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
• Colby Swanson and Heather Wallace, Momentum Innovation Group (MIG)
• KBS Builders
• Airia Brands Inc.
• Emerson Swan, Inc.
• GE Haier
• Mitsubishi Electric
• Blokable Inc.
• Factory_OS
• Volumetric Building Companies (VBC)
• Skender
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

Shanti Pless
Senior Research Engineer,
National Renewable Energy Laboratory (NREL)

Stacey Rothgeb
Senior Research Engineer,
National Renewable Energy Laboratory (NREL)
Partners and Team Members

Peter Schneider  
Senior Consultant, Engineering  
VEIC

Ankur Podder  
Buildings Advanced Manufacturing and Integration Science Research Engineer, NREL

Dr. Joseph Louis  
Assistant Professor, Civil & Construction Engineering  
Oregon State University (OSU)
U.S. DOE “Advanced Building Construction”

Low Carbon | Affordable | Fast | Appealing

Source: ABC Initiative webpage

Source: ABC Projects
Permanent Volumetric Modular Construction

Industrialized Construction

Off-site Construction/Factory-Built

Modular Construction

*Permanent Volumetric Modular Construction*

Figure created by NREL
Are Modular Buildings more Energy Efficient?

- 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

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

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

INTEGRATED DESIGN FOR MANUFACTURING AND ASSEMBLY

= BETTER PRODUCT & BETTER PROCESS

PROJECT PHASING

1. MAXIMIZE COMPONENTS OF ENERGY EFFICIENCY STRATEGIES with envelope, mechanical systems, and DERs through chunking into sub-assemblies that can be integrated offsite

2. 3. 4.

DESIGN FOR MANUFACTURING (DfM)

OPTIMIZE DESIGN OF ENVELOPE, MECHANICAL SYSTEMS, AND DERs as sub-assemblies with pre-run energy analytics to achieve off-site production efficiency

DESIGN FOR ASSEMBLY (DfA)

OPTIMIZE DESIGN FOR STREAMLINED CONNECTION OF BOTH ONSITE & OFFSITE COMPONENTS with continued focus on reducing site work by moving jobs into the controlled environment of off-site factory

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?”

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
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

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

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

Due to significantly **faster** sealing time, off-site sealing brings down costs by **40%**
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)
Can we imitate the bathroom pod approach for mechanical system?

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)

Integrated Mechanical Pods (Factory-Installed, In-Unit)

Quick-connect ducts in prefab soffits and drop ceilings

Outdoor units w/ balcony access

Prefab MEP racks

Atomized-sealing of envelope

Smart apartment controls platform

Off-site framing w/ Insulated Truss Studs (ITSs)

Factory-Installed solar systems

Figure created by NREL
Whole-Building Strategies Integration

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

- Prefab Walls with Fire Blocking
- Quick-connect ducts
- Prefab Plenum
- 5’x5’x8’: In-Unit All-Electric Best-In-Class Equipment, Home Battery, MERV 13 filters
- Fresh Air Distribution Register (high up)
- Pod Door
- Return Air Grille with Baffle (low)
- Outdoor Unit Access from balcony
- Façade Trim Elements
- Exhaust Air Out
- Outdoor Air Intake
- Perforated Screen Box for unrestricted air flow
- Outdoor condenser units
- Combined drain for condensate management
- Outdoor Unit Access from balcony

Figure created by NREL
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.

Source: NREL

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.
Part 1

Peter Schneider
Senior Consultant, Engineering
VEIC

Factory-Built
Zero-Energy Modular Homes
Affordability
Zero Energy Modular HVAC Innovations

A Case Study of Factory-Built Energy Exchange Pods
Driven by purpose, committed to impact, 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
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
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
Energy Exchange Pod

- Air Source Heat Pump w/ inline duct heater
- Battery Gateway
- Solar PV Combiner Panel
- Over-Current Protection Device
- Energy Recovery Ventilator
- Battery
- Heat Pump Water heater
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
Factory Install

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

veic
Plenum with integrated sweep to deliver air to both Sides of the home and reduce resistance to airflow.
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.
House delivered and set with HVAC already commissioned at factory.
Solar gateway.

To install in the field or factory?

Troubleshooting in the field.
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

“We love the peace of mind, knowing that we are assured good indoor air quality. I just changed the filters today!”

Spencer & Cliff, Duxbury
ZEM owners since 2017

“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.”
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?

MacLeamy curve (2004)

IPD= Integrated Project Delivery
“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

<table>
<thead>
<tr>
<th>1. Physical Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Material Interaction</td>
</tr>
<tr>
<td>3. Energy Interaction</td>
</tr>
<tr>
<td>4. “Headache Factor”</td>
</tr>
</tbody>
</table>

Rule-sets

| 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
2. Hiding: Precedents

**Not Integrated**

**Hidden:** Screen Box, Façade Element, Indoor Feature
2. Hiding: Integration with Façade Elements
2. Hiding: Integration with Façade Elements

Screen boxes hiding outdoor/condenser units for each apartment with balcony access

Screen boxes hiding outdoor units

Screen boxes hiding outdoor units

Exhaust Air port
Operable Opening
Operable Window
Operable Opening
Exhaust Air port
Operable Opening

Outdoor Air Intake

Outdoor Air Intake
Outdoor Air Intake

Figure created by NREL
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

Figure created by NREL
“Variability” within Integration

Figure created by NREL
DfMA moves work from On Site to Off-Site Factory

- Pre-fit, pre-package all equipment and ductwork
- Outdoor units, footings, and condensate drains are chunked
- Prefab chassis is built to house all the equipment and functional parts
- Screen Box is added to cover the outdoor units
- Fully-fitted MechPod and Screen Box are dropped into Wet Module either in factory or on site
- Minimal site work is performed with quick-connect ducts and pipes
- Wet Module-Dry Module mate-line connections are completed on site after modules are set in place

Figure created by NREL
Part 3

Dr. Joseph Louis
Assistant Professor
Civil & Construction Engineering
Oregon State University (OSU)

Process Analysis
Discrete Event Simulation
Virtual Reality
• 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?
Many factories operate with daily **PLANNED** and **UNPLANNED** activities.

The Invisible Factory Dilemma

Digital Twin and Sensors tell you what **ACTUALLY** happens.
• 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 built product

• We want to focus on building process
  • Quantify effect of design changes and modularization on the process performance of factories
Process-based Digital Twin

Figure created by NREL
Process Digital Twin Considerations

- Equipment
- Space
- Materials
- Labor

Discrete Event Simulation-Enabled Virtual Reality
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
Detailed modeling of human workers
Ergonomic analysis
Productivity studies

https://youtu.be/U8nZkwbAW28

Figure created by OSU
Data Collection Strategy

How to obtain data for the virtual model?

Event

Sensor Data

Information

Analysis

Location

Sound

Video

Where?

What?
Utilize surveillance cameras
Automatically measure time spent in stations
Computer Vision Pilot Testing: Workers

Quantify time spent by workers on activities

Watch Full Video:
https://drive.google.com/file/d/1PNTWo8lThwOcvJTwRKlu3EQfA6zk7Xku/view?usp=sharing

Courtesy: OSU
• 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
Results from Simulation

Time to Create 100 (Partial) Modules (hrs)

When to restock appliance inventory?

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
Bibliography

- **NREL Industrialized Construction Innovation research area**
- **Energy eXchange Pod (EXpod) overview by NREL**
- **Factory-Built, High Performance and Affordable Homes: Notes from the Field**