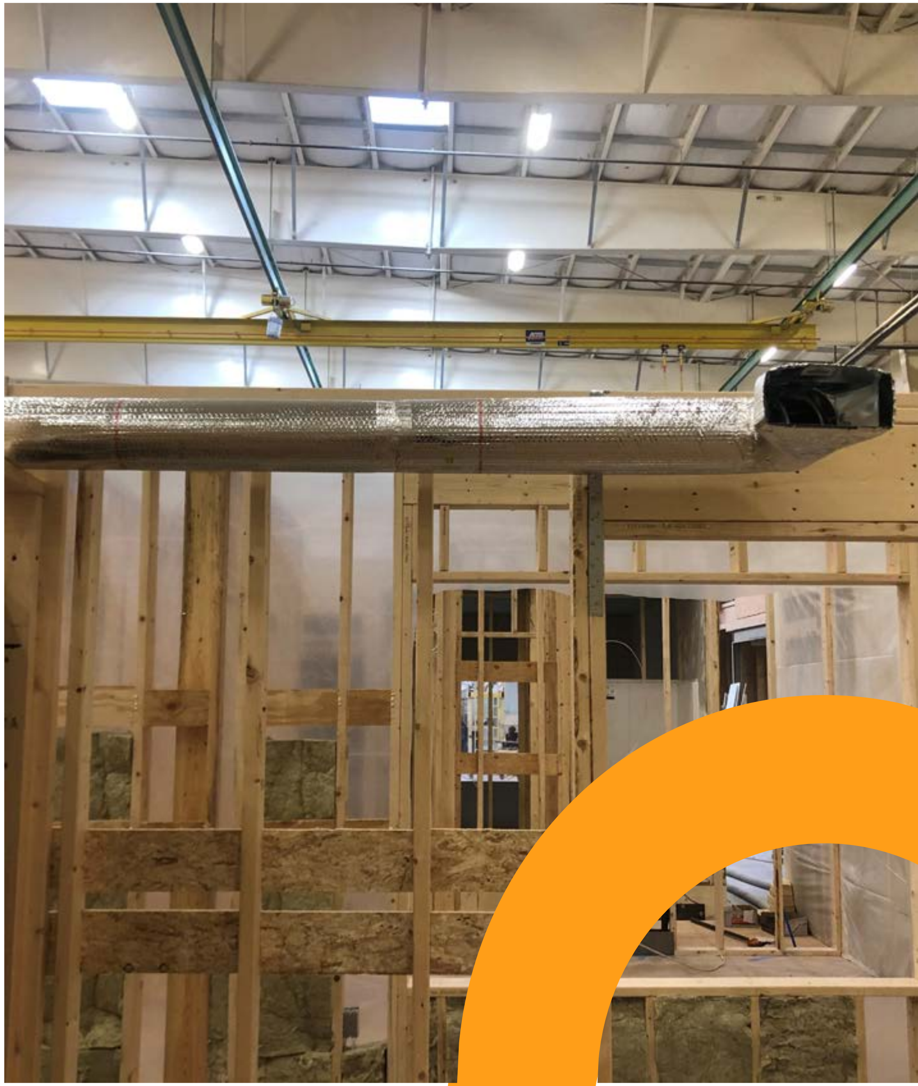
Distribution



Factory Install

Installing distribution at framing stage – gypsum wall
Board will run behind ductwork on walls and ceiling.



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Mechanical room

Plenum with integrated sweep to deliver air to both
Sides of the home and reduce resistance to airflow.

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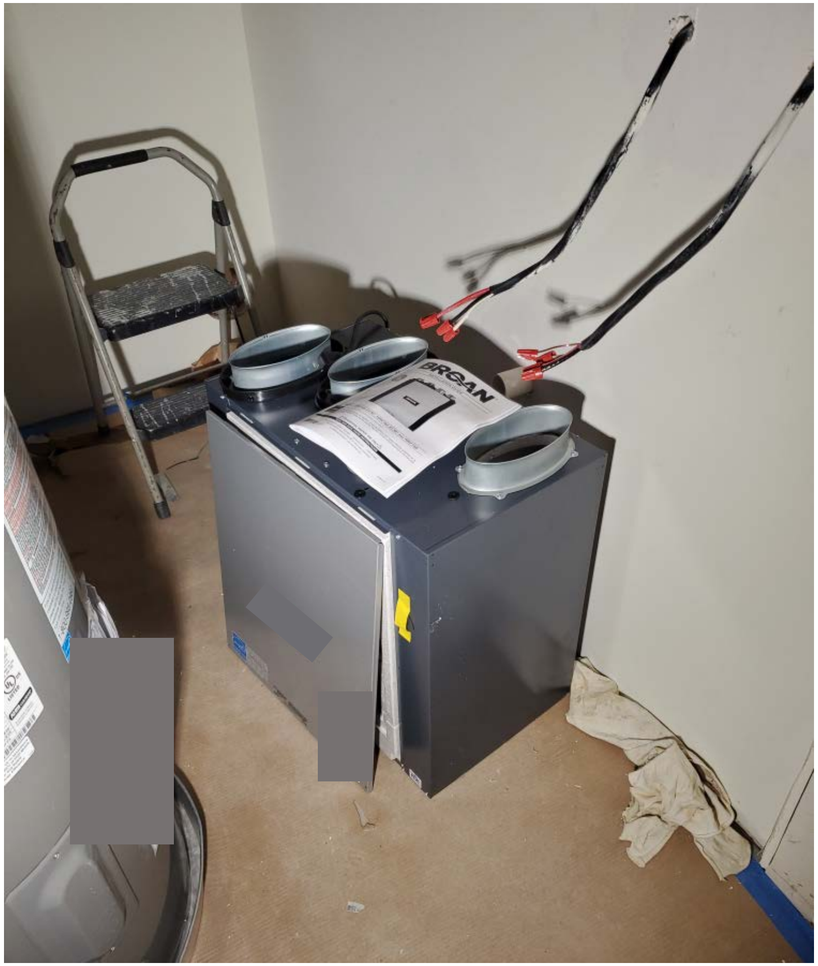
Coordinating equipment delivery to factory.

Tying HVAC equipment into distribution.



Ensuring proper space for install and future service.

Injection port for fresh air via ERV.

Condensate integration.

CO2 On-Demand Control.

Transfer grille for AHU return air.

Careful planning around plumbing & electric.

Heat pump compressor install. Gable end install so it can travel down the road.

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House delivered and set with HVAC already commissioned at factory.

Solar gateway.

Troubleshooting in the field.

To install in the field <u>or</u> factory?

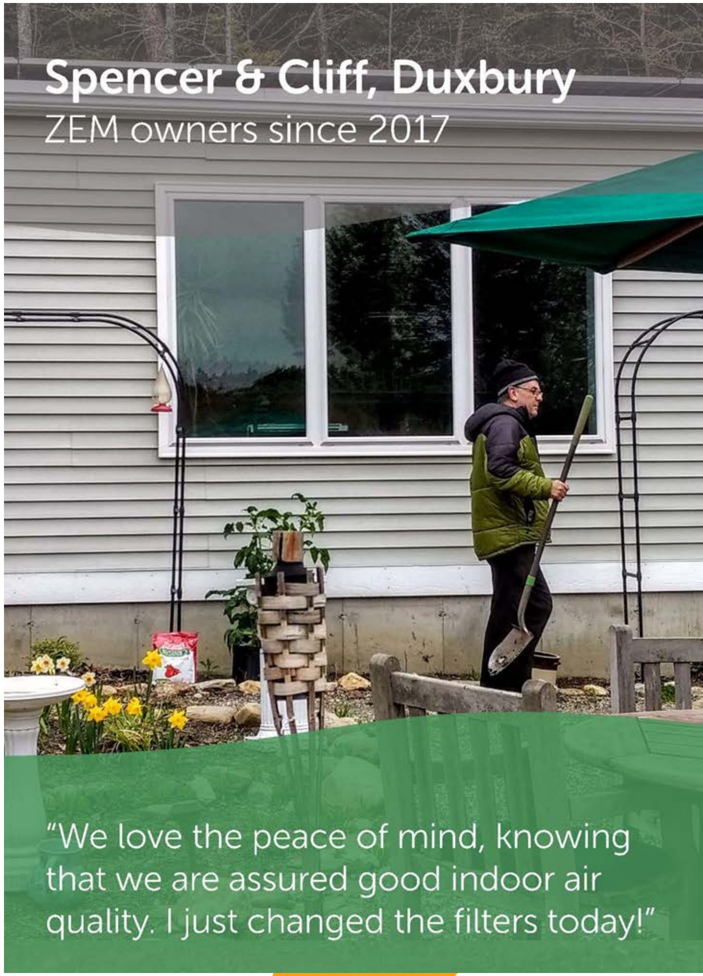
Where We're Heading

Next Steps…

- Develop Energy Exchange Pod frame in which to build system off-line
- Evaluate cost-benefit to building Pod off-line and flow of assembly line
- Evaluate process to crane set Pod into home and tie into module's distribution, plumbing, and electrical
- Incorporate full battery install in Energy Exchange Pod
- Evaluate how this applies to multifamily volumetric modular

Thank you.


Wally, Waterbury
ZEM owner since 2018
"Winter outages were stressful in my old house. When the power went out in my new home, I stayed in a t-shirt! The temperature hardly dropped."


Spencer & Cliff, Duxbury
ZEM owners since 2017
"We love the peace of mind, knowing that we are assured good indoor air quality. I just changed the filters today!"

Part 2

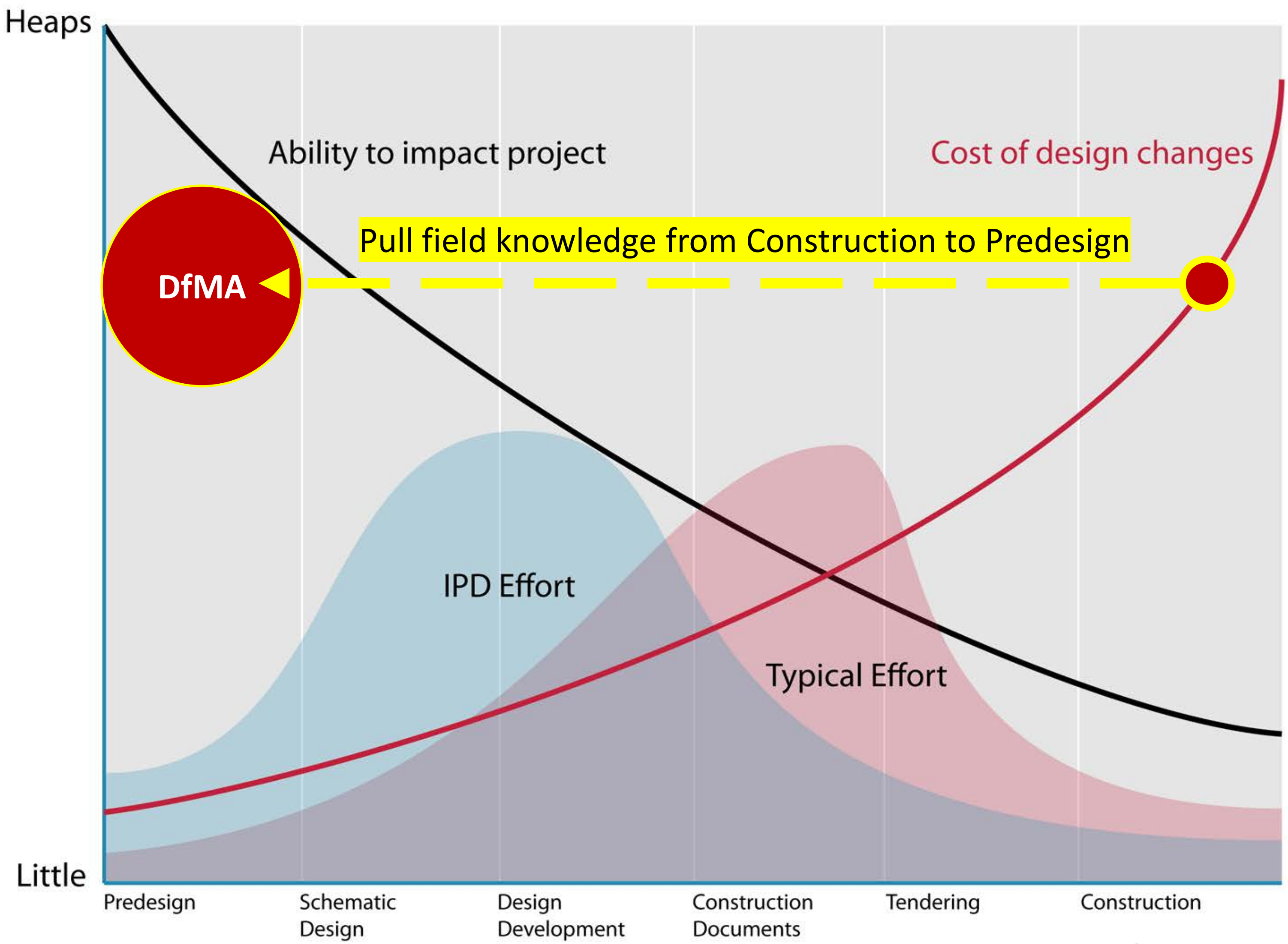
Ankur Podder
Buildings Advanced Manufacturing and Integration Science
Research Engineer
NREL

Design for Manufacturing and Assembly (DfMA)

DfMA Integration Logic and Rule-sets

Generative Variability and Rapid Prototyping

How to make DfMA really matter?



IPD= Integrated Project Delivery

MacLeamy curve (2004)

"Integration" can mean a lot of things

Chunking

Fusing

Homogenizing

Hiding

More…

Typical DfMA Integration Logic

Step 1: **Select** a system or a set of components

Step 2: If a system, **Decompose** into components

Step 3: **Integrate** components through:

1. Chunking
2. Hiding
3. Homogenizing
4. Fusing

…

Result: ***DfMA-informed productized solutions***

Typical DfMA Integration Logic

Step 1: **Select** a system or a set of components

Step 2: If a system, **Decompose** into components

Step 3: **Integrate** components through:

1. Chunking?
2. Hiding?
3. Homogenizing ?
4. Fusing?

...

How do we decide?

DfMA Integration Rule-sets

1.Chunking ? | 2.Hiding ? | 3. Homogenizing ? | 4. Fusing ?

Interactions between components → **Rule-sets**

- 1. Physical Interaction
- 2. Material Interaction
- 3 Energy Interaction
- 4. “Headache Factor”

Required?	4
Desired?	3
Indifferent?	2
Undesired?	1
Detrimental?	0

DfMA Integration for Mechanical Systems

Step 1:

Selected system: Centralized Mechanical Systems

Step 2:

Decomposed components:
In-unit All-Electric Best-in-Class Efficiency Equipment for Space Conditioning, Energy Recovery, and Domestic Hot Water

Step 3:

Integrate components through:

1. Chunking
2. Hiding
3. Homogenizing
4. Fusing

...

Result:

Integrated Mechanical Pod Solutions

1. Chunking: Precedent

Modular Process **Skids** in Industrial Engineering –
"System in a Box"

• Air handlers • Boilers • Chillers • Heat exchangers • Water heaters and tanks • Water pumps (for domestic, heating/cooling, and firefighting water) • Main distribution piping and valves • Sprinkler distribution piping and pumps • Back-up electrical generators • Elevator machinery • HVAC (heating, ventilation and air-conditioning) equipment • Uni-strut corridor modules containing HVAC, pipework, electrical tray/ladder/basket, sprinkler and drainage

1. Chunking: In-A-Pod

- Few major components: **Energy Recovery Ventilator (ERV), ducts, condensate management, indoor unit/Air Source Heat Pump (ASHP), air distribution plenum, Heat Pump Water Heater (HPWH), Battery, pod door with fresh air register and return air grille, pod platform, and pod chassis**

- All structural and functional components can be grouped into: **Generation components, Distribution components, Storage components**

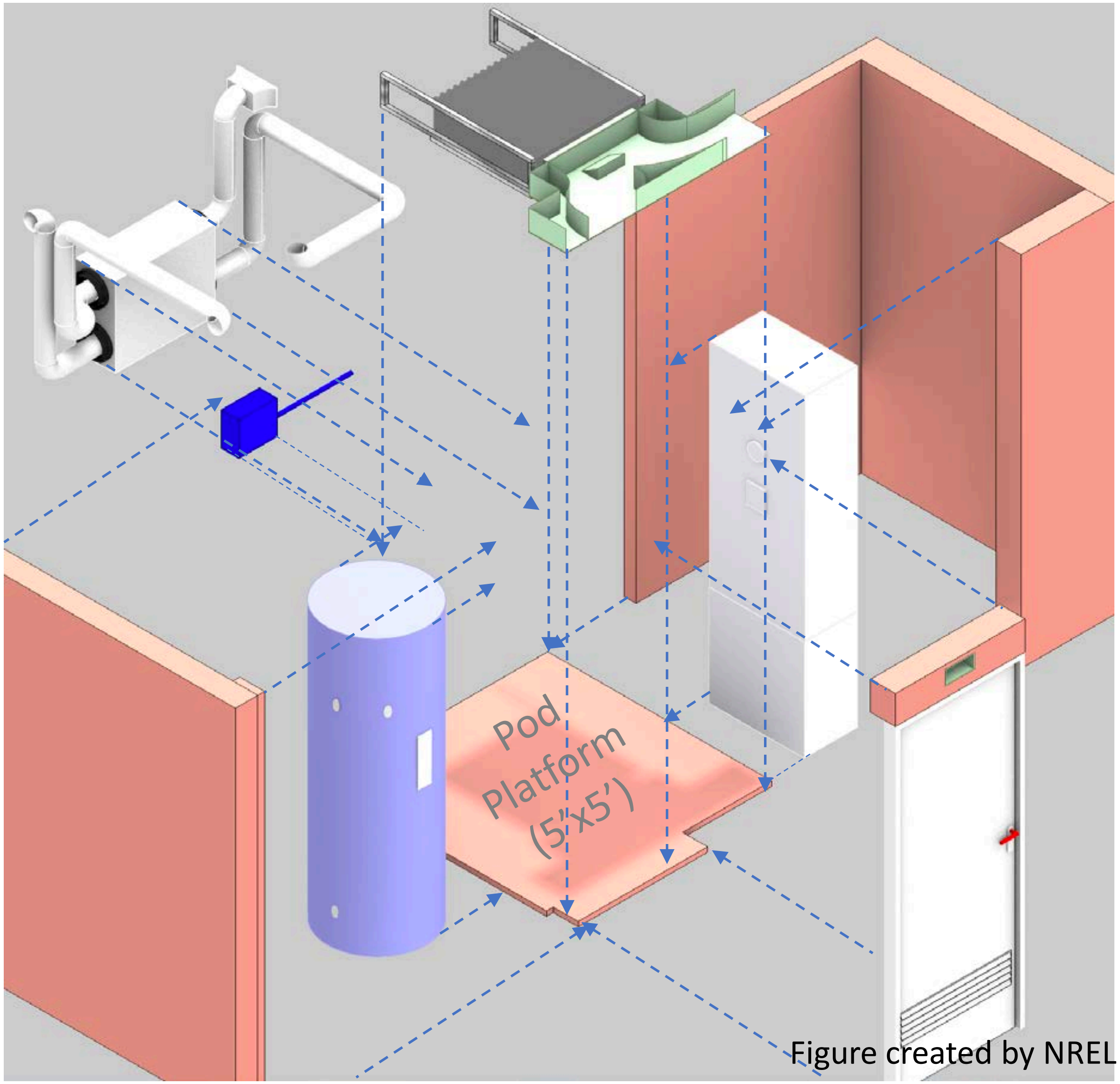


Figure created by NREL

2. Hiding: Precedents

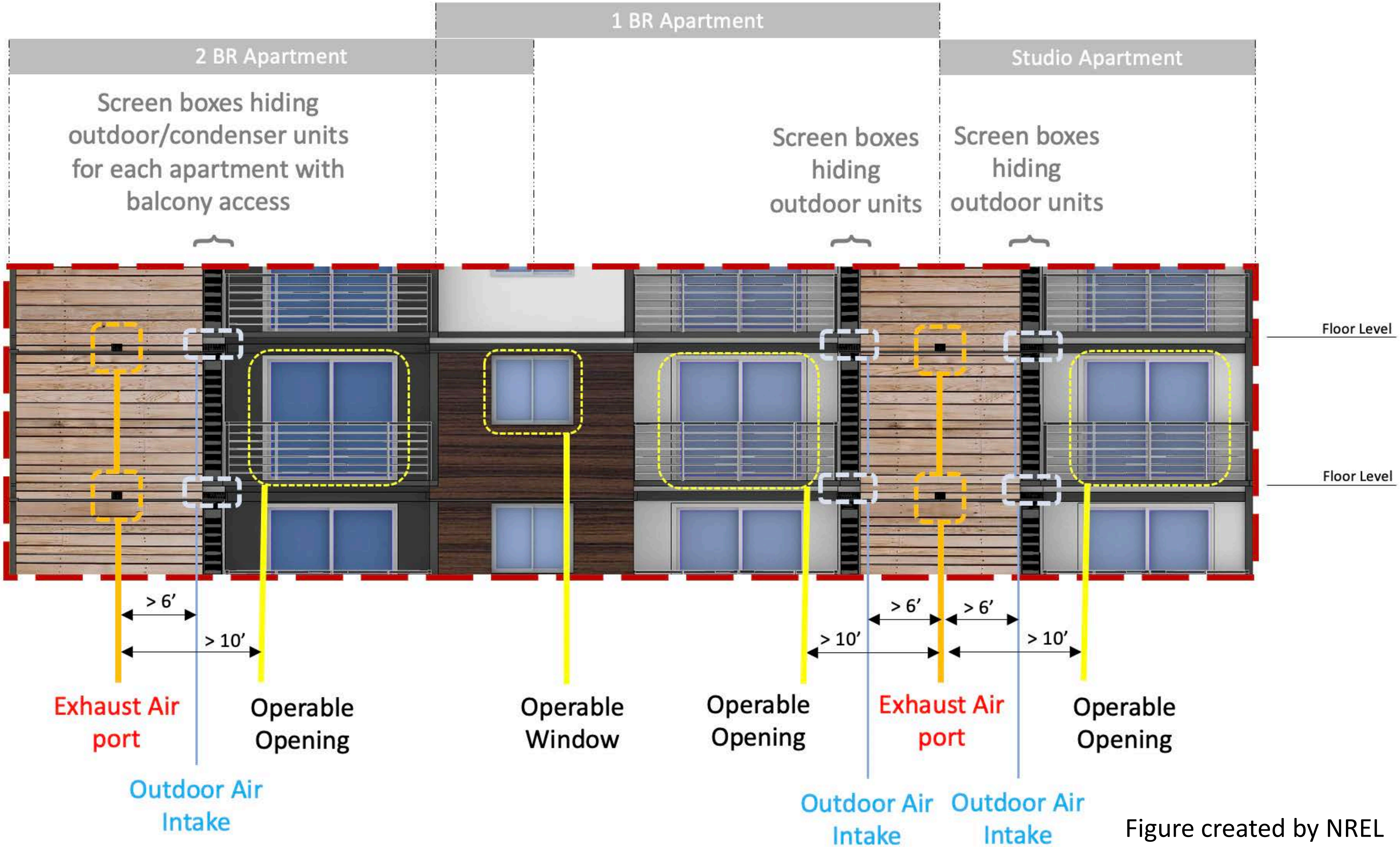
Not Integrated

Hidden: Screen Box, Façade Element, Indoor Feature

2. Hiding: Integration with Façade Elements

Figure created by NREL

2. Hiding: Integration with Façade Elements



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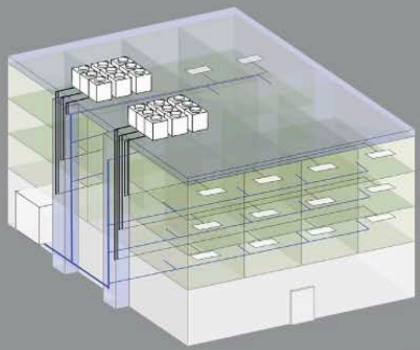
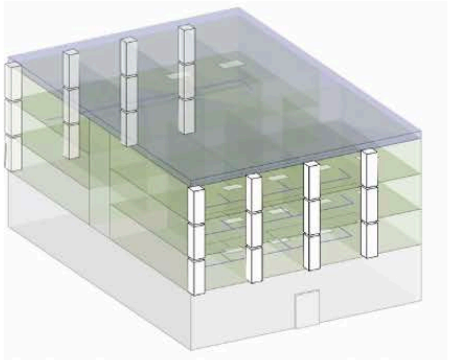
Integration is a Moving Target

Centralized System



Semi-Centralized Systems by Floor

Unitized



Extent of Chunking

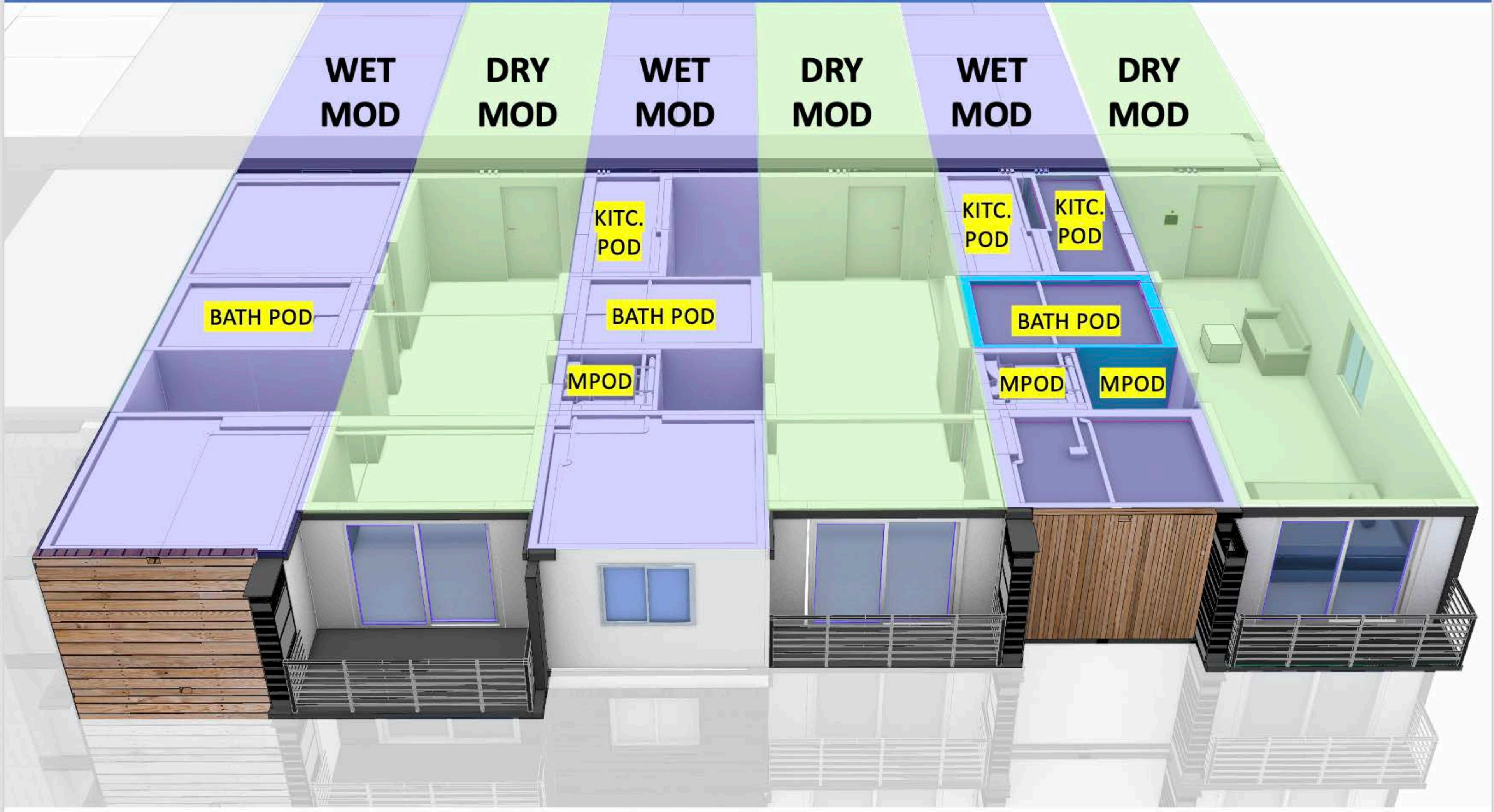
Extent of Hiding

Extent of Homogenizing

Extent of Fusing

Figure created by NREL

“Repetition” within Integration



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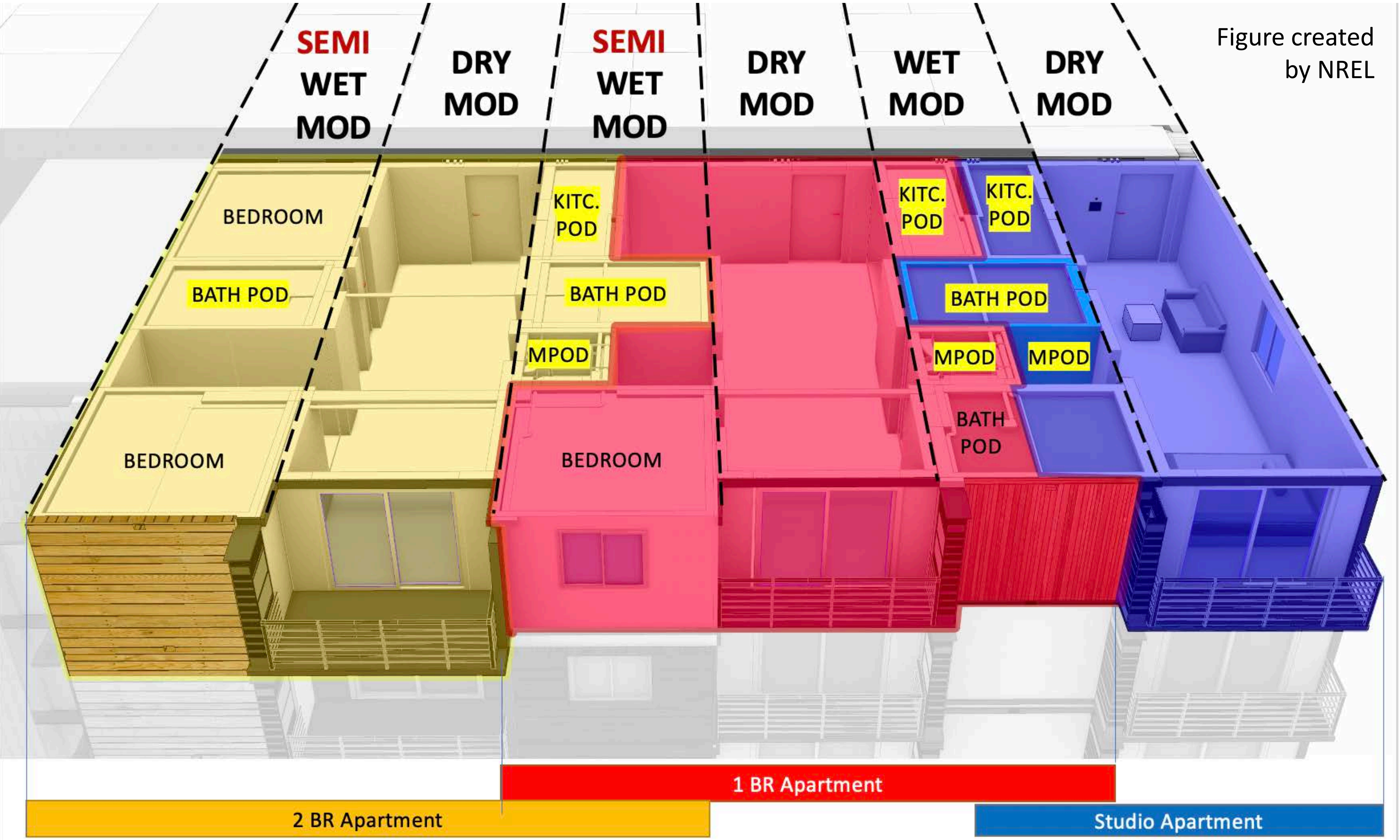
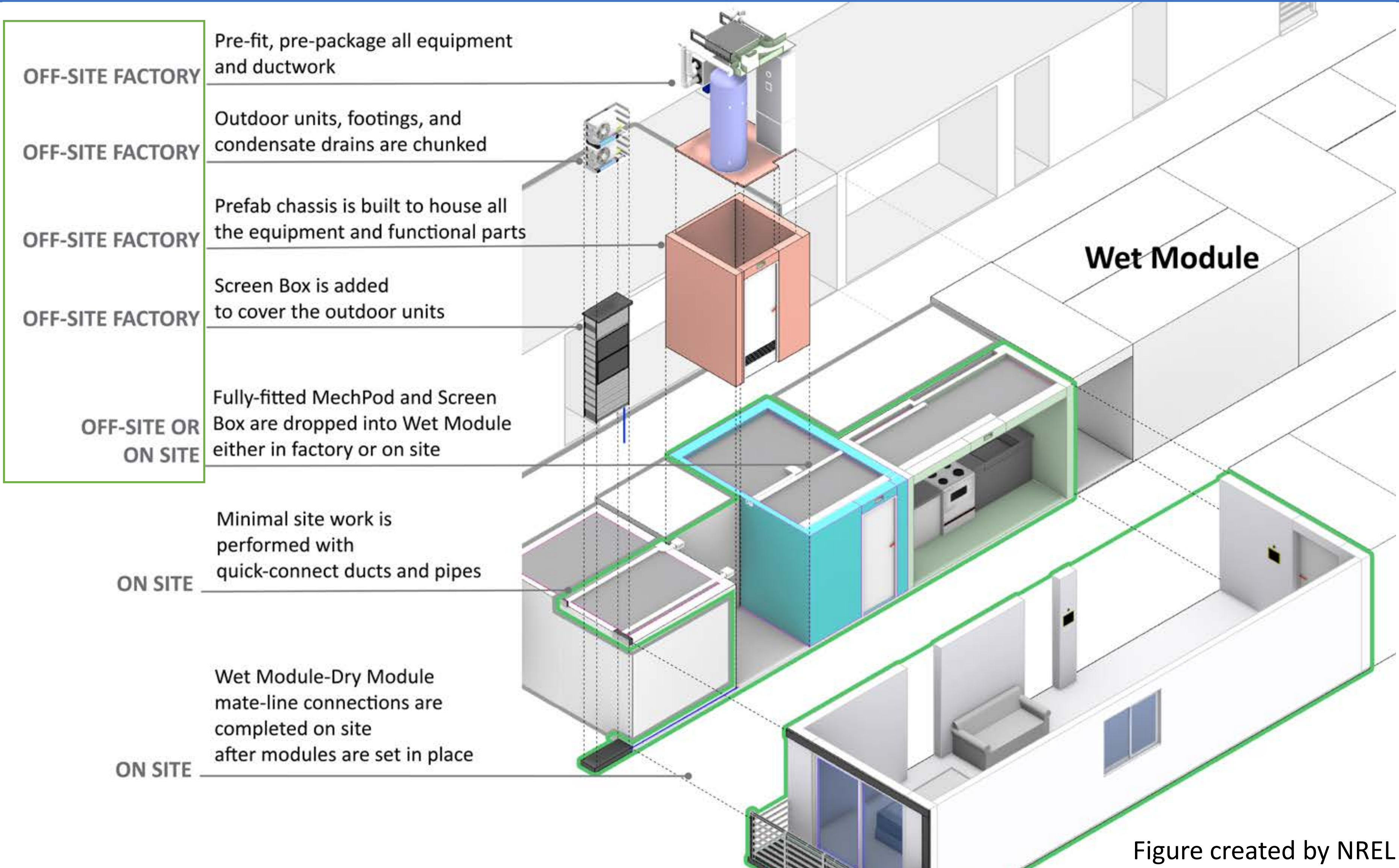
“Variability” within Integration



DfMA moves work from On Site to Off-Site Factory



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Part 3

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Process Analysis

Discrete Event Simulation

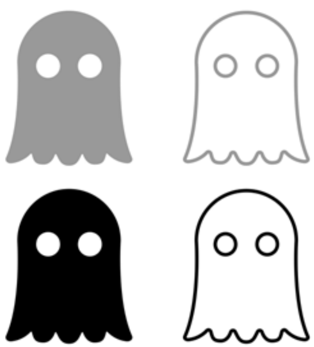
Virtual Reality

Understanding impact on processes

- Modular is attractive due to productivity gains possible
- Product change can impact processes in factory
- Processes are more important in factory due to tight integration between stations
- How can we understand the process impacts of creating subassemblies in factory floor?
- What other changes need to be made across factory floor to decisions need to accommodate sub-assemblies?

Understanding processes in Offsite

Many factories operate with daily **PLANNED** and **UNPLANNED** activities



The Invisible Factory Dilemma

= GAP

Digital Twin and Sensors tell you what **ACTUALLY** happens

Figure created by OSU

Digital Twins in AEC industry

- What is a Digital Twin?
  - Virtual model of a process and/or product that enables the pairing of virtual and physical worlds

- Current Digital Twin Usage in AEC
  - Building operation and maintenance (Qiuchen, et al. 2020)
  - Construction schedules for project management (Yusen et al. 2018)

- Current Industry Focus on <u>built product</u>

- We want to focus on <u>building process</u>
  - <u>Quantify effect of design changes and modularization on the process performance of factories</u>

Process-based Digital Twin

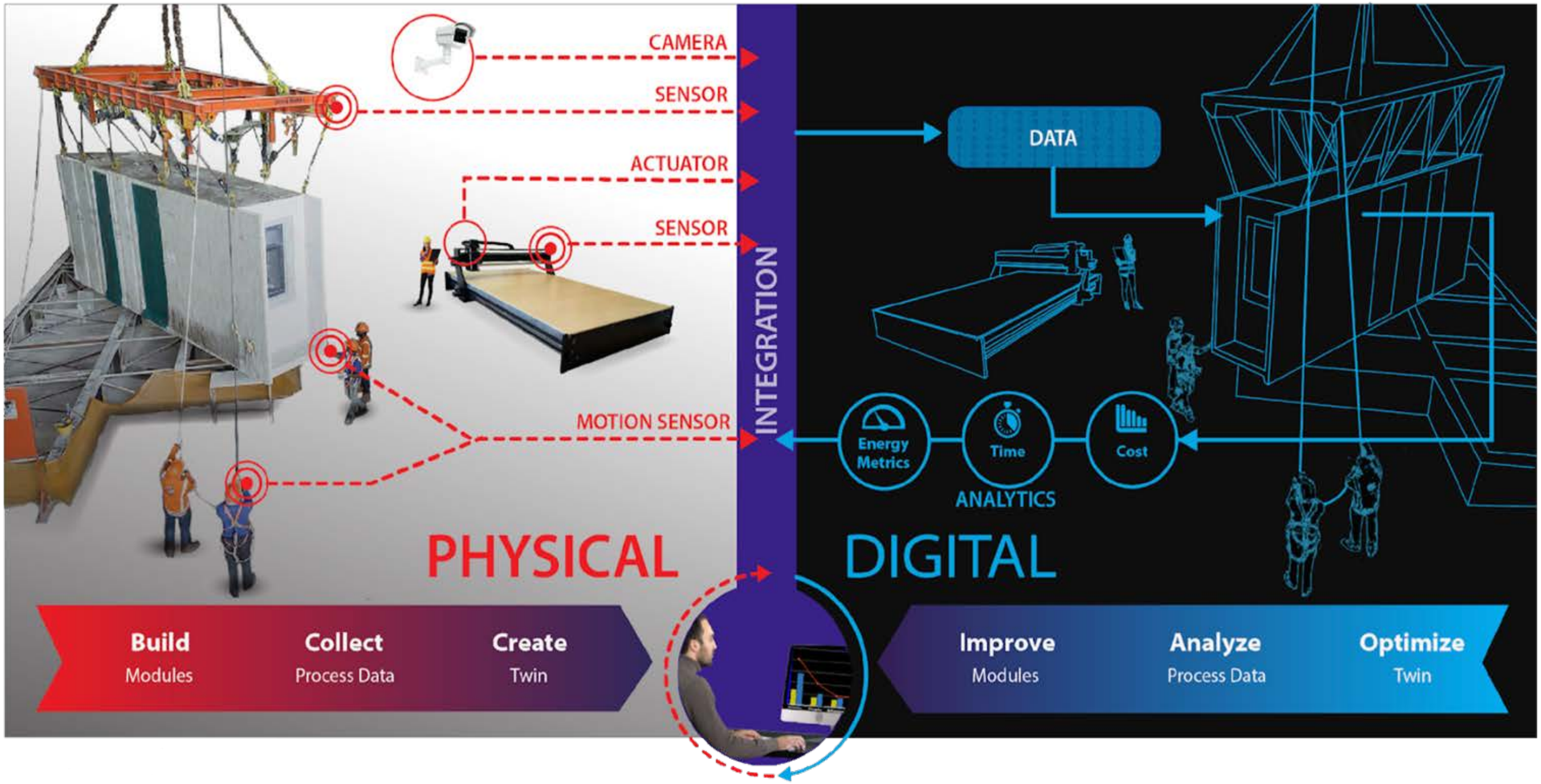
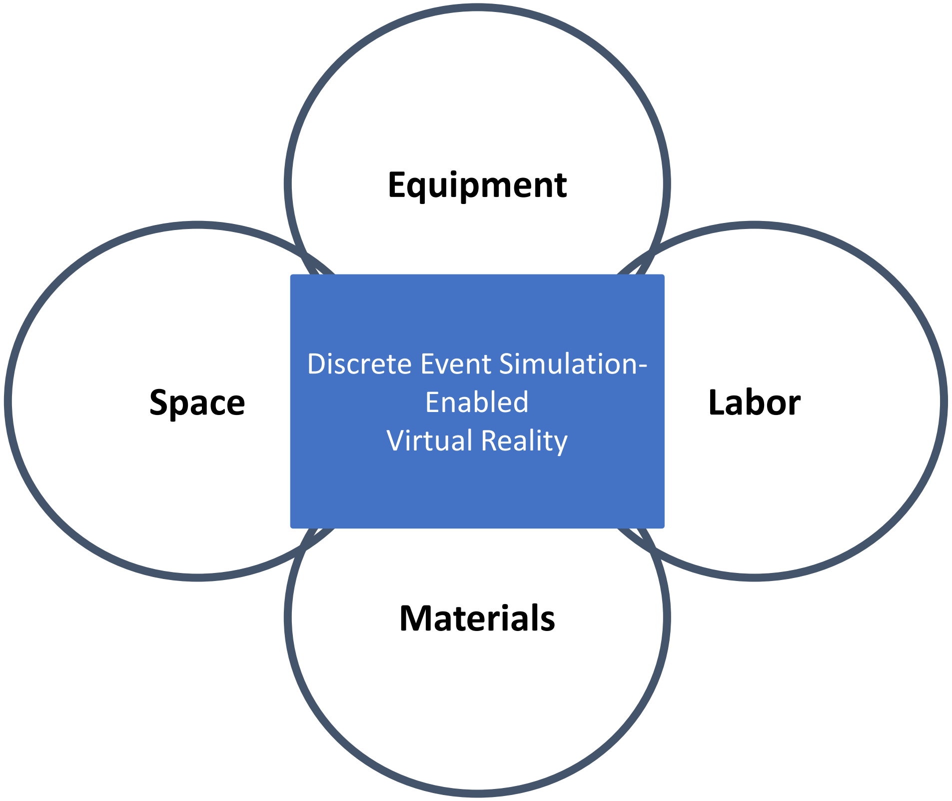


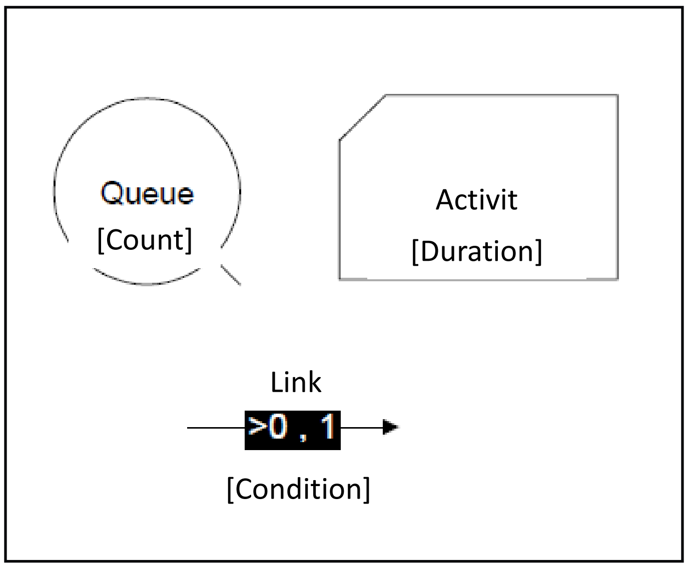
Figure created by NREL

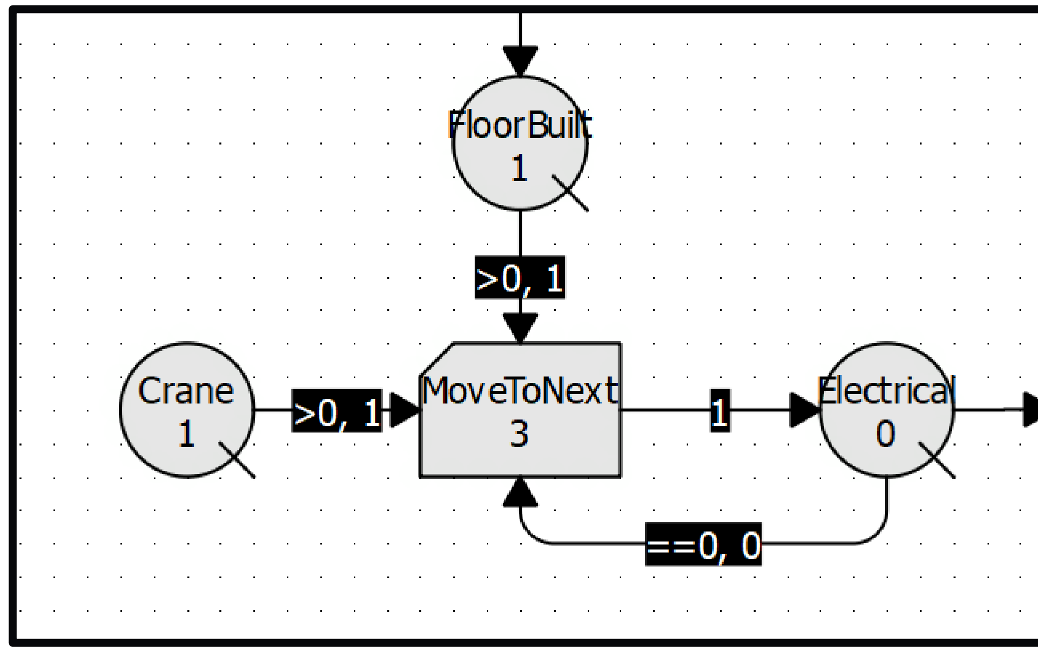
Process Digital Twin Considerations



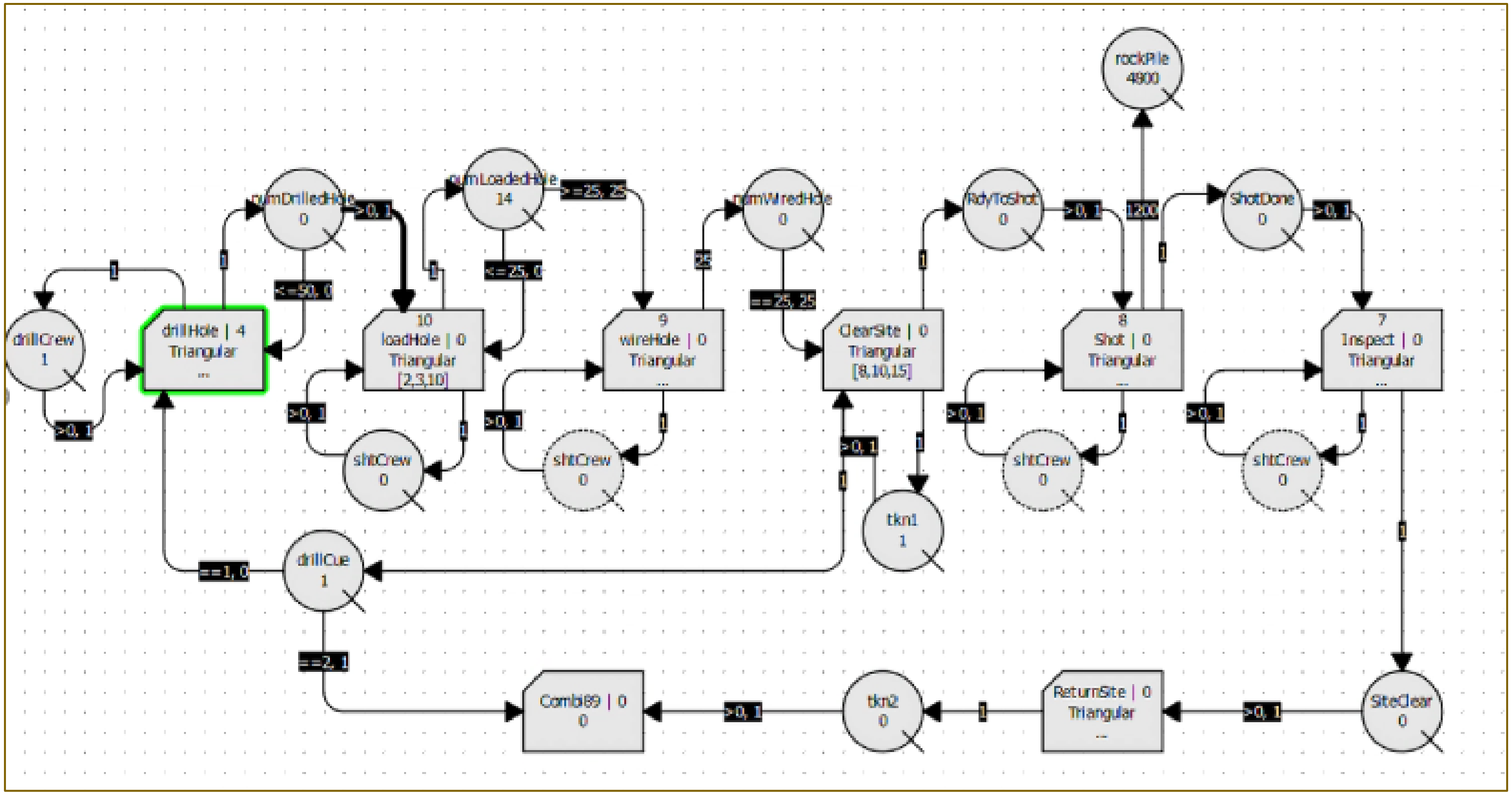
Discrete Event Simulation Modeling

Discrete Event Simulation (DES): Method for simulating processes as discrete activities that are dependent on the availability of resources

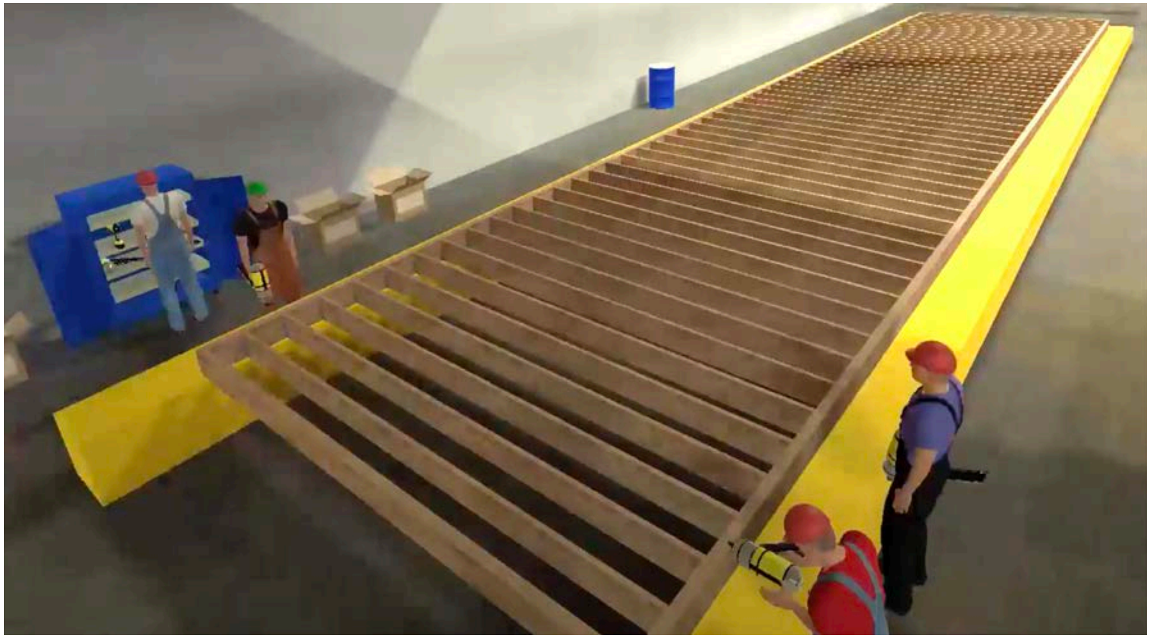




Example of DES Model



Flythrough of Offsite Construction



Detailed modeling of work processes

Experimenting with different crew size

Insight into process and space usage

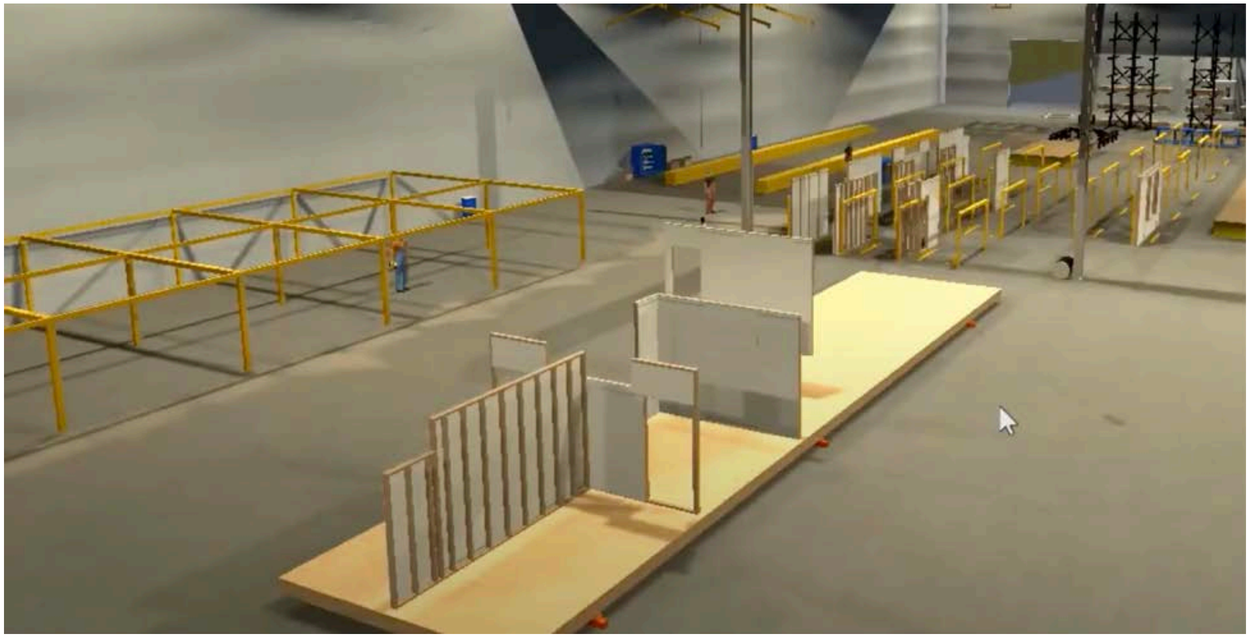
Higher level overview of factory

Understanding resource interdependencies

https://www.youtube.com/watch?v=k9co4-WTWf0

Courtesy: OSU

Factory Process Overview



Detailed modeling of human workers
Ergonomic analysis
Productivity studies

https://youtu.be/U8nZkwbAW28

Courtesy: OSU
Figure created by OSU

Data Collection Strategy

How to obtain data for the virtual model?

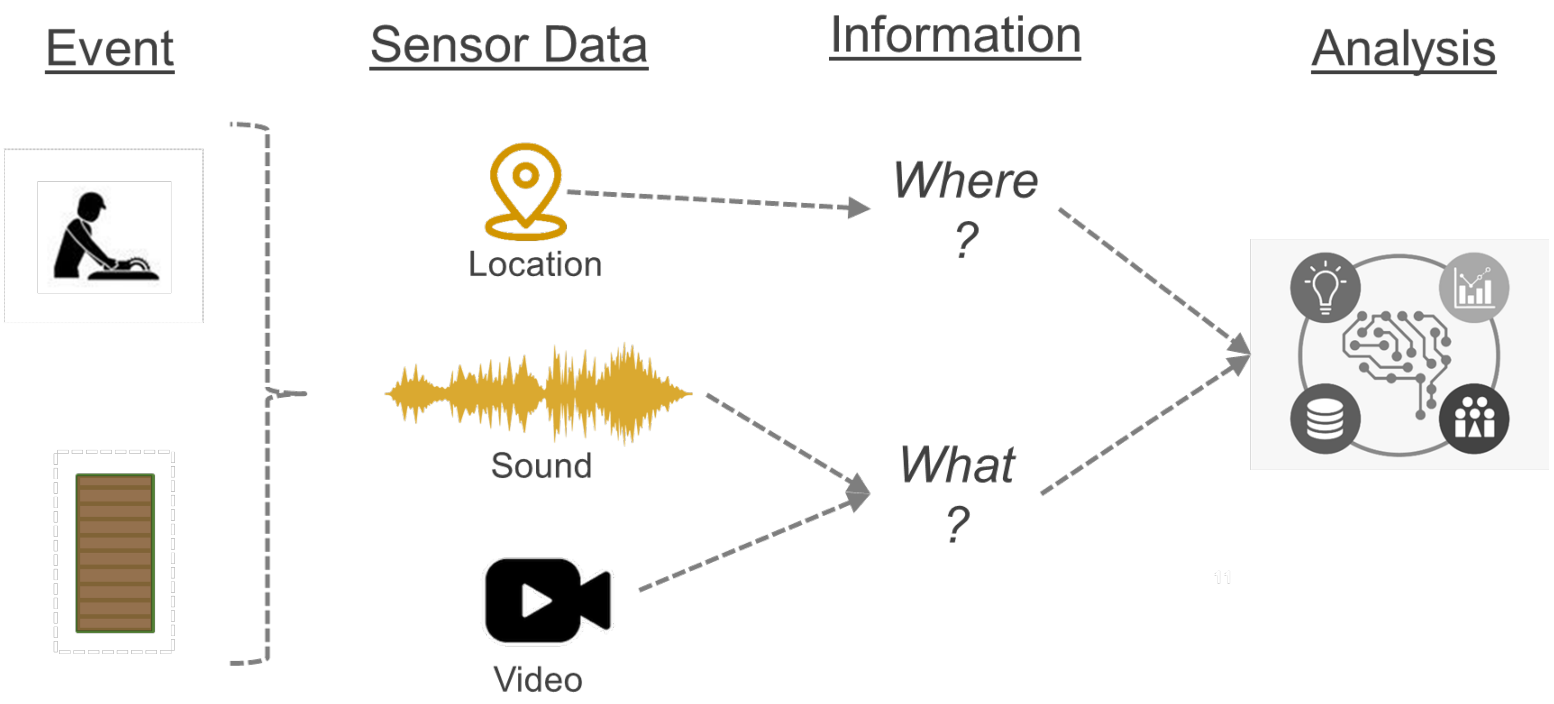


Figure created by OSU

Computer Vision Pilot Testing: Modules

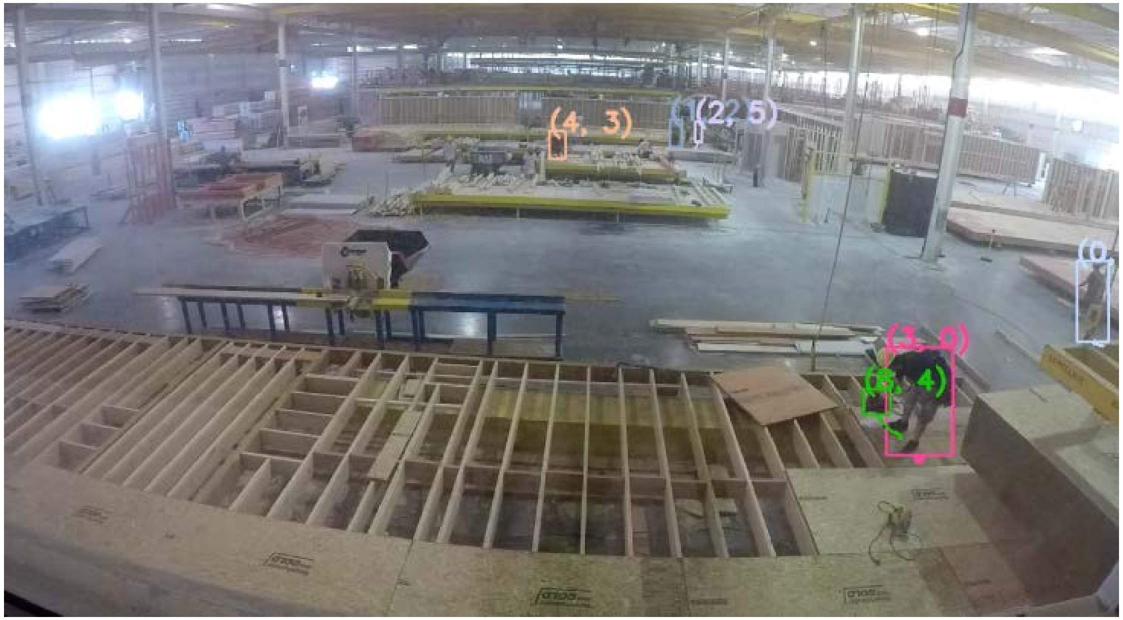
Utilize surveillance cameras

Automatically measure time spent in stations

Courtesy: OSU

Computer Vision Pilot Testing: Workers

Watch Full Video:
https://drive.google.com/file/d/1PNTWo8lThwOcvJTwRKIu3EQfA6zk7Xku/view?usp=sharing



Quantify time spent by workers on activities

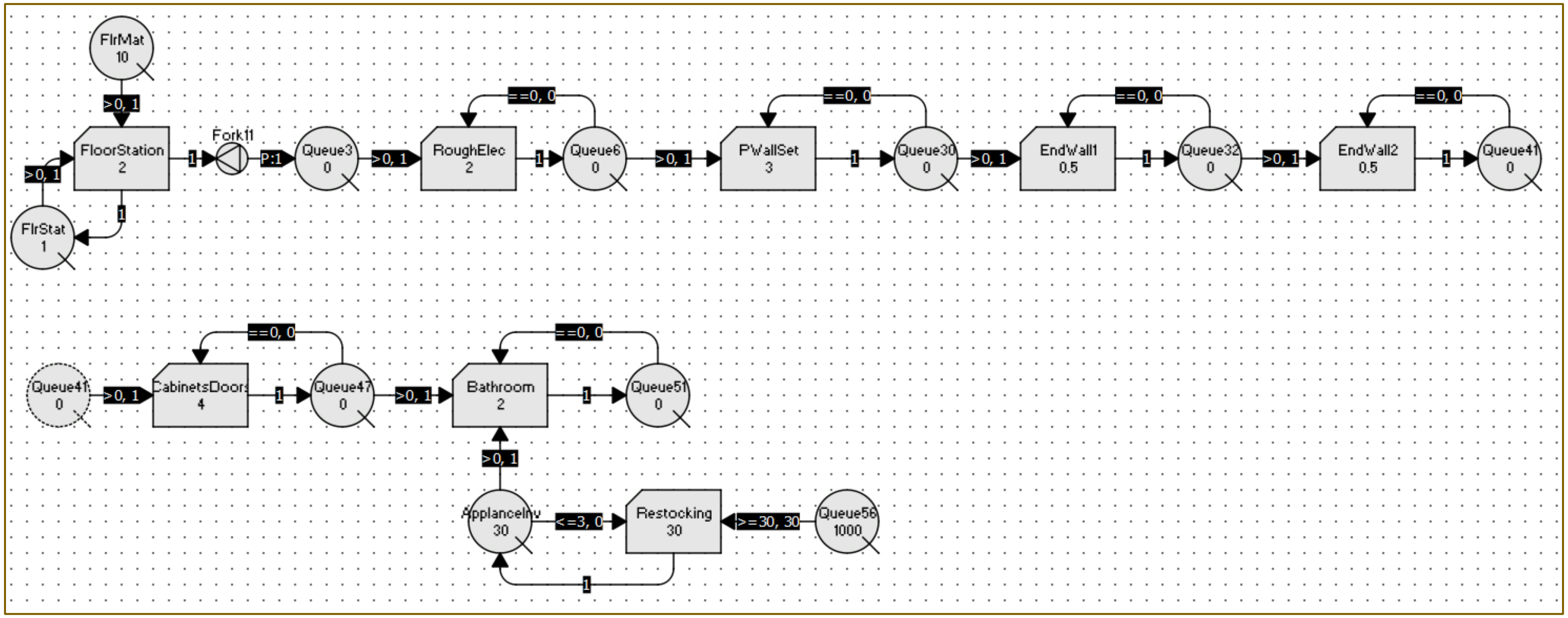
Courtesy: OSU

Studying subassembly impact

- Use case of bathroom pod subassembly
  - Factory started manufacturing bath pods separately
  - What impact does this have on appliance inventory management?
  - How do other stations need to change to ensure efficient production?

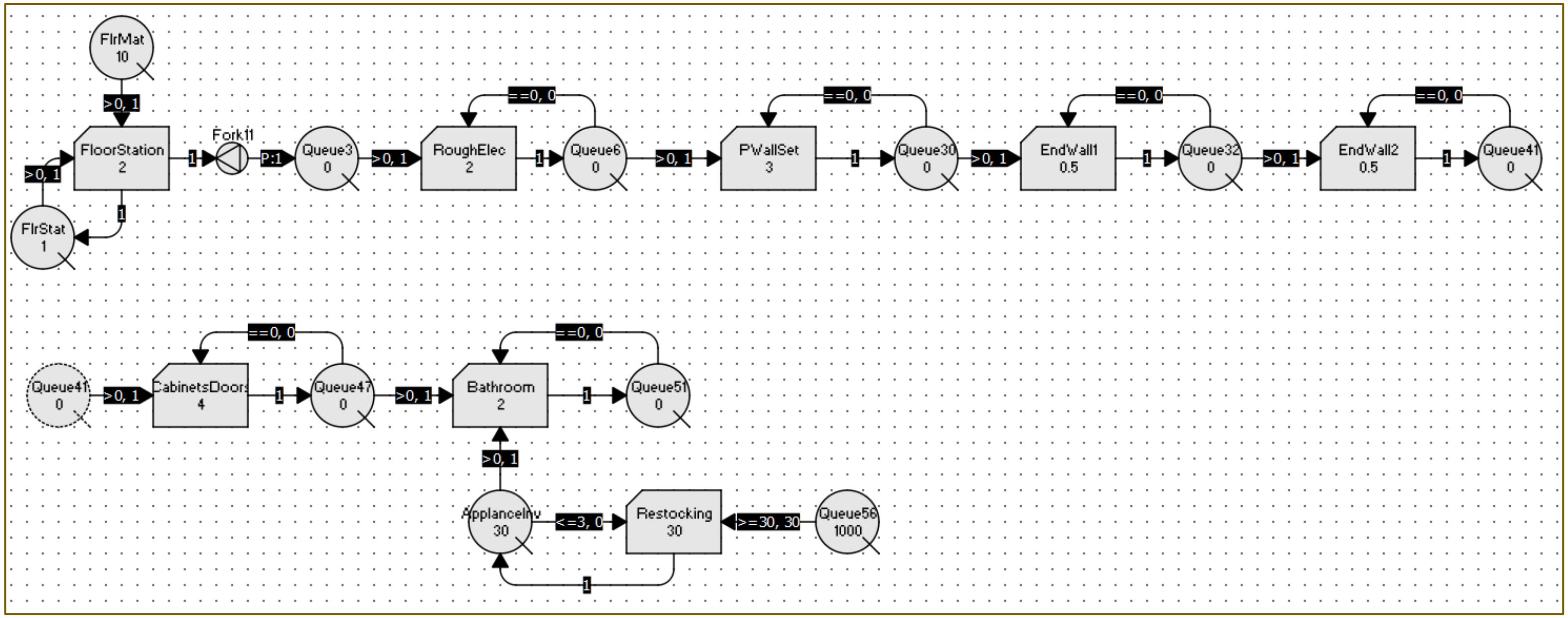
Courtesy: OSU

DES Model without Subassembly



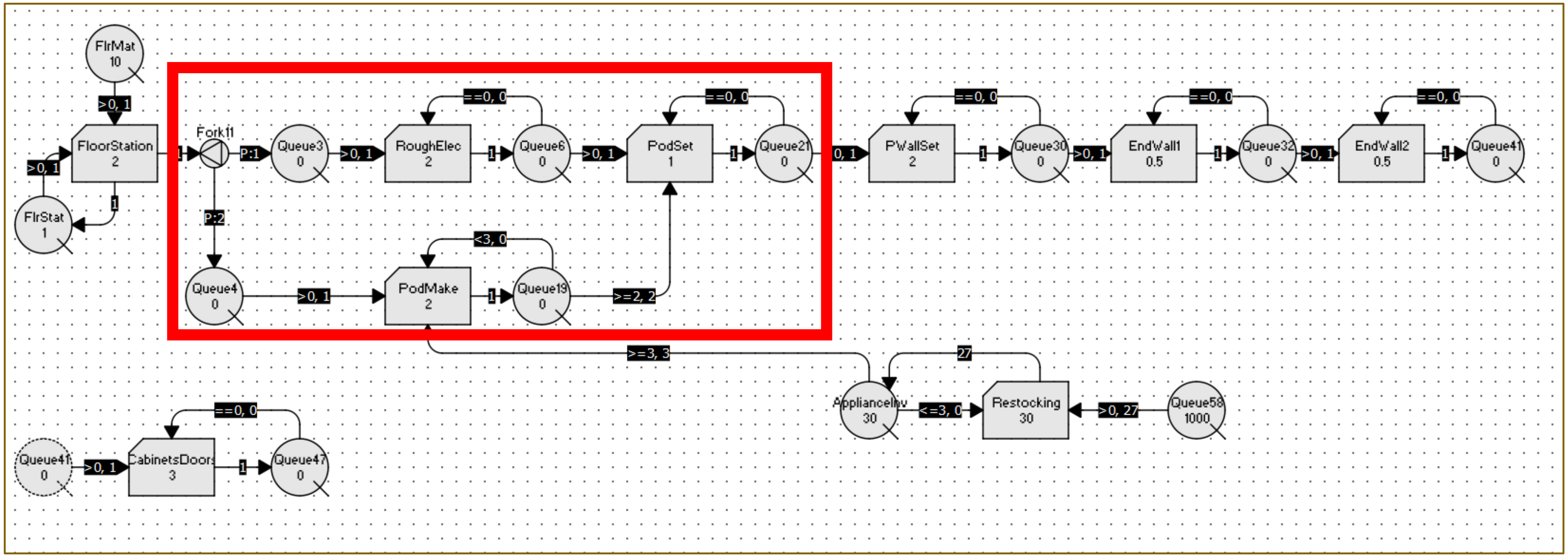
Courtesy: OSU

DES Model with Subassembly



Courtesy: OSU

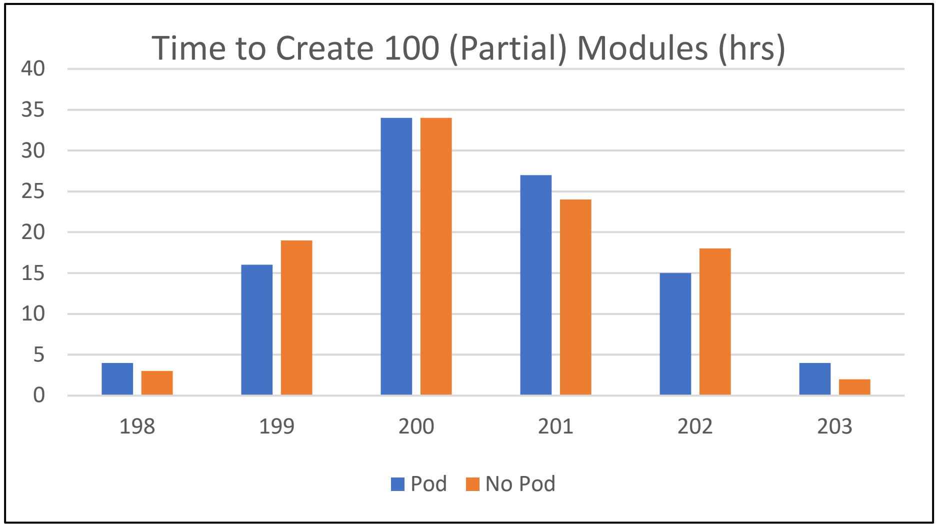
DES Model with Subassembly

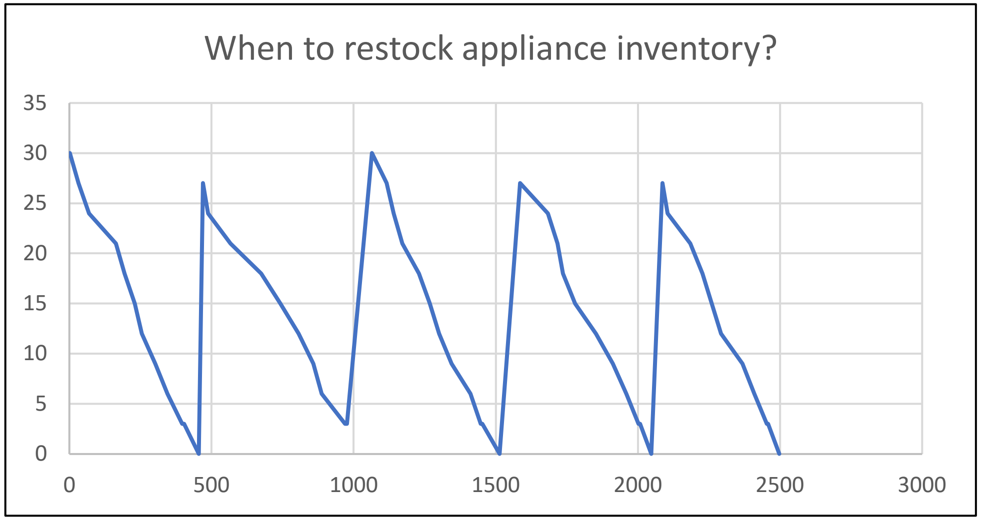


Courtesy: OSU

Results from Simulation

Courtesy: OSU





Next Steps with Process Analysis

- Obtain **baseline activity data for mechanical systems installation** offsite and onsite
- Compare with **mechanical pod assembly and installation**
- Perform **time and cost analysis**
- Identify **changes for inventory management and space usage when modularizing** mechanical systems

Conclusions

- We now have methods that can utilize Advanced Manufacturing and Industry 4.0 Industrial Engineering approaches to better integrate complex and costly energy strategies into the design and construction process:

  - Requires a design that maximizes off-site and prefab approaches
  - Leverage productivity gains and repeatability of processes available in factory-built modular

- Solutions available to meet our needs for low cost, low carbon affordable housing

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Get in touch to learn more!

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