Zero Energy Modular Factory Initiative

How to Create and Build a Zero Energy Modular (ZEM) Housing Factory Serving Affordable Housing

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Context

This report is the second volume in a two-volume series exploring the demand for and capacity to build Zero Energy Modular (ZEM) homes in New York State.

Volume 1: Market Analysis for Zero Energy Modular Homes in New York State[1] assesses the market potential, defines the technical and economic costs and benefits of a ZEM pilot, inventories current market supports such as affordable home loan products and financial incentives for energy efficient homes, and explores whether there are existing modular builders that could build ZEM and to what extent new capacity needs to be developed.

Volume 2: Zero Energy Modular Factory Initiative developed the necessary tools to enable investments in a ZEM factory and provides a foundation for interested parties to better understand how to efficiently and effectively set up and operate a ZEM factory.

Volume 1 was sponsored by NYSERDA. Volume 2 was possible with funding from The New York Community Trust. These two resources bring together all the components for successful market launch into one package that can be used in New York and beyond, to bring the ZEM solution to scale.

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Thank you to the project funder, the New York Community Trust.

[1] http://www.veic.org/resource-library/volume-1-market-analysis-for-zero-energy-modular-in-new-york-state

Foreword

Demand for clean energy, including net zero buildings, is surging across New York State. New Yorkers recognize not only that clean energy investments are good for our health and our planet, but also that they pay off handsomely to both our state economy and to individual wallets.

NYSERDA strives to boost both the supply and the demand for clean energy products and services. Some industries have blossomed with support from NYSERDA; solar power in New York increased by more than 1,000 percent from 2011 to 2017, leveraging more than $2.8B in private investment. Other industries are nascent, with parallel opportunity for growth; Zero Energy Modular (ZEM) construction is one such industry.

ZEM is an important industry because it contributes to the state's goal of clean energy access for all residents. Over 150,000 mobile and manufactured homes are occupied today across New York State. These homes provide an affordable pathway to home ownership. However, they are often grossly inefficient, as well as unhealthy, especially as they age. Many have structural and safety issues that prevent performance-improving retrofits. ZEM provides an opportunity for these residents to reduce their net home energy consumption to zero, with a resulting positive effect on monthly bills and the overall cost of living.

Manufacturers of ZEM have made sizeable investments in ZEM construction; in 2019, the first ZEM homes rolled out of New York factories. If demand continues to grow, then much more ZEM building capacity will be needed. This manual represents the first-ever attempt to consolidate information and provide a tool-kit to current or future investors in ZEM factories. It makes an important contribution to the future of net zero energy homes in New York, to the benefit of our economy and to the residents who will live in these homes.

John Scicchitano, Director, NYSERDA

Executive Summary- The Zero Energy Modular Factory Initiative

As construction costs soar, modular housing is an increasingly attractive option for developers and homeowners. The emergence of zero energy modular (ZEM) homes presents an opportunity to combine the cost-savings of modular construction with the benefits of zero energy. Affordable housing developers in particular face staggering challenges. Rising construction costs, labor shortages, hurdles with land acquisition and fluctuating federal and state grant and capital pools can make it costly and slow to add new, affordable units to the nation's housing stock. First cost and minimum code compliance often dominate decision-making priorities. The ZEM Factory Initiative proposes a new business model to address the shortage of affordable housing units: growth of ZEM factories to manufacture energy-efficient, affordable units, and sell them directly to affordable housing developers. In addition to providing high quality and healthy homes to those who need them most, ZEM factories can create living wage manufacturing jobs. The ZEM Factory Initiative will bring the clean energy economy to rural areas, serving as catalyst for transformation of the affordable housing market.

Zero energy modular homes are built to meet a stringent zero energy standard. A ZEM home can be built at a lower cost and a higher quality than a similar site-built home. The ZEM home model uses construction principles that result in comfortable homes, with excellent indoor air quality, durability, and low energy use. ZEM homes are generally all-electric and paired with solar panels to offset the home's energy use. ZEM homes can also include grid-connected batteries. In partnership with local utilities, these homes can be part of a grid modernization and battery storage efforts.

This document is a how-to manual that provides open source information about the ZEM Factory Initiative concept. The manual provides guidance for developing a ZEM factory, including factory plan options (size, labor requirements, costs for start-up). The manual, written as the companion piece to *Volume 1: Market Analysis for Zero Energy Modular Homes in New York State*, provides a template that could be used in New York State and nationally. We expect this manual will be interest to three primary target audiences:

Factory Developers

This guide provides information and a toolkit that can be used to develop a business plan for a new factory, or when evolving an existing factory's production toward 100% ZEM homes. We provide a description of production steps and construction options . The guide also provides information relating to third-party certification and permitting requirements, and considerations for working with affordable housing providers.

Affordable Housing Partners

This guide will provide affordable housing providers information on the benefits of ZEM homes, building characteristics, ZEM homes third-party certification options, expected construction timeline, and strategies that factories can employ to produce and deliver a home to income-qualified buyers.

Funders and Social-Enterprise Investors

This guide, along with Volume 1: *Market Analysis for Zero Energy Modular Homes in New York State*,[2] demonstrate that building factories to build ZEM homes for affordable housing providers can be done by private sector business entrepreneurs. However, some barriers remain, and support will be needed to launch this market in New York State and nationally, and to accelerate the replacement of old building stock with affordable, zero-energy housing for income-qualified residents. We present examples of projects that are ready to be launched, and next steps that will result in the launch of this market in New York State and provide zero-energy homes for New York's most vulnerable residents. For investors, ZEM factories are a mission-aligned social enterprise that is committed to reducing greenhouse gases and providing a stable long-term investment.

ZEM Factory Minimum Requirements and Market Supports:

- Minimum start-up funds needed to establish a ZEM factory: capital requirements will of course vary with factory size, but we estimate than a minimum of $500-700,000 will be needed to start a factory of 50-70 modules per year capacity.
- Labor requirements: we estimate that a small to medium ZEM factory would require 20-50 full-time staff.
- To ensure that production is optimized and costs remain affordable, we recommend than ZEM factories design a lean manufacturing process, and limit home customization.
- ZEM factory and housing development case studies demonstrate that the market is ready for this solution and with sufficient state support to launch a pilot, we expect ZEM housing to grow in New York in the next decade.

ZEM factory owners will need to have a steadfast commitment to serving the low-income affordable housing market and prioritize greenhouse gas savings and social and environmental impacts over high profit margins. That said, ZEM factories must be able to generate profits, provide fair wages that benefit all employees, and generate income to reinvest in the factory and trainings. ZEM homes have enormous potential to transform the housing landscape in New York, and we believe ZEM factories can be equally transformative to local economies, providing stable, living wage manufacturing jobs.

[2] http://www.veic.org/resource-library/volume-1-market-analysis-for-zero-energy-modular-in-new-york-state

Benefits of the Zero Energy Modular Concept

Efficiencies of Modular Construction

Modular homes have several advantages when compared to on-site, stick-built construction,[3] due to being built in factories, rather than outdoors. The site-built homes are exposed to weather delays, potentially lower quality supplies, and lack of organization. Factories aim to remove or reduce these issues.

> A modular factory can be set up to create a safe, comfortable, organized, and efficient space for workers

One advantage that factories provide is a safe and efficient space for workers since the climate-controlled space can be organized much more easily than an outside space. Unlike construction sites, where weather delays are common, and tools are moved daily from a storage box or truck to the work area, modular construction takes place in a climate-controlled environment, where tools and material are systematically organized in a way to reduce waste and delays. The climate-controlled space allows workers to be comfortable regardless of the weather and ensures the long-term performance of the building material. There is also no risk that the materials will get wet or degrade due to weather or UV exposure.

Another advantage is the speed at which modular homes can be built once the workforce has been trained for specific tasks, leading them to quickly become efficient at those tasks and performing them better and faster than a worker trained on all stages of a house's construction. Faster and more efficient construction leads to lower costs per square feet. In the Northeast, onsite construction slows in the winter months; this slow-down can be avoided with a factory. During labor shortages, it is easier and more cost-effective to find and train individuals for specific tasks, rather than finding or training someone for all tasks, as seen in site-built construction.

The construction times for a modular home are usually shorter than for a site-built home, due to the efficiencies of line production, reduced set-up times, equipment organization, and ability to work through inclement weather. Unlike site-built construction where change orders are the norm, the design and construction process in a modular factory follows a strict process and timeline. Reducing change orders results in less waste, reduced material costs and avoiding costly time delays. In addition, as the module is being built in the factory concurrently with the job site being prepared, this also reduces the overall time of construction.

The quality that ZEM homes can achieve is also much higher than equivalent site-built construction. Houses need to be built well enough to be transported by carrier and lifted by cranes without damage. As a result, modular homes are typically stiffer and can often better able to withstand strong winds.[4] Factories that have invested in some degree of automation have more sophisticated equipment that can cut the material to very precise measurements. In the case of a turnkey package, the home can be finished in the factory, including air sealing, insulation, and testing of the envelope air-tightness (for single module homes).

[3] For a more thorough discussion of the benefits of modular construction over stick-built, see: *The Modular Home*, Andrew Gianino, Storey Publishing, 2005

[4] FEMA, Building Performance: Hurricane Andrew in Florida. Observations, Recommendations, and Technical Guidance, February 1993. P. 29

To streamline the design process and logistics of line production, homes are often built to the most stringent building code that the factory delivers to, since differences in code vary by location. Also, a modular home can be more easily built to high levels of energy efficiency because the drywall is installed before the external sheathing and all the penetrations to the thermal envelope can be sealed from the outside (e.g. outlet boxes). In addition, modular home factories often require higher quality material from their suppliers. For common materials like lumber, the factory can send back low-quality material and request a replacement from the manufacturer. A one-off site constructed project is under more pressure to accept lower quality material that is delivered to the job site, to prevent delays. Finally, there is typically more quality control during construction than a site-built home, as factories often have a staff person dedicated to quality control.

Modular Homes

- Safe and comfortable space for worker, protected from weahter variability
- Better organized workplace
- Materials protected from sun and weather
- Overall lower costs when production process is streamlined
- Material can be bought in higher volume and lower cost, with off-season pricing in the winter
- Workforce can be specialize in fewer skills
- Quicker turn around time
- Less material waste
- Homeowner saves on construction loan and insurance

Site-built Homes

- Daily set-up and clean-up adds to construction time
- Crews spend more time moving equipement and material
- Vulnerable to weather events and vandalism during construction
- Custom build can mean higher costs for materials and labor
- Crews must typically have a comprehensive skillset
- Construction times are longer
- More waste in the construction stream

Because modular construction has different processes and timelines than site built, ZEM partners such as affordable housing developers and mortgage lenders must be willing to modify existing internal processes and re-train staff to ensure projects can harness the cost reduction benefits. This is an important consideration for ZEM pilot partners.

A more thorough discussion of the benefits of modular construction can be found in Volume 1: Market Analysis for Zero Energy Modular Homes in New York State.[5]

Zero Energy Homes for Low Income Affordable Housing

Affordable housing developers face staggering challenges. Rising construction costs, labor shortages, hurdles with land acquisition and fluctuating federal and state grant and capital pools add to the

[5] http://www.veic.org/resource-library/volume-1-market-analysis-for-zero-energy-modular-in-new-york-state

difficulties facing affordable housing developers. First cost and minimum code compliance often dominate their decision-making priorities.

What is unique about this concept is that ZEM factories will sell directly to affordable housing developers. Many standard modular factories engage with dealers who then work with clients. The dealer interface can increase the costs of the home. The ZEM Initiative will include a front office sales function that provides education and life cycle cost calculations that help affordable housing developers and prospective homeowners understand the total cost of ownership. A ZEM sales team or affordable housing provider can explain to prospective homeowners how zero energy homes reduce or eliminates energy costs, and how the quality and durability of the home reduce maintenance costs.

ZEM homes are all-electric, healthy homes built to the highest level of efficiency. A roof or ground mounted solar PV system is designed to produce as much energy as is used annually, and zero energy construction reduces the risk of energy cost volatility for residents because energy cost will be fixed for the life of the solar PV panels. They can also include grid-connected batteries. In partnership with local utilities looking to manage their peak loads, ZEM homes can be part of a grid modernization and battery storage effort.

Like many states, New York struggles with an increasing demand for, and inadequate supply of, affordable housing both for rental and homeownership. ZEM Factories build for two affordable housing types: low to moderate income single-family homeownership or rental units, and mobile and manufactured housing replacements

ZEM homes designated for single family units must meet specifications of a developer such as aesthetics and size. Zero energy homes cost more than a baseline minimum code compliant home upfront (5-10% more)[6] but will save over the long term. ZEM factories will coordinate with affordable housing developers to access local energy efficiency and renewable energy programs that will help buy down the first cost of the home.

ZEM homes provide a unique solution to those living in mobile or manufactured housing communities who would like to purchase a new zero energy home. Manufactured housing, also factory built, is regulated by the federal government through the Manufactured Home Construction and Safety Standards, commonly referred to as the HUD Code, which was last updated in 1994. At this point in time, manufactured homes built to meet a stringent zero energy standard are not offered for sale to homeowners. A ZEM home sized to fit on the footprint of a MMH reduces energy burden for low- and moderate-income (LMI) households, adds high quality housing stock quickly, and provides a truly affordable alternative to traditional MMH, which are often energy inefficient and can be expensive to own as a result.

[6] Alisa Petersen, Michael Gartman, And Jacob Corvidae, The Economics of Zero-Energy Homes Single-Family Insights, Updated 2019 With Cold Climates Addendum, Rocky Mountain Institute

Market Assessment and Industry Characteristics

The findings from Volume 1: Market Analysis for Zero Energy Modular Homes in New York State[7] confirms that there is significant interest in and potential market demand for ZEM as an alternative to manufactured housing and single-family homeownership or rental. In Volume 1, the demand for ZEM homes is estimated at 10,000 homes over the course of a decade, but the limited capacity for building ZEM homes is the most significant barrier to advancing this housing solution.

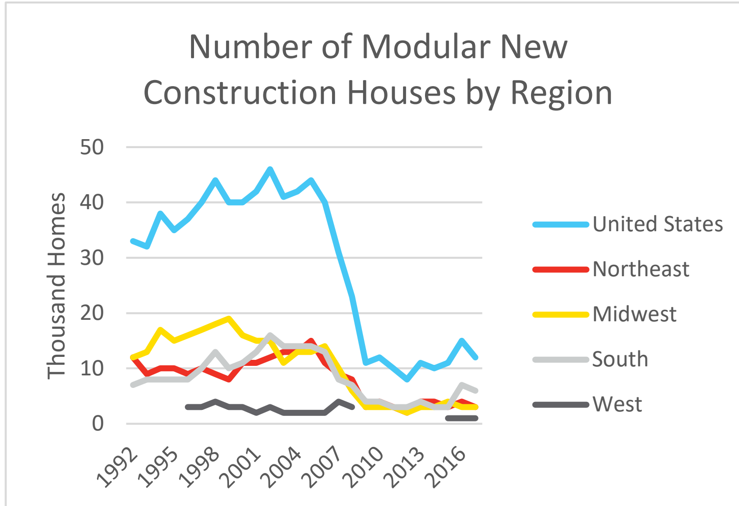

Figure 1: Modular home construction trends.

Prior to 2007, 39,000 modular homes were built each year nationally, including 11,000 in the Northeast. Following the downturn of the economy in 2008, this number declined to 12,000 nationally, including 4,000 in the Northeast (Figure 2).[8]

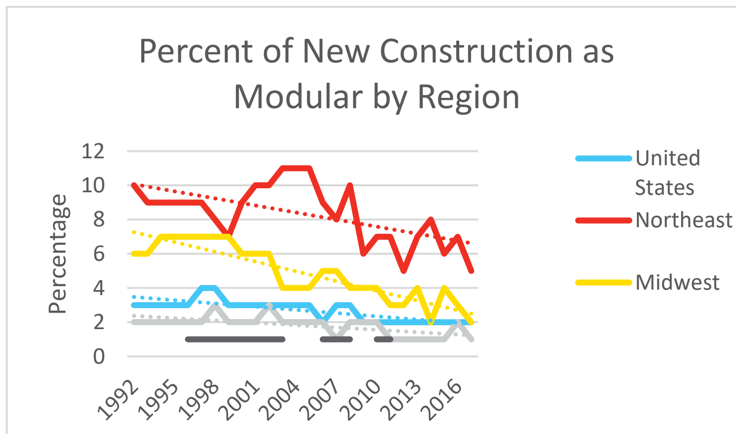

Figure 2: Percentage of modular construction by region.

While most of that decline was due to an overall decline in the number of new homes built, the share of the new construction market occupied by modular construction has also declined in every region of the country, and although the Northeast remains at the top of the list for percentage of new modular homes built, the historical decline is apparent.[9]

Currently, a dozen modular factories deliver homes to NYS, with a few incorporating energy efficiency and renewable energy as part of their business model. Depending on factory size and deliver capacity, between 5-10 additional ZEM factories will need to come online to meet the estimated demand over the next decade. Due to the current state of the market, it will take financial and regulatory support to further develop ZEM factory capacity to meet the demand projected over the next decades.

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[7] http://www.veic.org/resource-library/volume-1-market-analysis-for-zero-energy-modular-in-new-york-state
[8] Census data, Type of Construction Method of New Single-Family Houses Completed
[9] Census data, Type of Construction Method of New Single-Family Houses Completed

Zero Energy Modular Construction Process

Characteristics of ZEM Homes

Zero energy modular homes are modular homes that are designed and built to meet a zero-energy standard. ZEM homes, like standard modular homes, are constructed in a factory in "modules" that are transported on a trailer to the site where they are placed on a permanent foundation by a crane. For homes built with multiple boxes, the boxes are joined together, and exterior finishes are completed on site. The modules must conform to size limitations when traveling on the road, determined by federal, state and local transportation regulations for height, length and width. See Appendix V for more information on specific sizes and restrictions.

To achieve zero energy, a ZEM home design goes through a design process to first reduce energy demand, then size a solar PV system to generate the energy used on an annual basis.

Generally, to ensure air tightness and efficiency performance, ZEM homes should preferably be fully finished in the factory, including all interior and exterior finish work and HVAC. Garages are also usually built on-site because the floor is concrete as opposed to wood and that doesn't lend itself to modular construction.

A ZEM home built for a climate in the Northeast would be built to meet a prescriptive envelop standard, such as the one provided as an example in Table 1.[10] This standard can be achieved through a number of construction practices listed in Appendix V. However, the building design and energy modeling will determine the exact envelope and mechanical characteristics of the home. This in turn determines whether individual home designs can be considered zero energy or meet specific certification requirements. Pictures are provided in the section ZEM Construction Tasks and Process Flow that will help better understand design details.

The building design and energy modeling will ascertain the exact characteristics. This in turn determines whether individual home designs can be considered zero energy or meet specific certification requirements.

Table 1: Example of building characteristics of an existing ZEM home, in northeast climate zones 6.

Envelope	
Floor	R-40
Walls	R-42
Windows	U-0.21
Doors	R-5
Ceiling	R-60
Infiltration	1.0 ACH50

[10] The following resource can help define prescriptive envelope standards in other climate zones: https://buildingscience.com/sites/default/files/migrate/pdf/BA-1005_High%20R-Value_Walls_Case_Study.pdf

Mechanicals	
Heating	13.5 HSPF
Cooling	30.5 SEER
Hot Water	2.75 EF
Duct Insulation	n/a because ducts are in the conditioned space
Duct Leakage	n/a because ducts are in the conditioned space
Ventilation	Balanced, 50 cfm, 62w
Lights & Appliances	
Efficient Lighting	100% LED
Appliances	ENERGY STAR+
Photovoltaic System (PV)[11]	
Climate Zone 4	5 kW
Climate Zone 5	6 kW
Climate Zone 6	7.5 kW

Homes can be designed with lower R-values, as long as they have extremely low air leakage and negligible thermal bridging; however, this will require a larger PV system. The exact design should be cost optimized to find the right balance of insulation vs. solar PV production, especially as solar PV costs continue to decline.

ZEM home design model utilizes construction principles that result in comfortable homes, with excellent indoor air quality, durability, and low energy use:

- Continuous insulation throughout the entire envelope without any thermal bridging;
- Extremely airtight building envelope, preventing infiltration of outside air and loss of conditioned air;
- High-performance windows (double or triple-paned windows depending on climate and building type) and exterior doors;
- Solar gain managed to exploit the sun's energy for heating purposes in the heating season and to minimize overheating during the cooling season;
- Balanced heat- and moisture-recovery ventilation; and
- Minimally sized space conditioning system.

By utilizing high performance building principles, balanced ventilation with heat recovery, high-efficiency, all-electric HVAC, and ENERGY STAR lights and appliances, the energy demand and heating and cooling loads of a home are significantly reduced. After the efficiency is maximized, the solar electric PV system is designed to produce as much energy as the home uses on an annual basis. ZEM homes apply this principle while integrating strategies to keep the homes affordable and accessible to income-qualified buyers and renters. Strategies that can be used to keep costs low include lean manufacturing, just-in-time (JIT) deliveries, minimal batches and shorter lead times, and flattening the supply chain. These strategies are discussed further later in the report.

The finish that is accomplished before delivery depends on specific business models. Except for areas where modules are joined on-site, a ZEM Home should be fully finished in the factory including all interior and exterior finish work, HVAC, flooring, plumbing, electrical and appliances to ensure air tightness and expected efficiency performance.

Foundation

There are three options for ZEM home foundations: crawlspace, piers, and full basements. Modular homes are usually not built on a concrete slab because access is required for all utilities (water, sewer, electrical) below the first floor, which is not possible with a slab. As with site-built homes and regardless of the foundation type, it is important to ensure that the quality of the foundation is high so that the high-quality ZEM home is not compromised by a lower quality foundation. The foundation should be frost-protected and have good drainage, to ensure the home will not shift seasonally, potentially resulting in cracks.

Figure 3: ZEM home being installed on a crawl space.

The foundation type will be dictated by regional variations and site-specific considerations. For modular homes with multiple modules, one critical detail is the location of columns to support the marriage wall.

Modular factories typically design the foundation to ensure it matches the home being built, and work with a local general contractor (GC) that is familiar with construction practices and foundation details for highly efficient homes. The GC will prepare the site and install the foundation. Manufacturers usually prefer to design the foundation, to ensure that it matches the house being manufactured in the factory, rather than have the GC design the foundation.

First Floor System

The floor strategy for a ZEM home depends on whether the home is placed on an uninsulated and unconditioned space, such as a crawlspace or piers, or a properly insulated, conditioned, and ventilated space like a finished basement. Most ZEM homes will be installed on an uninsulated, unconditioned space to reduce cost. This means that the first floor will need to be fully insulated, air sealed, and weather-tight while in the factory to maintain the benefits of modular, energy efficient construction.

While single module ZEM can sometimes be installed without a crane, further reducing costs, many ZEM homes require a crane to lift the home off the trailer and place it on the foundation. Floor assemblies for ZEM homes are designed to sustain the additional stress associated with the delivery and crane set and are therefore built differently than both manufactured and site-built floors.

Exterior Wall Assembly

ZEM homes can be a single module or multiple modules. For ZEM modules, standard construction is 2x6, 24 inches on center, resulting in less wood than 16 in on center, for example, and fewer potential thermal bridges from the studs.

The ZEM exterior wall assembly must be durable, have thermal bridge-free construction, be super-insulated, and air tight. To meet these stringent standards, factories can follow construction steps that prioritizes high performance building standards. For instance, factories can install gypsum wall board before exterior sheathing so all penetrations (e.g. electrical outlets) can be sealed from the outside before insulation is installed. Another approach that ensures air tightness involves installing all exterior wall gypsum wall board prior to setting interior walls or soffits, to ensure a continuous air barrier. These construction methods are not available when building on site, because with site-built construction, the priority is to finish exterior sheathing to protect the home from the weather.

Some modular factories take a hybrid approach, assembling a home using both modular walls and structural insulated panels (SIPs), which are built in a facility that specializes in a panelized wall construction. While SIPs are more expensive than many modular wall systems, this approach can be used to reduce factory labor requirements and the time required to build a house. However, one of the drawbacks is less flexibility for modifications (e.g. changing the location of switches). It can also be challenging to find a distributor for SIP panels, depending on the ZEM factory location. SIPs can be used as walls in modular zero energy construction[12] for affordable housing but they tend to be costlier. A factory would need to have sufficient production volume to be able to negotiate a reasonable price to use SIP walls in affordable housing production. Alternatively, SIPs could also be used only for very specific applications.

Roofs

If a ZEM home roof is designed flat or slightly pitched to meet size limitations determined by transportation regulations for height, it should be finished (insulated, air and weather-tight) in the factory. If the home's design requires a steeper pitched roof, modular builders can integrate part of the roof system in the factory through a hinged roof system.

Sections that contain the roof can be more challenging if the roof has a steeper pitch built on-site, or as panel construction, rather than in modular factories. Porches and decks would cause the module to exceed the size limitation.

Figure 4: Example of hinged roofs (Huntington Homes, Vermont).

[12] E.g. modular homes built by https://www.solarhomefactory.com/tech and http://gomodularhomes.com/about-us/

In the MMH replacement scenario, ZEM homes incorporate a low pitch shed or gable roof system. As with other assemblies, the roof systems are designed to ensure a thermal bridge-free assembly, long term durability, super-insulation, and air tightness. Completing the roof system in the factory not only makes achieving these characteristics easier in a climate-controlled environment but also allows the factory to install the majority of the solar PV system, further reducing site work and the system's overall costs. The low pitch roof also allows the ZEM home to be sited without ideal solar orientation when compared to a home with a steeper pitched roof. The flatter roof assembly is similar to a commercial PV installation, where solar production is maximized in the spring, summer and fall with reduced production in the winter when the sun is lower in the southern sky and snow may accumulate on the modules.

Figure 5: ZEM low-pitch roof in a MMH replacement project

Windows and Doors

For a ZEM home, windows and doors are specified to ensure comfort at the perimeter of the home without confining distributed heating and cooling to those locations. ZEM homes utilize highly insulated and highly airtight casement, awning, fixed-pane, and tilt-and-turn windows. Unlike single and double hung slider windows which rely on a tracking system and single gasket where sashes meet, ZEM windows rely on a multi-gasketed, compression closure system for a tight seal.

HVAC and Hot Water

HVAC systems are very important in ensuring the house meets the zero energy goals. Not only is the choice of an appropriate HVAC system critical, but having it installed correctly is also a key to meeting the expected building performance. All components (e.g. vents, outdoor compressors, indoor units) must be located in an appropriate part of the house for the system to work most efficiently and for the heated or cooled air to be distributed evenly. Typical modular homes do not have the HVAC system installed in the factory, but rather rely on an HVAC technician to install the system on site after the house is delivered and set. The HVAC system in a ZEM home is finished in the factory, other than a few duct connections required in multiple-box homes. Commissioning is also performed on site after the HVAC system is fully installed. Every ZEM home should have all ducts located within the thermal envelope, ENERGY STAR certified equipment, and Water Sense fixtures to reduce water usage (including hot water).

Solar PV

A PV system that is matched to the expected electric load of the home is typically installed with a ZEM home. It is generally better to reduce the electric load of the home first and size a smaller solar PV system, than install a larger than necessary solar PV system in a less efficient home, as this would be costlier and may not as beneficial to the electric grid.[13]

Figure 6: Solar PV system on a flat roof.

A modular home with a 2/12 roof pitch (12.5%) or less can be placed in most orientations due to the low slope without significantly impacting solar production. As the roof pitch increases, a solar PV system will be more impacted by its orientation and should be sited within 15 degrees of true south. Tools (e.g. the National Renewable Energy Lab (NREL) PV Watts tool) should be utilized to evaluate sites and design the system for a specific location. All of the PV system's wiring, inverters, and racking system can be installed in the plant prior to shipping. Once the home is set on site, the modules can be installed and connected, reducing the cost for installation compared to a typical site-built PV system.

For sites where solar PV is not optimized due to immovable shading, building configuration, or site orientation, a ZEM home should be installed without the rooftop solar component and off-site or community solar should be utilized to cover the house's energy usage. This would be necessary for the ZEM house to be considered zero energy, and may be required in the future for eligibility in zero energy incentive programs.

ZEM Home Certifications

Zero energy means that over a year, the houses produces as much energy as it consumes, resulting in zero energy consumption, and negligible energy bills for the resident. One way to verify that a home meets the design criteria, is to have them certified by a national home labeling program. These certifications can usually be done by working with local companies that are accredited for each certification label.

Certifications can take place at the factory and home level and will require partnerships with RESNET Accredited Home Energy Rater. As part of the design process, ZEM homes should be designed to qualify for specific national building certifications. Certifying these homes provides several advantages:

[13] E.g. https://www.hiveforhousing.com/design/residential/did-we-get-zero-energy-wrong-arizona-builder-designs-for-the-grid-not-net-metering_o

1. Quality assurance that these homes will perform to the highest standard possible
2. Marketing recognition and support
3. Technical assistance and support

The certification process follows the following steps:

Enrollment
- The builder enrolls the project in a voluntary certification program
- A Rater is then assigned to the project

Design Review
- The home design is reviewed by the rater

Inspection and Certification
- Inspection and certification with a home energy model, which will in turn provide a Home Energy Rating (HERS) Index.

Participating ZEM factory builders will need to partner with HERS Rater(s) to provide a Rating Certificate for each home. An energy model takes the home technical specifications, dimensions, climate zone, and performance testing and generates estimated annual energy consumption. The results of the model are converted to a score or index. The lower the number, the less energy a home consumes compared to a similar home built to the minimum energy code. Zero energy buildings combine energy efficiency and renewable energy generation to consume only as much energy as can be produced onsite through renewable resources over a specified time period.

The following are certification programs a ZEM factory should consider:

- **US Department of Energy (DOE) Zero Energy Ready Homes (ZERH)** certification is given to homes that demonstrate exceptional energy efficiency performance. More information can be found here: https://www.energy.gov/eere/buildings/zero-energy-ready-home. To qualify under this program, the home must be designed to meet **ENERGY STAR** certification requirements. The home must also meet the full certification in **EPA's Indoor airPLUS** Program, a labeling program that helps achieve good indoor air quality.
- The **Passive House Institute U.S. (PHIUS)** offers a labeling program called **PHIUS+** that combines a thorough design verification protocol with a stringent quality control program done on site by PHIUS+ raters and verifiers. More information about the details of the standard can be found at http://www.phius.org/phius-2015-new-passive-building-standard-summary

ZEM Construction Tasks and Process Flow

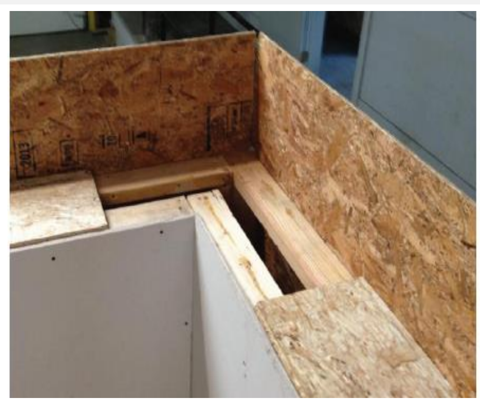
Table 2 below illustrates the critical steps required for constructing a ZEM home in the factory. An existing factory can modify their designs and production steps to integrate the characteristics of a ZEM homes into their processes. A new factory can use these critical steps described below to assist in the design of a production line specific to ZEM homes. It is essential that ZEM homes meet the designed air sealing requirements and all construction steps should aim toward that goal. For example, crews should understand that they are responsible for sealing any hole that they make in the building envelope.

The following steps and their order will vary depending on the construction strategy and house specifications used to achieve zero-energy, and whether the ZEM home is a turn-key mobile home replacement, or a more typical modular single-family home. The steps and description below assume the home is completed at the factory, including all interior and exterior finishes, HVAC, hot water system, flooring, lights and appliances, and fully painted. This is an example and in practice the steps may vary depending on home design and factory configuration.

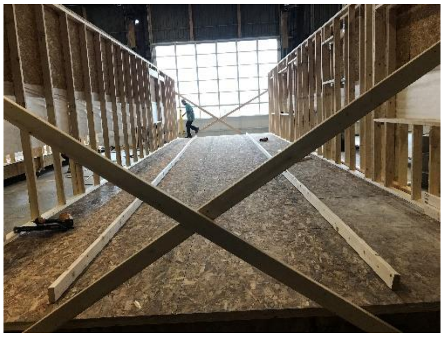
The steps below assume that the floor will be insulated and made weather-tight at the factory (which is necessary with an unconditioned crawlspace or pier foundation). Insulating the floor at the factory takes advantage of the benefits of modular construction, compared to insulating, air sealing, and installing the weather barrier on site.

The tasks can be grouped into fewer stations or separated into additional stations. Some tasks could be pulled out of the production line into subassembly bays, if any activities slow down the flow of modules and creates bottlenecks. As a case study and example of how these steps could be set up, detailed installation steps used at the Vermod factory are provided in the Appendix IV.

Table 2: ZEM construction tasks.[14]

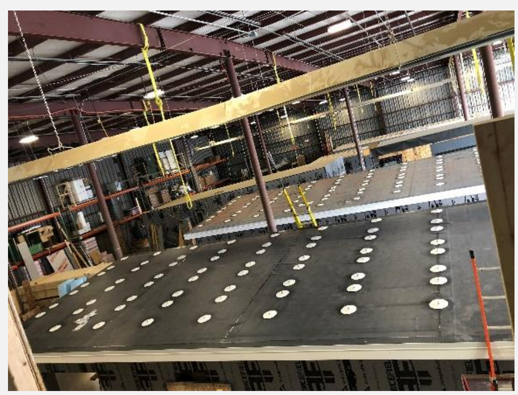
Activities	Details
Cut framing components (off-line)	• Cut framing components for ○ Floor ○ All walls ○ Roof, fascia, and soffit
Assemble floor and walls	• Subassemblies (off-line): ○ Build Floor ○ Build exterior walls with window/door opening subassemblies (on deck, Figure 8): • side walls • end walls • marriage wall (if house is comprised of more than one module) ○ Assemble partition walls, not on deck, to be erected later  **Figure 7: Upper section of sheathing running one foot past the top of the wall.** • Install exterior top sheathing on exterior walls**:** if the roof is built using SIP panels, they will need to rest on a structure connecting them to the walls. One strategy to achieve that is to install the top part of the sheathing (1/2' OSB for example), so that a foot of it sticks out higher than the wall, to connect the air and weather barriers (Figure 7). The sheathing can be installed Figure 8 on the exterior walls before they are set, for ease of installation.

[14] All photos are from Vermod, Vermont

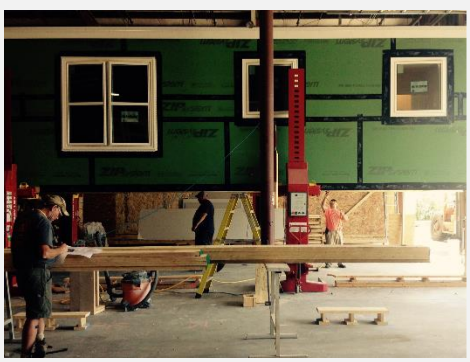
Activities	Details
	• Erect and install walls on floor (Figure 9)  **Figure 9: Double walls raised onto the floor.**  **Figure 8: Exterior walls being built on deck.**

Assemble and set roof	• Subassemblies:
	  ○ Build subassemblies for roof
	  ○ Build roof/ceiling
	• Install roof onto walls (e.g. Figure 10 with SIP panels)
	
	Figure 10: Crane lifting roof onto walls.

Drywall and rough-ins	• Best practice construction to achieve a very tight building envelope is to sheath, tape, and mud all the exterior walls (and ceiling if applicable, Figure 11) to act as an air barrier prior to building the interior walls, soffits, and HVAC  **Figure 12: Installation of HVAC soffit and interior partitions.**  **Figure 11: Drywall installed on all exterior walls and ceiling.** rough-in. ***This is different from how most modular factories operate.*** Depending on the factory layout and crew workflows, this might not be practical or might add a bottleneck. A tight building envelope can still be achieved by installing interior partitions before the drywall, and using an

Activities	Details
	alternative air barrier approach, but this may add time, costs, and labor to the construction. If drywall is installed on ceiling prior to the partitions and rough-ins, the roof may need to be installed prior to this as well (see next bullet point). Drywall is typically glued to the studs, then screwed. • Install interior partition walls. • Installing the soffit for the HVAC ductwork on top of pre-installed drywall (Figure 12) is best practice but will require framers to come back down the production line and will need to be factored in the production workflow. The HVAC installers can do the soffits and the ductwork as one phase of work. • Install rough electrical in walls. • Air seal/ spray foam all penetrations (e.g. around electric boxes) from the exterior of the home. It is not necessary to spray foam every stud bay, especially if the drywall was glued to the studs. • Build plumbing subassemblies. • Install rough plumbing in wall. • Rough in mechanical/ ducts.
Drywall interior partitions and paint	• Hang drywall on interior/partition walls • Tape, mud, and sand drywall • Prime and paint all walls and ceiling
Sheath and insulate roof	• Can be done simultaneously with interior drywall and rough-in installations • Install rough electrical and plumbing in roof (if applicable) • Sheath and insulate roof (if applicable)
Prep/ drop roof (if applicable)	• Shingle roof or install rubber membrane for flat roofs (if applicable) • Install fascia and soffit (Figure 15) • Install anchors for the PV racks, and racks (Figure 13). On pitches less than 4/12 the building code often does not allow for shingles on the roof. In that case, a rubber membrane can be installed in the factory and anchors for the PV racks can be installed. These consist of special adhesive-backed fasteners. The PV modules are typically installed on site to avoid damage during transportation. On steeper roofs, roof trusses can be delivered to the site and the PV racks installed on site.  **Figure 13: PV anchors installed on rubber membrane.**
Prep walls, set windows,	• Install finish electrical • Insulate exterior walls, from the outside (Figure 14) • Sheath walls, tape all seams and rough openings (Figure 15)

Activities	Details
exterior finish	• Install windows and exterior doors • Install siding and exterior trim   **Figure 15: All seams taped, fascia being installed.** **Figure 14: Insulation with dense pack cellulose, top and bottom sheathing already installed.**
Interior finishes	• Interior finish: paint trim and doors off line and then touch up after installation • Install interior doors • Install flooring • Install interior trims and touch up as needed • Install cabinets and counter tops • Install appliances • Exterior door casings • Install closet shelves and doors • Finish interior painting • Install door hardware • Install finishing plumbing, fixtures, bath hardware and accessories
Finish electrical, and mechanical	• Install HRV or ERV (if applicable, Figure 16) • Install heat pump (if applicable, Figure 17) • Install Water heater

Activities	Details
	• Install light fixtures • Install panel trim  Figure 17: Compressor for heat pump installed on brackets on the outside of the house.  Figure 16: CERV and heat pump water heater in mechanical closet.
Finish plumbing and floor	• Jack-up house with hydraulic lift or move to sunken floor • Install plumbing in floor (if applicable)  Figure 18: ZEM home jacked-up on hydraulic lift.  Figure 19: Insulation, and partially installed sheathing. • Insulate and sheath floor. If the building is going to be delivered as a finished product ready to set on a foundation or piers, the floor will need to be insulated in the factory.

Activities	Details
Load shiploose, pack and ship	• Clean Modules • Test systems • Final inspection • Build, load, and strap shiploose material • Strap refrigerator and other appliances as necessary • Load on carrier

Site Work, Delivery, Setting, and Finishing

Ideally the factory would not only build the modules in the factory, but also transport, set and finish the modules, and do the site work, to ensure the quality is maintained in all components of the house and throughout the process. This will not always be feasible depending on the location of the home and the factory's business model. The factory may perform only some of the tasks outside the factory, in which case the responsibility for the house will be transferred at various points. The site work begins before the module leaves the factory and is the responsibility of the GC throughout the construction process. After leaving the factory, liability and responsibility for the modules transfer over from one party to the next as illustrated in Figure 20 below

During assembly in the factory, the modules are the responsibility of the factory, and liability resides with the factory. Once the module is lifted onto the truck, it becomes the responsibility of the trucking company. Another transfer of liability takes place once the crane lifts the module to set in onto the foundation, when it becomes the responsibility of the set crew. The general contractor (GC) will become responsible for the house following a walkthrough of the building with the set crew. The general contractor will retain liability on the house until the final walkthrough and handout to the customer.

If any defect or quality issues is found at the transfer points or while the house is under the responsibility of one of the parties, the party responsible will be charged with fixing the problem.

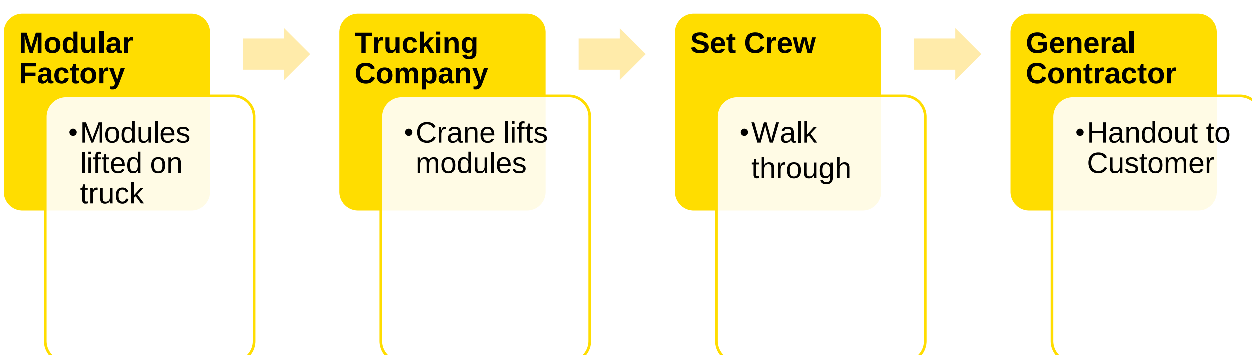


Figure 20: Liability and responsibility from construction to final handout to customer. The factory may perform some or all of these tasks.

It is essential that the set crew and GC are vetted by the ZEM factory, to ensure they have been trained to work on ZEM homes, have experience setting and finishing modular homes (including joining multiple boxes) to ensure structural, air tightness, and insulation requirements are maintained. The GC should understand key characteristics of a ZEM home and avoid potential pitfalls when setting and finishing a ZEM home. This is vital to ensure that the ZEM home performs as expected and conforms to all building code, voluntary energy standards, and third-party certification inspections before being handed over to the customer.

Figure 21: Setting of a ZEM MMH replacement onto its foundation.

For multiple-module homes, the modules will need to be joined on site. To maintain the air tightness of the homes, two common methods are used to join modules:

- A rubber gasket located between the two modules to be joined;
- Planning for a small gap between the studs and joists where the modules will be joined and filling that space with spray foam.

In both cases the exterior sheathing will also need to be taped on all walls, roof, and underside of the house, when applicable. Joining the modules also involves finishing the flooring, exterior siding, and drywall where the modules are connected, as well as connecting the following systems between the modules:

- Electrical
- Ducts (e.g. ventilation ducts)
- Hydronic (if applicable)
- Plumbing

It is important that the same quality is maintained when joining the modules and finishing the home on site, as what was constructed in the factory. The set crew must understand the quality standard for the ZEM home and strive to meet it. Once the modules have been joined, a blower door test can be performed and any additional air sealing necessary to meet the ZEM standard and third-party certification can be done then.

ZEM Home Building Timeline

Compared to a traditional code-level home, a number of ZEM-specific characteristics will add time to the building timeline, such as air sealing, super-insulation, triple-glazed windows, balanced ventilation, and preparing the building for the solar PV system.

In addition, the time necessary to complete a home in the factory will depend on several factors:

- The comprehensiveness of finish of the module, i.e. what components are built and incorporated in the factory or installed on site after the modules are set. For example, flooring, HVAC, cabinets, etc. could be factory-installed or installed on-site.
- The number of modules per home and whether the factory is large enough to work on those modules in parallel, or whether the production must be staggered and modules stored at the factory site until delivery. Multiple modules also will require additional setting time to tie the modules.
- The complexity of the design and degree of customization available. One-off, custom homes take more time to build than designs that are repeated over many homes with few modifications.
- The complexity of the wall, floor, and roof assemblies. Highly insulated and tight building assemblies take longer to build because a lot of attention needs to be paid to the details, such as sealing all the wall penetrations, or integrating adjacent assemblies such as connecting the air barrier between assemblies.
- The factory layout. Line production saves time because materials can be stored next to the station where they will be used. Line crews are trained to perform only the tasks at a specific station and can do those tasks efficiently. Bay or crib construction can take longer because crews are generally able to do all the construction steps but may do each task less efficiently. The staging of material in crib construction cannot happen right next to the module being constructed and therefore requires more crew and material movement, which adds to the production time. Generally, more compact factories require less crew motion and less material transportation time than elongated factories, shortening the production cycle.
- The degree of automation. Machines can perform tasks such as picking up the lumber from a specific pile, cutting the lumber into the appropriate size and shape, nailing an assembly, dense packing insulation to the right density, sheathing, etc. at great speed. This can increase the production rate but at a higher upfront investment cost.

Given the factors above, production can vary from roughly 12 working days per home or less, to 45 working days or more per home. An hourly breakout is provided in Appendix VII as an estimate, underlining the fact that the time necessary for each step will vary depending on:

- The specific home design
- The strategy used to achieve zero energy
- The factory layout
- The efficiency of the construction process
- The crew's skills and productivity

Setting the home and finishing it on site can take a matter of days if all the systems have already been installed in factory, or 2 weeks to several months if additional work is required after setting the module(s) on the foundation. Individual tasks will require a variable amount of time, depending on the factors listed above. ZEM homes are a new concept and therefore, existing ZEM factories are currently small and do not take advantage of automation improvements. To learn more about the expected timeline with various factors, see Appendix VI.

ZEM Factory Business Plan Toolkit

Factory Size

For efficiency of production, this guidebook recommends that the ZEM factory exclusively produces ZEM homes and sells directly to customers or affordable housing providers. It will be easier for a factory to consistently meet the demanding zero energy requirements of a ZEM home is the staff builds exclusively to this standard. Existing factories that wish to exclusively produce ZEM homes may need to take some steps to adjust their production lines and sales plan, such as:

- Building new relationship with suppliers of material appropriate for ZEM production
- Working with existing modular home dealer relationships and affordable housing providers to agree on a few zero energy standard designs that allow for some customer customization, and mass produce those designs at a low cost
- Vetting existing facilities and operations against the requirements for a ZEM factory, including stations, equipment, labor, operations and equipment (see Appendix I)

The remainder of this section is focused on a new factory start-up.

Most modular and panelized homes factories in the Northeast used an existing building (e.g. warehouse or old plant) rather than building a new one. Supply of underutilized industrial buildings of the appropriate size does not seem to be a major barrier currently. The minimum building and lot requirements and staffing requirements for the factory will be based on planned production.

In Table 3, the size expected for a start-up factory are highlighted in the gray box. If market conditions were appropriate or demand was significant, for example pilot programs that create demand for ZEM homes, then a greater production volume and factory size may be achievable even for a start-up. The factory size and labor hours necessary to complete the work will vary depending on the complexity of the home built. A highly insulated, thermal-bridge-free and air tight house design will require more time to complete than a typical code-compliant modular home. A lean and highly efficient factory with a stable and well-trained workforce will likley be able to achieve a greater volume of production with lower labor hours and fewer employees than the conceptual averages presented in the table.

Variability on production rate and labor hours will also be a result of work content linked to module design and specifications. Some factories might finish some work onsite (e.g. HVAC), or have different levels of completion (e.g. turned key, or 80% completed), or customization levels including energy efficiency techniques/materials. The values in Table 3 assume a turnkey package including HVAC.

Table 3: Conceptual factory size and required workforce for a number of production scenarios, assuming one work shift.

Approx. Module per year	Approx. Plant Floorspace (sq. ft)	Approx. Labor Hours per Module	Approx. Labor hours Annually	Approx. FTE, Direct Production
50	**10-20,000**	**440-1,200**	**24,000**	**20**
70	**20,000**	450	31,500	20
160	**45,000**	400	64,000	30
260	70,000	350	56,000	30
350	95,000	350	91,000	50
440	120,000	350	122,500	60
530	145,000	350	154,000	80
620	170,000	350	185,500	100
720	195,000	350	217,000	110

Factory Location and Layout

Ideally, for homes shipped beyond the local market, a factory should be located within a short drive (15 minutes) of a major highway, to reduce transportation time and costs. Other considerations include the availability of incentives for brownfield development and availability of redevelopment funds. Regional development agencies are usually available to assist in site selection based on economic development incentives and New Market Tax credit (NMTC) available. Examples of subsidies offered in New York State are provided in a section below.

Figure 22: Rollers.

A start-up can secure a portion of the building and share it with other industries. As the business increases, the modular factory may have the option to occupy a larger part of the building. Factories should have column spacing and height clearances that are compatible with the factory layout. The warehouse, where materials are stored, can be attached or be delineated space within the factory. Incorporating staging within the factory is generally more efficient than in a separate warehouse. Generally, about 70% of the factory's square footage should be dedicated to the production line, and 30% to receiving, staging, and shipping.

To determine the factory size and layout of a factory relying on line production, one should:

- Work from the ZEM module specifications to determine the amount of work;
- Identify activities common to all modular construction and those specific to a ZEM home;
- Use published times for common activities and case studies for special ZEM activities;
    - Calculate the optimal number of workstations and layout to achieve the most efficient layout.

A number of layouts are possible for setting up a factory. The plan will depend on whether the units are built in place (Figure 24: Crib or Bay construction), whether they are built in a set production line and moved along fixed rollers (Figure 22) or rails, or whether they are on air pads (Figure 27) or casters attached to the modules, and moved along a more or less set flow. Tracks are generally not a recommended choice because debris tend to accumulate in the tracks and cause problems. Casters and air pads are the most flexible options for moving modules around the factory floor, with air pads being more expensive. Flexibility in moving the modules is helpful if a module needs to be temporary pulled off the production line, or if the factory expands or contracts with fluctuating demand and the layout of the factory line needs to be changed to accommodate for the change in demand. The following figures illustrate the various layout options. If the factory has a sunken floor to allow for work on the underside of the first floor (as opposed to using jacks), then this will place constraints on the layout options for the factory.

Figure 27: Air pads.

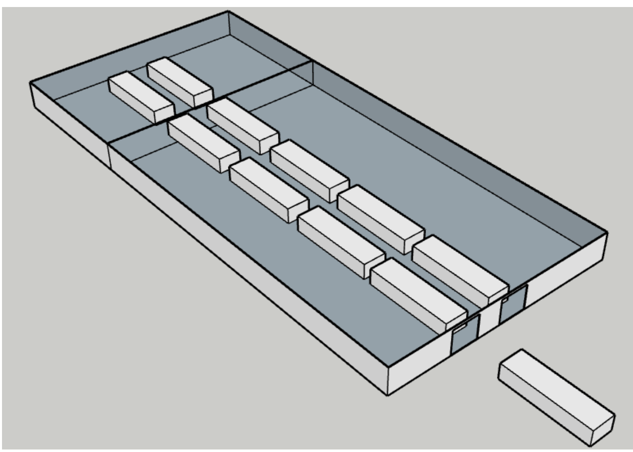


Figure 26: Shotgun line layout.

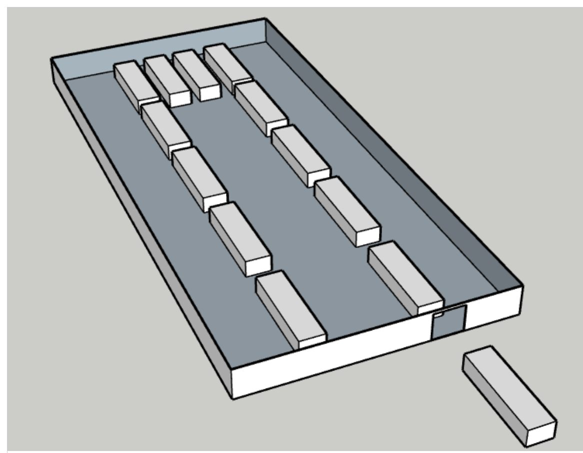


Figure 25: Horseshoe line layout.

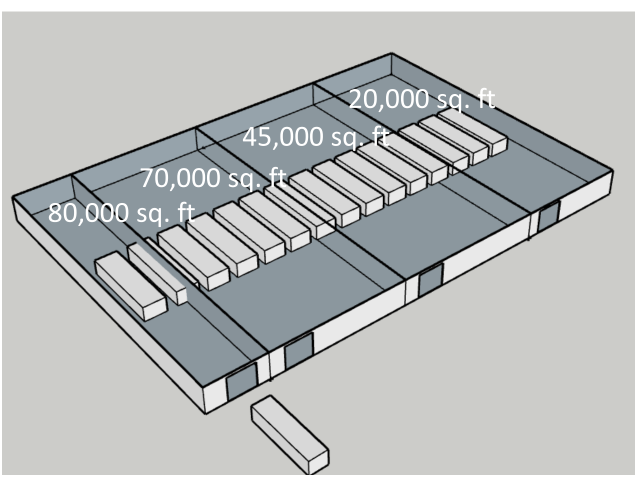


Figure 23: Sidesaddle line layout.

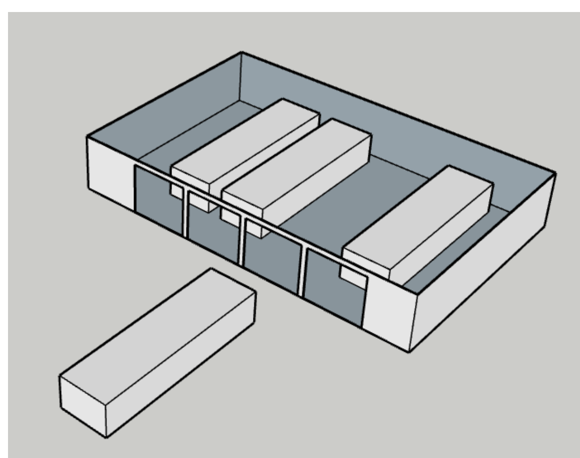


Figure 24: Crib or Bay construction.

"Crib", or "Bay" construction (Figure 24) works well for a start-up because it requires less equipment and does not require material handling equipment (e.g. cranes) and extra space to move the modules other than loading them on the carrier upon completion. Crib construction also works well if each module is highly customized or if the volume of production is relatively low. While a ZEM factory should strive for standardization of modules to keep costs low, if needed crib construction can also be set up so small modules can be moved around the space on casters, and laid out as they would be set, for complicated custom designs. However, crib construction has limited capacity to expand, without a major investment into an additional building space.

If the volume of production is higher, a line production can allow for shorter production time, and a relatively lower cost per module, with more specialized crews at each station. The shotgun line layout (Figure 26) is often used for line production. It can be modified into a T, an L, or a horseshoe shape (e.g. Figure 25), depending on factory layout and volume of production**.** A sidesaddle layout (Figure 23) may be preferred depending on building layout and construction processes.

Table 4: Summary of pros and cons of different plant layouts.

Plant Layout	Pros	Cons
Crib or Bay	• Well-suited for a start-up • Requires less equipment • Does not require equipment and space to move the modules other than loading them on the carrier upon completion • Suitable to more customized modules	• Limited capacity for expansion • Doesn't benefit from line production efficiencies • Required cross-trained workforce • Required higher levels or workforce coordination

Side saddle, (straight or L-Shaped)	Compared to a shotgun layout:
	• Because of the module orientation, the facility does not need to be quite as long, and can be more compact
	• It is easier to build catwalks in a more compact building
	  • Material does not need to be moved far in a compact building
		Compared to a shotgun layout:
		  • Access to the interior of the module (for homes with multiple modules) is only through the marriage wall and if that is against another module, access is more difficult.

Shotgun layout (straight, L or U-Shaped)	Compared to a side saddle layout: • Better access to the interior through the marriage wall, a forklift can drop sheetrock directly into the module if it is in a shotgun position, it cannot in a sidesaddle.	Compared to a side saddle layout: • Long facility may be required, resulting in material and people needing to move further, taking more time.

Whether the construction line is sidesaddle or shotgun, the number of workstations and amount of work done at each workstation can vary, to adapt to the facility size and layout. If space allows, a module can be pulled out of the construction line to customize or add additional features that would create a bottleneck if the module stayed in the line. From an efficiency standpoint, factories should construct mostly standard modules, with customization allowed as tiers or packages, as excessive customization reduces production efficiency.

The number of stations in the construction line are determined by starting with two basic models that the factory is expecting to produce, determining the steps to construct those modules, and then consolidating the steps to fit the factory plan. With line production, if demand increases, the number of stations can be consolidated, and more work done at each station, to allow for higher volume production. For a 20-40,000 sq. ft factory, an example would be to have two sidesaddles with bay station pull-outs for customization or floor construction. This would allow the production to take place in a compact facility.

If the production line starts as a linear sidesaddle, and if space allows, the production line can be modified to L-shaped, or U-shaped for increased production (e.g. Figure 25). Similarly, a shotgun production could be modified to a sidesaddle production line to increase the number of stations and scale up production.

Access to the factory from more than one side is preferable, to allow material delivery close to where it is stored. Oversized garage doors (e.g. 18'x20') will be required where completed modules exit the factory. Outside the building, there needs to be another 100 feet of pavement for truck movement, and some storage area for completed modular boxes that cannot be shipped on the day they are completed for unforeseen reasons. Factories typically strive to ship the modules upon completion to avoid needing to store the completed modules on site and risk damage to the modules.

Factory Set-Up Costs

A detailed list of equipment needed for a modular factory is provided in Appendix II and summarized by category in Table 5 below. The tools necessary for a modular home factory will be highly dependent on the level of automation and manufacturing processes - which will in turn be dependent on the volume produced. High-automation levels only warrant the investment if the volume of production is high. On a small volume of homes, the investment in sophisticated machines will likely never be recovered.

Start-up factories will need to acquire fewer tools if they hire subcontractors for specific, specialized tasks. One way for a start-up to minimize risks in the initial stages of production is to lease or rent space and equipment instead of buying them immediately. Alternatively, the factory could purchase second-hand equipment, for example from other modular home factories that have upgraded their equipment or went out of business. These approaches also work for established factories that are adding ZEM to their product line.

Start-up factories can increase the level of sophistication of the assembly lines as the production volume increases. Smaller factories and factories with fewer employees will see lower tool costs; larger, more automated factories will see higher tool costs, but often fewer labor hours per module.

Tools will also depend on what components of the house are built in the factory and what components are installed after the house is set. For example, if the floor system is fully insulated, air sealed and made weather-tight at the factory, the factory may have hydraulic lifts to elevate the home to fully detail the underside of the home. If the floor is left uninsulated, hydraulic lifts may not be needed.

In the table below, we assumed a start-up factory (rather than expanding production to ZEM homes in an existing modular factory) moved into an existing warehouse that was not previously utilized as a modular home factory. Therefore, we are assuming costs such as wiring the building and setting up compressed air at each station are necessary. These costs will vary depending on the actual building. We included costs for a larger factory are included as well, for comparison purposes and in the cases where a factory developer has access to a large amount of capital and is interested in lowering per module costs through higher volume production.

The costs presented below are approximative and conceptual, to provide a general range of costs. Actual costs may vary. Costs and number of units required are based on literature review and professional judgment. Costs will vary greatly depending on whether the factory owns delivery trucks or hires as needed. More details costs are provided in Table 5, to assist in designing budgets and business plans for specific situation. The costs presented below assume all new equipment, costs could be reduced by up to 40% by acquiring used equipment from idle or closing plants. Equipment costs will also vary regionally.

Table 5: Conceptual new equipment and start-up costs by factory type

	Small, crib-build factory • **20-40,000 sq. ft** • **50-70 modules/yr**	**Small, line production, low-automation factory** • **20-45,000 sq. ft** • **70-160 modules/yr**	**Larger, Higher Automation Factory** • **70-100,000 sq. ft** • **250-360 modules/yr**
Equipment Costs Subtotal (See Appendix II)	**$452,000**	**$793,800**	**$1,400,000**
Wiring	$30,000	$135,000	$300,000
20'x18' garage doors[15]	$32,000	$16,000	$16,000
Plumb building for central compressor	$3,000	$13,500	$30,000
Construct paint booth	$10,000	$10,000	$20,000
Office furniture	$500	$1,200	$1,500
Computer systems (hardware, software)	$10,000	$45,000	$100,000
Building Set-up Subtotal	**$135,450**	**$445,700**	**$967,500**
Prototype home cost	$150,000	$150,000	$150,000
Total	**$737,450**	**$1,389,500**	**$2,521,500**

Building operational costs (lease, electricity, heating, water) will vary depending on building characteristics. Adequate ventilation is needed to meet OSHA regulations, and while in the summer it can be done by opening doors and using fans, ventilating the building in the winter will impact heating costs. The right ventilation can prevent air quality problems. Although OSHA does not have indoor air quality standards for modular factories, it does have standards about ventilation and standards on some of the air contaminants that can be involved in indoor air quality problems. Areas exposed to more fumes and droplets, such as painting stations, may require additional ventilation, in addition to the use of personal protection accessories. While using spray foam to insulate wall cavities is not recommended due to air quality concerns, if the factory decides to use this method, it may require additional ventilation requirements, in addition to general factory ventilation.

[15] Note: crib factories require more large garage doors than line production, because one door is associated with each bay.

Understanding capital costs and operating costs will be important for the factory developer to understand the return on investment. For example, assuming a ZEM home can be built for $130 per square foot, and sold for $150 per square foot, or $150,000 for a 1,000 sq. ft home, then the margin will be $20,000 per home. Assuming a small crib factory building 50-70 homes per year, then $1-1.4 million will be available to cover costs and reinvested in the factory and its employees. Assuming a highly efficient line production can cut construction costs by 25% compared to crib construction, then the margin per home would become $60,000 (production cost of $90 /sq. ft, assuming the home retail price remains the same) and may justify the investment in line production and automation. Therefore, the return on investment will be highly variable depending on factory type and layout, operating costs, and production volume.

Labor Requirements

The cost structure for a typical modular producer is:

- Materials: 45-50%,
- Overhead 35-45%, and
- Labor 10-20%.[16]

Direct labor requirements will vary depending on the production volume. For a production of one to two modules per day (a 20,000-45,000 sq. ft factory), we would expect a total staff of 30 to 70 employees, with about three quarters of employees involved in module construction, and one quarter in support or managerial positions. Factories with a smaller volume of production will have a smaller staff. For example, Vermod employs 20-25 FTE for a production of about one module per week.

The staff in a ZEM home factory will differ from a typical modular factory in terms of the organizational culture: the common goal is not to simply build a home, it is to build a ZEM home. This common goal affects every decisions and steps along the way. For example, an employee in a ZEM factory should know that every time they make a hole in the envelope, they are responsible for plugging it. Because of this cultural difference and need for attention to details at every step, there is an advantage to having a ZEM factory exclusively producing ZEM homes. ZEM factories may also more often rely on external experts for the design and verification phase of modular construction. For example, the designer may rely on a technical expert (internally or externally) that is familiar with Passive House design and modeling, and that stays in touch with latest energy efficiency technologies, to ensure the home will meet the expected ZEM specifications. In addition to QA/QC staff, the factory may also lean extensively on the energy raters that they use for third-party certifications, to ensure the ZEM home meets the ZEM design goals.

The example in Appendix VII provides a conceptual example of how the labor would be broken out among the trades and positions. In smaller factories, employees may hold more than one position, while in larger factories, each position would have a dedicated staff person. These staffing requirements will vary depending on the exact process flow, the number of stations and the standard module design. If stations are combined and crews perform more than one tasks, production will be slower, but staffing requirements will be lower.

[16] Source*: Factory Design for Modular Homebuilding*, Michael A. Mullens, Constructability Press, 2011.

Using the estimated labor hours by task and trade and labor rates by occupations, provided in Appendix VII, a prospective factory developer can begin to estimate total annual labor costs. In addition, the following indirect labor positions will be required. In small factories, one person may fill two or more of these roles:

- General manager
- CFO
- HR director
- Accounts payable and receivable manager
- Purchasing manager
- Engineering manager/QA
- Production manager

Lean Manufacturing

One key aspect of keeping costs low is to follow Lean manufacturing principles. Lean production methods focus on the value stream and reducing waste. Lean manufacturing principles call for constant improvements in processes, standardization, and the identification and remediation of all wasteful activity. The basic premise of lean manufacturing is to add value to the product as it moves down the line, reduce cycle time, and eliminate waste. Lean production principles need to be considered throughout the process, from sales, to design, to production. A lean production case study for Vermod is provided in the Case Studies section, to illustrate the benefits that can be gained from designing a lean factory. Lean designs can result in 50-80% waste reduction and production capacity increase.[17]

TAKT Time

"TAKT" time is the average factory cycle time per module (hours/module, as an average of standard models produced at the factory):

Available Time for Production / Required Units of Production = Takt Time.

TAKT time is useful when planning a new factory because it helps assess the number of hours necessary for building a house, hence the number of weeks in production and workforce requirements. TAKT time will also help in the layout of work stations, to ensure a continuous flow of modules or crews throughout the construction process. This in turn will help determine the factory layout, to ensure that the layout allows for continuous flow. In line production, TAKT time determines the schedule when the modules move down the line. In crib construction, TAKT time is used to determine the frequency of rotation of crews. TAKT time can help estimate what the factory is capable of producing, how to balance workload, and identify if any tasks should be moved to the side of the production line to avoid bottlenecks.

[17] http://www.1000ventures.com/business_guide/lean_production_main.html

Efficient Production

Production is most efficient when orders are level, and production can avoid peaks and valleys, which tend to overburden people and equipment and lead to waste (e.g. fixing errors, overproduction, unnecessary movement of people and product, waiting, excess inventory, performing tasks that do not add value to the customer). Generally, operational performance is higher when product is standardized, and declines as more customization of modules takes place, because each new custom design may require a new process or steps that factory workers need to learn. More standardized module designs make it easier to plan and balance the workload among workers. Custom designs may put more unplanned work on some staff, and that overload may vary with each project.

Production is most efficient when orders are level, and production can avoid peaks and valleys

Increasing production allows a factory to spread overhead costs over more products, rendering the products cheaper per unit. There are several ways to add capacity to a factory:

- Adding more hours to schedules, such as overtime for short term, or additional shifts for longer term
- Reducing cycle time and reducing bottlenecks (e.g. drywall)
- Reducing set-up time, so more staff time goes towards production
- Phasing capacity growth, using expansion walls, a flexible equipment layout, etc.

Even if production is not increased, increasing production efficiency can lead to cost savings. Production efficiency can be achieved by standardizing processes and activities. Efficiency can be improved by detecting and eliminating wasted time or resources from the following waste categories:

Defect and corrections	•Defect and corrections needed to fix the defect (e.g. drywall cracks that need to be fixed down the line)
Overproduction	•Producing more than is needed or before it is needed
Motion of people	•Unecessary crew movements. Moving equipment closer together and reducing crews travel distance within the factory increasing the time available for production work.
Waiting	•For example, waiting. for upstream activities to finish, or for material, or for shared tools, or for malfunctioning tools to be fixed
Transportation of materials	•Unnecessary movements of materials or products. keeping workers, equipment, and materials in close proximity saves time. Movements that do not directly add value to the finished product (e.g. moving a pile of material out of the way to access other material)
Excess inventory	•Excess inventory and storing of material
Performing unnecessary tasks	•For example, unnecessary processes and paperwork that do not add value to the customer)

Figure 28: The eight types of waste considered in the lean process.

The equipment and technology need to be reliable and tested before being incorporated in the production line. Customized designs that require the incorporation of new material or technology adds risk of delays and bottlenecks to the production line. However, building science and technologies are rapidly changing and factories need to have a process for integrating these as they become best practice.

Another way to lower production cycle time is to limit the time required for set-up at each station. This can be done by allowing some set-up to be done in parallel with the previous production run. Reducing set-up time for tools, material, and equipment is easier to do in a production line configuration than in a crib or bay construction configuration. In crib construction, the storage space around the module is more and requires more frequent set-up and break down of what crews need for each task. In a bay configuration, crews cycle through rather than modules flowing through stations. As a result, each time a new crew comes, and new activity starts, the set-up for the previous activity needs to be packed-out and the new activity set-up.

One of the key principles of lean manufacturing is to ensure that no problems are hidden. This can be done by ensuring that the factory is organized such that:

- The factory is orderly;
- All equipment is clean and ready to use;
- Items are sorted through and rarely used items discarded;
- The 3 items above are standardized and maintained over time.

Reducing Bottlenecks

The goal of a modular home factory is to achieve continuous flow. Ideally, the modules should move down the production line in a synchronized flow, where all modules move to the next activity at the same time. This ideal may be hard to achieve due to process time varying between stations. Roofs and wall framing, along with drywall finishing are often bottlenecks in a production line. There are strategies that can help avoid blockages and bottlenecks to achieve a more synchronized flow:

- Incorporating queuing time into the flow;
- Planning buffers- reliable assignments that crews can do while waiting for the module if there is a backlog;
- Enabling workers to move downstream to complete work, or upstream to start early or help colleagues finish work. This helps absorb variations in cycle time;
- Incorporating flex workers throughout the plant that can work on any station to help complete tasks that are falling behind;
- Empowering all employees to inspect and identify defects and ensuring the worker responsible for the defect is notified immediately.

Lean manufacturing relies on value stream mapping, or identifying every value-added step in the production process. This can be done factory-wide, or for individual stations or steps. The end goal of value stream mapping is to eliminate steps that do not add value. Value stream mapping consists of the following steps:

1. Develop a sequence of critical tasks that form the lengthiest path through the project and what would result in the shortest time to complete the project. This is called the Value Stream Map;

2. Document critical performance metrics: quality, cycle time, productivity, inventory;
3. Observe, document, and analyze waste;
4. Pilot-test potential improvements, and fine-tune improvements;
5. Institutionalize the improvements;
6. Implement continuous improvement practices, through continuous improvement teams incorporating employees representing all levels of the company.

This discussion of lean manufacturing only touches on lean manufacturing principles. For a more detailed discussion of Lean methods, see Resources section.

Manufacturing Flow Management and Customer Relationship Management

Depending on the sales plan and approach to customization, a modular factory could theoretically range from a "buy to order" supply chain where every house is customized and there is a long lead-time between customer order and home delivery. The other extreme is a "ship to order" model where there is no customization but short lead times and more economies of scale from producing a product with no customization of home features. In reality, ZEM factories are likely to be somewhere in between these two extremes. The supply chain strategy will depend on whether the approach allows for extensive customization or not. For a ZEM factory seeking to reduce costs and serving affordable housing, an approach limiting customization would be recommended.

Allowing for some customization can be useful to gain a lead in the market, but it's important to set limits to the level of customization allowed. One approach is to offer tiers and levels of options for finishing details, rather than allowing for any customization the customer desires. With a tier approach, building material can be procured for each tier or package of options, without having to customize procuring the supplies for each customized project.

Production will generally follow these steps, from start to finish:

- Sales: inquiry to close (including lost sales)
- Design: standard designs or custom configurations
- Pre-build: design reviews, third party process (required for out of state production)
- Drawing packages with building specifications
- Production
- Pre-ship: final inspection
- Delivery: including set, punch list, on-site work
- Occupancy

Generally, a factory will need to standardize the production with standard components and standard models, which will limit the impact of customization on the production line and schedule. Having a well-established portfolio limited to the home designs that sell well (for established factories), or limited to a few models designed with a good understanding of what the target market wants (for start-up companies), will help maintain a smooth factory workflow and simplify the procurement process. A ZEM pilot can help drive demand. A pilot should be designed to build demand for a limited number of models.

A key principle of lean manufacturing relies on material being delivered just-in-time for utilization on the construction line soon after they are delivered. Orders and delivery schedules should be aligned with cash flow plans. Reliable supply of material is critical for a continuous workflow and production activities. Delays in delivery can result in bottlenecks on the supply chain, therefore there is a risk in relying on just-in-time delivery. Reversely, if production is behind schedule, supplier deliveries will build-up inventory level, and if production is ahead of schedule, there will be a shortage of parts. A ZEM factory should develop relationships with local manufacturers, especially if there are local manufacturers of products that are preferable from a health and environment perspective (see Appendix III: Building Material List for examples).

A ZEM factory is likely to order material from a number of suppliers including:

- Manufacturing (e.g. lumber, drywall, OSB)
- Retailers and distributors (e.g. windows, finished doors, pre-made cabinets, fixtures, HVAC, etc.)

Whether the factory can purchase materials directly from the distributor or will have to purchase from a retailer will depend on the structure of the supply chain for specific products, and the volume purchased. If the factory is purchasing large quantities, they may be able to bypass the retailers for products such as insulation material. However, unless the factory is large, the factory is likely going to be purchasing from retailers for windows, doors, HVAC systems, etc. If customization is more limited, the volume of each product purchased will be greater and the factory is more likely to be able to avoid the retailer markup and buy from the distributor directly.

Bulk Material

Typically, for bulk material that is used on every project (e.g. studs, drywall, etc.), there will be regular deliveries and a certain amount of inventory on hand at the factory to ensure continuous workflow. Contracts can be arranged with reliable local suppliers for just-in-time delivery. Using the same supplier for multiple components will help build a strong relationship with suppliers, simplify the ordering, and delivery process and may result in volume discounts from the supplier. The factory may need different strategies to manage each supplier, based on the volume of product purchased from each, and whether items are bulk supplies ordered on a regular basis, or specialty items that have longer lead time.

Specialty Items

For specialty items (e.g. windows, HVAC systems, kitchen counters, etc.) orders will be project specific and a close relationship with the suppliers can help ensure deliveries are not delayed. There are a few ways to mitigate that risk:

- **Relying on multiple suppliers.** This approach may not be feasible for key products used in ZEM homes, such as specific triple pane windows, SIPs, and specific heat pumps and ERVs. Relying on multiple suppliers will complicate the planning process. If the factory has a good relationship with a supplier, this approach may not be necessary. This will need to be balanced with consolidating the number of suppliers as discussed above.
- **Safety stocks or buffers**. This approach works best if modules have minimal customization. For example, triple pane windows could be stocked if the same window models and sizes are used on multiple projects. Stocks and buffers are not aligned with lean production principles and will

need to be balanced with those principles. However, safety stocks may help mitigate risks of delays and bottlenecks.

- **Postponing construction of the module** until key specialty parts that would create a bottleneck are in stock.
- **Postponing installation of the specialty part** until that part is delivered. In this approach, the module could either continue moving down the production line until the part is available and the part be installed down the line, or the module could be pulled aside in a bay. For example, the module would be held from moving down the line until the customers decides on the countertops.

The ZEM factory will need to make decisions relative to what to buy pre-made and what to make in the factory. For example, the roof can be made in the factory, or can be purchased as SIPs. Similarly, stairs and decking could be produced at the factory and shipped, or built on-site. There will be a trade-off between costs and labor hours that will be factory- or even project-specific. If SIPs are not available locally, some factories have made them on site using a separate production line, others have used trusses instead of SIPs for the roof. Cabinets are another example of what could also be made on-site or ordered pre-built. The factory should ensure products are available before committing to offering that option. If no reliable supplier can be identified locally, the ZEM factory can elect to:

- Ship from far away, running the risk to have additional delays in supplying the product,
- Make the product on site, for example in a separate production line, or
- Find an alternative design for the home.

As with any construction business, it is important to vet suppliers and ensure that:

- The supplier will be able to produce or distribute the product;
- The lead time for the product is aligned with module production schedules and the deliveries will be on schedule.

It can help to visit the supplier's factory to ensure the product quality will be as expected. As with any construction project, material should be inspected at delivery and defects and warranty issues should be dealt with at that point.

Factories should strive to manage demand and translate demand effectively into a smooth workflow. The production workflow and ordering process need to be aligned with how customer orders are handled, as well as how warranty issues are dealt with. For example, while a ZEM factory will be primarily focused on affordable housing, a ZEM factory may still be receiving orders from two main client types, and this will help balance the factory's budget:

1. Well-informed, environmentally conscious early-adopters seeking customized homes at a higher price point;
2. Income-qualified residents in need of affordable housing and organizations representing them, with some of the orders coming in as bulk orders for a dozen homes or more.

The factory processes need to be able to handle both types of customers. For example, a start-up may receive orders from an affordable housing developer, but there may be delays in obtaining funding from various agencies that support the project, or in doing site evaluation for solar PV, performing the appraisal, etc.

The process need to be able to handle these delays in individual and bulk orders, for example by defining when projects get put into the schedule and material ordered. If the orders are put into the pipeline and the customer's funding then falls through or is delayed, this may disrupt the construction workflow. One approach is to only put the orders into the schedule once all financing has been approved and all grants received and to look forward and keep an eye on what will be in production two weeks ahead.

Factories may be able to cut down on material cost by entering into low-profits partnerships with suppliers that support the environmental and social mission of a ZEM factory serving affordable housing. A ZEM factory may also be able to secure grants for material substitution for healthier or more environmentally friendly products.

Inspections, Quality Control, and Permitting

Quality inspections take place at the factory to meet different goals:

- Ensure that the construction meets the expectations of the design and specifications for the project;
- Confirm that the building meets building codes and certification requirements;
- Highlight energy efficiency and air quality attributes of the buildings.

Quality assurance (QA) ensures that a process has been designed and put in place that verifies that the product will meet set quality requirements. Quality control (QC) is the inspection of the product against set quality criteria. To meet these goals, quality assurance inspections take place at different points and through different avenues, as summarized in Table 6:

Table 6: Quality assurance and quality control at the factory

Inspection type	Where and when in the process	By whom	Extent of inspection
Internal quality assurance and quality control to ensure product meets design, specifications, and workmanship standards	At each station, or after key steps in the construction process	Usually, internal staff, e.g. in-house dedicated inspector, or plant manager. It can be someone with lots of experience or a plant manager or more of an engineering background. It is important that the internal QC staff is disconnected from workers performing the work, to provide honest feedback.	Each station has a QC manual that the workers follow. The inspector reviews the work and communicates any issues to the workers a that station. A blower door or duct blaster test may be done early in the process on a voluntary basis to fine-tune the QA/QC process, but once the expected quality is met routinely, it is usually no longer necessary.

Inspection type	Where and when in the process	By whom	Extent of inspection
Quality assurance for code compliance verification	As defined by building code, usually at rough-in and after key systems are installed, e.g. electrical, plumbing, HVAC, etc. At the design phase, construction phase, and after the house is finished, as locally required	Local code enforcement official, or third-party inspector if the final house site is too far from the factory, or if there are specific requirements to use a third-party inspector	Inspection includes electrical, mechanical, plumbing and building aspects, to ensure all the work done is in compliance with the rules and regulation specified in the building code Completes the final occupancy inspection and issues a Certificate of Occupancy for the project if no code violations are noted in the building code
Home certification/labeling verification to obtain recognition for energy efficiency features	Depends on program, some like PHIUS Passive House label require a review of designs Often an inspection is required after insulation is completed, but before the walls are closed up (Thermal Bypass inspection) Final inspection once the home is complete and set on site	Third-party independent inspector or rater. The rater's qualifications will vary depending on the specific labeling program (e.g. LEED, Energy Star, PHIUS+)	Final inspection usually includes a blower door, duct blaster, and ventilation flow checks.

State Requirements in New York

- ### Factory Licensing

Construction businesses in New York State are regulated at the local and municipal level, and a general contractor license must be obtained from the local government. Each municipality has its own licensing requirements. A construction business is also required to register with the Secretary of State.

Construction businesses must obtain home improvement contractors licenses to work in the cities of New York, Buffalo, Yonkers, and Long Beach and in the counties of Suffolk, Nassau, Westchester, Putnam, and Rockland. However, in most counties, construction of a new home is not considered a "home improvement".

- **Modular Home Insignia of Approval**

Under the definition of the NY Division of Code enforcement, a modular home is "a factory-manufactured dwelling unit conforming to applicable provisions of the New York State Uniform Fire Prevention and Building Code (Uniform Code) and bearing insignia of approval issued by the Secretary of State of New York State." Modular homes are regulated by Part 1209: *Regulations and Fees for Factory Manufactured Buildings*.[18] In Part 1209, manufactured buildings are defined as:

Factory manufactured home means a structure designed primarily for residential occupancy, constructed by a method or system of construction whereby the structure or its components are wholly or in substantial part manufactured in manufacturing facilities, intended or designed for permanent installation, or assembly and permanent installation, on a building site.[19]

There are two methods by which modular building plans may be approved by the Department of State (DOS):[20]

- An application may be submitted for approval of a new individual model or system subject to a full review performed by the DOS. This may take 3 to 4 weeks for an initial response.
- A new individual model may be submitted to the DOS for approval following an application under the third-party review program, subsequent to a review completed by an approved third-party review agency. Generally a review performed by the DOS under this program is limited to checking for compliance with established submission standards and code review.

Details and full regulations to obtain an insignia of approval for a modular home can be found in Part 1209: *Regulations and Fees for Factory Manufactured Buildings*.[21]

Local jurisdictions may also have specific requirements for housing intended as rental housing.

Healthy Buildings Materials

For affordable housing to be successful, it needs to provide a healthy environment for its occupants, require little maintenance over time, be resilient to extreme weather events, and be built of components that are long-lasting.

It is important to use building materials that are not harmful to health for two primary reasons:

- To maintain good indoor air quality in the home. Along with a home design that eliminates moisture and mold risks, and provides optimal ventilation, using products with low volatile organic compounds (VOC), semi-volatile organic compounds (SVOC), and formaldehyde emissions will ensure good air quality in the home, and reduce health risks for the occupant (e.g. asthma). Limiting the use of non-volatile toxic substances is important as well, as those can be inhaled as dust or absorbed through hand-to-mouth contact in young children.
- To protect the air quality in the factory. Eliminating the potential harmful product from production should be favored. The impact of harmful products that cannot be eliminated from production can be mitigated with personal protection equipment and adequate ventilation.

[18] https://www.dos.ny.gov/dcea/manufinfo.htm
[19] https://www.dos.ny.gov/DCEA/pdf/Active%20Cert%20List%20MFG%20Housing%2011082017.pdf
[20] https://www.dos.ny.gov/dcea/fmb_si.html
[21] https://www.dos.ny.gov/dcea/manufinfo.htm

In 2018, the Healthy Building Network conducted a review of some of the building material used at the Vermod factory, a ZEM factory located in Vermont. A summary table of their findings and recommendations is in [Appendix III](#).

Factory Location and Demand for ZEM Homes in New York State

VEIC performed a market analysis of New York State and based on housing trends and market capacity research estimated that 10,000 ZEM homes could be installed in the state. There is a dire need for quality affordable housing in the state of New York. This could be accomplished by replacing and displacing existing and new homes with ZEM homes with a production ramping up to 1,800 ZEM homes per year by 2030. The market potential in New York State is more fully discussed in Volume 1: *Market Analysis for ZEM in New York State*.[22] To select the location of a potential ZEM factory, it can help to look at the location of resident-owned parks, as they could be the primary target of a pilot ZEM mobile home replacement program. It is also helpful to look at the location of existing plants that would be able to produce ZEM homes. This information is provided in Figure 29. A factory located near Highways 87 and 90, for example, would be able to serve the eastern part of the State for a ZEM pilot. As additional resident-owned parks are established, private owners identified, or affordable housing partnerships secured, additional ZEM factories can be developed to serve that geographic location.

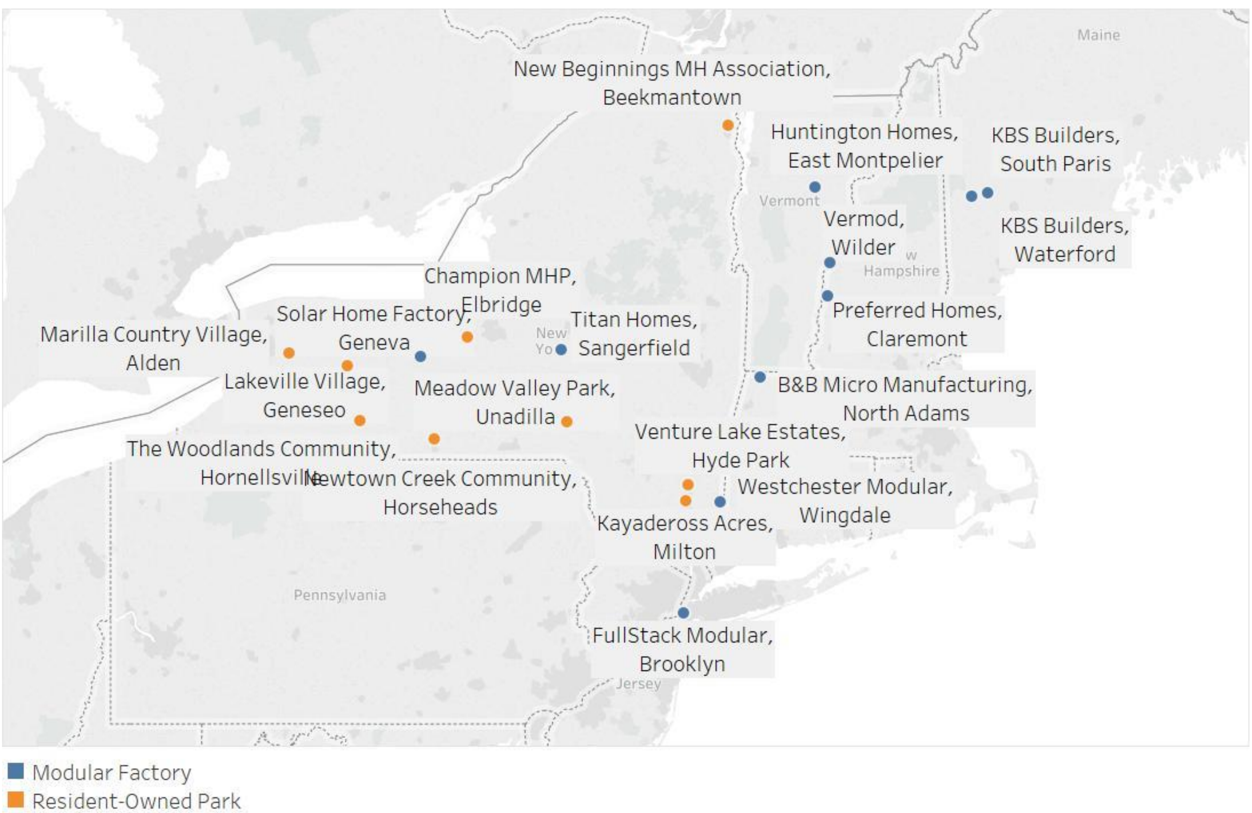


Figure 29: Location of resident-owned parks and existing modular factories.

[22] http://www.veic.org/resource-library/volume-1-market-analysis-for-zero-energy-modular-in-new-york-state

Factory size and workforce can be estimated, recognizing that values will vary depending on production processes and factory set-up. Using the conceptual factory sizes in Table 3, to produce 100-500 homes annually in New York State (assuming 2 modules per home), ramping up to full production capacity, there would need to be 2-10 start-up ZEM factories by 2024. Between 2024 and 2030, assuming a demand increasing from 500 to 1,800 homes per year, some of the start-ups would need to increase production and a few additional factories could be built in different areas of the state. By 2030, the ZEM market could be served by the expansion existing ZEM factories and the development of a few larger factories serving the whole state.

Deciding on whether to favor several smaller factories over one larger one will depend on a balance of several factors:

- Production costs: larger factories generally producing cheaper modules;
- Transportation costs: several regional factories generally transporting modules shorter distances than one large factory;
- Labor availability: one larger factory may have difficulties hiring the necessary workforce, depending on location;
- Local economic development: benefits of a small factory supporting the local housing demand and need for jobs vs a larger, centralized factory serving a larger region.

Plant capacity as designed may be different from the actual production per day, due to labor shortages, orders being over or under expectations, and the peak and valley inherent to varying demand and production over time. Variability in production rates and labor hours will also be associated with varying housing specifications, degree of customization, and the percentage of the home that will be finished in the factory, vs. finished at the site.

Business Structure Options

The ZEM factory can play several roles in producing and selling homes. Each approach has benefits and drawbacks (Table 7). Recent trends indicate that more and more factories chose to act as dealers for the region where they are located. Some factories are also playing the developer role, delivering homes to communities created with a factory's specific home design in mind.

Table 7: Pro and cons of business approaches

Business roles	Pros	Cons
Factory only—constructs modular homes	• No need to have a design center at the plant. • The inventory can be moved to dealers.	• Retailers can significantly add to the cost of a home, depending on their mark-up. • Missed opportunity to market the brand to the customer through factory tours.
Dealer/ retailer as well— designs and sells homes directly to customers	• Avoids retailer markup. • More control over the use of the brand. • Direct contact with customers to support marketing and word-of mouth.	• Factory needs additional staff to sell homes, manage home design, and marketing.

Developer as well— purchases land, develops land, sells to customer	• Create demand as well as supply homes through housing developments.	• Additional distinct business model to develop, grow, and manage.
General contractor as well— prepares site, sets and finishes the home. May also own the transportation fleet (optional)	• Ensures installations are performed appropriately. • Avoids contentious assignations of responsibility for problems	• Additional skill set require. • Manage labor, material ordering, and many aspects of site work.

Business structure will impact taxes, ability to raise money, business registration paperwork, and personal liability. It can be helpful to consult with business counselors, attorneys, and accountants to choose a business structure.

- **Sole proprietor**: this structure does not produce a separate business entity; the business owner can be held personally liable for any business debt and obligation. This is a good option for low-risk businesses and may not be the best option for a ZEM factory, which may have a risk of significant debt and obligations.
- Partnerships:
  - Limited partnerships;
  - Limited liability partnerships: this structure protects each partner from debt against the partnership, and partners won't be held responsible for the actions of other partners.
- **Limited liability company (LLCs):** LLCs protect personal liability and, in most cases, personal assets in case the LLC faces a lawsuit or bankruptcy. LLCs can be a good choice for medium- or higher-risk businesses, or owners looking for certain tax advantages compared to a corporation.
- **Corporation (C Corp):** a C Corp is a legal entity that is separate from its owner, offering stronger protection for the business owner, but at a higher cost, and more detailed record-keeping and reporting. Corporations can raise capital through the sale of stock.
- **Non-profit corporation (501(c)(3) corporations)**: Nonprofits do work that benefit the public and for that reason, are tax-exempt. Non-profits must follow similar rules as corporations. Non-profit status allows the business to re-invest net profit into increased production. Non-profits may not have direct access to any available economic development tax credit incentives.
- **Cooperative**: this business structure allows for an organization to be owned and operated for the benefits of those using its services, or by its employees.
- **Public sector**: for example, educational organization, such as community college, vocational school, etc.

Public-private partnership (PPP or 3P, or P3): There is no consensus on a PPP's definition. PPPs can be understood both as a governance mechanism and a brand. Generally speaking, with a PPP:

- The infrastructure need and proposed solution originates from the public sector.
- The project design, financing, and construction is done by the private sector.
- The operation and maintenance and ownership falls back on the public sector.

PPPs allow for sharing of the risk and the development of innovative solutions. PPPs often involve a long-term contract between a public sector authority and private business. In projects aimed at producing public goods, the public sector may provide a onetime subsidy or grant, or tax breaks or guaranteed revenue, to make the project financially viable.

Subsidies, Tax Credits, Grants and Loans Available

A number of incentive and tax credit options may be and will contribute to determining the location of a ZEM factory. Incentives may be available for brownfield development or there may be redevelopment funds available. Regional development agencies are usually available to assist in site selection based on economic development incentives and New Market Tax credit (NMTC) available locally. Incentives may reduce start-up costs enough to be a significant factor in site selection.

Many states have a tax-credit-based incentive program for the development of businesses that lead to job development in state. For example, New York state offers the following programs through Empire State Development. Tax credits are typically not directly applicable to non-profits, that do not have sufficient tax liability, but a partnership with a private entity (e.g. a LLC tax partner) may be possible to gain access to these incentives. The following programs may be applicable to a factory developer in New York State:[23]

- **Excelsior Jobs Program**, which qualify businesses for tax credits for each job created. Manufacturing firms creating at least 5 jobs are eligible. The program offers:
    - Excelsior Investment Tax Credit
    - Excelsior Real Property Tax Credit, for businesses locating in economically distressed area, or in industries with higher employment and investment thresholds.
- **Regional Council Capital Fund Program (ESD Grants – REDC**), which offer grants to private businesses, non-profit organizations, and others, for capital investments that result in job creation. Examples include acquisition of land, buildings, and equipment; soft costs and planning and feasibility studies related to a capital project.
- **START-UP NY**, which offers tax-based incentives and innovative academic partnerships. The program offers the opportunity to operate tax-free for 10-years on or near eligible university or college campuses in the state.

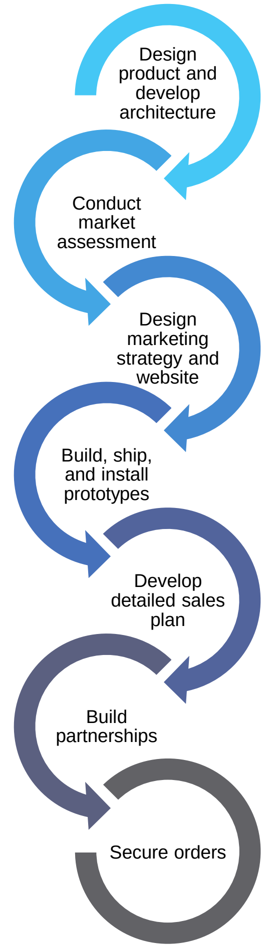
Empire State Development maintains a directory of small business programs available in the state, including programs relating to: [24]

- Technical assistance
- Funding Incentives
- Industry-specific programs
- Workforce recruitment, development, and benefits
- Government contracts and market expansion, and

[23] https://esd.ny.gov
[24] https://esd.ny.gov/sites/default/files/SmallBizDirectory_Jan2019.pdf

Getting started: Pre-Launch Preparation and First Three Years

To start a factory, the following steps need to take place. Depending on the business structure, factory size, and demand some of these steps may be omitted or the order of the steps may vary, and many of these steps will happen in parallel (Figure 30). When deciding upon a certain ramp-up strategy, factories will need to consider utilization, product variety, ramp-up time, and decoupling level (e.g. what standard components to produce prior to the customized order):



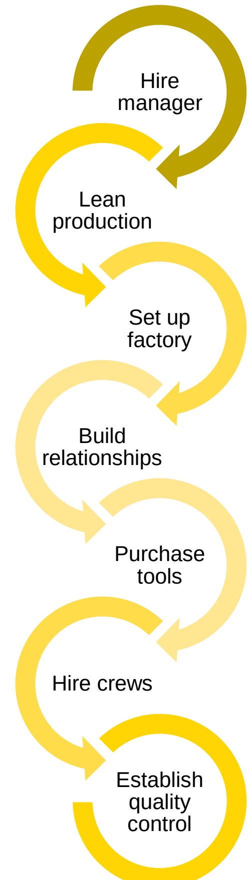
Pre-launch:

1. **Design product and develop product architecture.** Designs should be in alignment and compatible with Lean production principles. Start with only a few floor plans and expand to more plans as demand and production picks up.

- **Conduct market assessment**. Conduct a market analysis of the potential demand for ZEM homes, this will help determine the size and configuration of the factory. These markets studies have already been conducted in a few states and are publicly available. If demand is approximately 50 homes or less per year, then "Crib" or "Bay" construction may be the best fit. If market demand is expected to be more than 50 homes per year, then it may be worth considering line production, which has the potential to lower costs and speed up production time per module.
- **Develop business plan and raise capital** for new factory and field installation operations (if vertically integrating site preparation and setting the home).
- **Design marketing strategy and website.** The website will serve two purposes: a sales tool for home buyers to advertise the final product, and a communication tool with affordable housing partners and investors**.**
- **Build and ship prototype(s), hire sub-contracting installation crew (if needed), install prototype(s)**. First the company will design, build and install one prototype home in the targeted market area. This prototype will be built through another modular home factory as the new factory will not be up and running yet.
- Develop detailed sales plan.
- **Build partnerships with affordable housing** providers, land trust, and other organizations.
- Develop detailed capacity plan and production processes. Estimate labor requirements and cycle time.

- **Secure orders**, using the home prototype as marketing tool.

In addition to the pre-launch tasks listed above, there may be a need to train the local workforce to ensure sufficient staffing levels at the factory. The ZEM factory could work with the local community college or technical school to develop a job-training program that would ensure long-term availability of qualified workers.



Factory set-up (several of these steps are likely to happen concurrently)**:**

- Hire factory manager.
- Engineer a Lean production factory.
- **Set up the new factory**. The factory general manager will select the factory site and lease, purchase, or build the factory. The factory management team will then set up the equipment, purchase the inventory, and hire line leads and crews for the factory and field installation. The management team will also seek local partners for the initial field installations.
- **Build relationships with suppliers** of material appropriate for ZEM production.
- **Purchase tools and hire permanent crews.** Once there are firm orders for roughly 1/5 of the expected production for year 1, with substantial commitment for more from affordable organizations (roughly four times as much during the first year of production), the new factory should be staffed with dedicated staff.
- **Establish quality control, quality assurance** protocols and hire a third-party, independent quality control agency, if necessary.

Once a factory has been secured, a start-up can choose to hire sub-contractor crews to get the business off the ground. Planning on an increase in demand, the factory can then purchase tools and hire a permanent crews once sufficient orders have been secured. Sub-contracting teams can provide the tools required for their crafts. However, finding the right subcontracting crew might be challenging, depending on the region, and the crews will likely need additional trainings and close supervision, to ensure they build all details according to ZEM specifications.

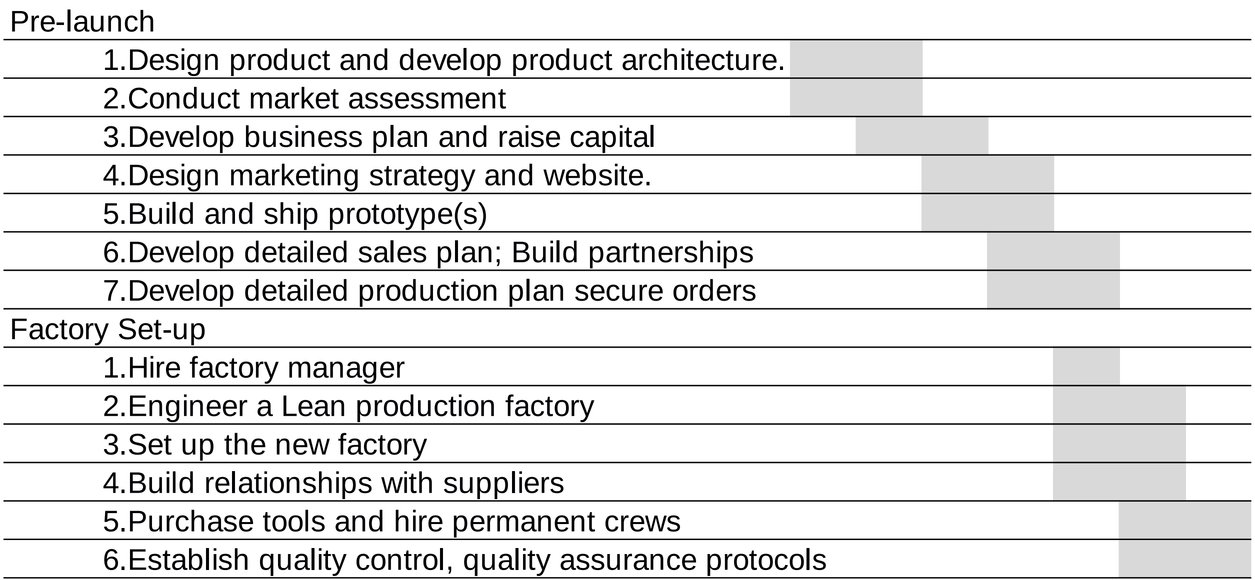


Figure 30: Getting started Gantt chart

Working with Affordable Housing Providers

New York State has an extensive network of for-profit and nonprofit affordable housing developers that could potentially purchase and redevelop a manufactured home community with ZEM homes using either an ownership or rental model. More details are provided in Volume 1: Market Analysis for Zero Energy Modular Homes in New York State.

Roles and Responsibilities

In the standard modular home market most customers purchase from a dealer. Dealers may procure homes from several manufacturers. In a vertically integrated modular company, the factory sells directly to the customer. This model is becoming more common, especially when the factory is well established, and has a recognizable name and brand, with an associated quality expectation. Generally, the dealer, developer, or factory designs, prices, and orders home from manufacturer. Once the home is manufactured, the General Contractor (GC) turns that home into a livable home. The GC is responsible for site preparation (foundations, etc.) and setting and finishing the home. Many dealers and manufacturers also function as GC or are closely affiliated with GC. It can be tricky for modular home factories to work with GCs not familiar with modular, as there is not much educational material available, and some specific knowledge of modular buildings are needed to properly set and finish the home.

When working with affordable housing, the ZEM factory will sometimes serve as dealer, designer, manufacturer, and/or GC for setting and finishing the home on-site.

By not selling homes through a separate dealer and making deals with affordable housing providers directly, the ZEM factory can cut on costs associated with this intermediary. Partnerships with affordable housing, land trust, and other community organizations replace the traditional sales department of a for-profit modular home producer. The partnerships will facilitate bulk purchase of houses. ZEM can also work for tribal and other groups. The partnership approach will result in very low marketing costs, limited to a website and brochures.

The affordable housing partnership approach between the factory and the housing provider will result in very low marketing costs, limited to a website and brochures. If homes are sold directly to home owners as well, then a more substantial marketing effort will be needed. In some cases, such as Habitat for Humanity projects, a volunteer workforce can be expected to contribute to the construction of the home, which can help lower costs. That volunteer workforce can contribute to finishing the home once it has been set on-site. In a Habitat-owned factory model, if the factory were located near a housing development project, volunteers would also be able to help in the factory.

Designing with Affordable Housing in Mind

For ZEM housing to be successful and accessible to affordable housing providers, it needs to **provide affordable, durable, and low-maintenance housing.** Pricing needs to be competitive compared to stick-built zero-energy housing. Grants and subsidies can help bridge some of the difference, but financial support should be expected to launch this new market and the product needs to be able to sell itself once the market is established.

Re-using designs allows the factory to avoid design and permitting costs.

For ZEM to keep costs low and keep homes affordable, factories will need to focus on mass production and limit customization. Limited customization not only improves production efficiency, it also reduces design costs. Re-using designs allows the factory to avoid costs related to designers, architects, engineers, inspections and inspection stamp costs. In reality, a certain degree of customization will always take place with each home but setting boundaries on that customization will be necessary to keep costs low. Limited customization also simplifies permitting and approvals, instead of each design needing a review and approval, a design kit can be approved instead.

For affordable housing to be successful, it needs to:

- Provide a healthy environment for its occupants,
- Require little maintenance over time,
- Be resilient to extreme weather events, and
- Be built of components that are long-lasting.

It is important that the houses are well-designed and well-built with these criteria in mind. A healthy environment for the tenants and workers requires choosing healthy building materials, limiting materials emitting VOCs, air sealing properly to avoid condensation and mold issues, and providing sufficient ventilation.

Additionally, house designs should be available that are compliant with universal design criteria:

- Accessible to all regardless of age, size, abilities, and disabilities
- Allows owner to age in place
- Provide step-less entrances, wider hallways, larger doors. Standard hallway in modular homes is 36 inches, accessible hallways would have 6 inches added.
- Include user-friendly items, such as door handles and faucets

- Allow sufficient room for a chairlift or elevator in stairwells
- Offer roll-in showers, tub with transfer seat

Other Strategies to Keep Costs Low

- Streamlining and standardizing communications to and between crews, engineers, designers, and management can result in better quality and more efficient production.
- The factory itself can be made more energy efficient: smart factory and retro-commissioning are strategies that can help reduce overhead costs.
- With higher production volumes and greater production efficiency, price points should decline, thanks to fewer FTE per module, lower costs materials due to higher volume contracts.
- Transportation and finish costs could be minimized (and quality increased) if these are internal capacities rather than subcontracted responsibilities.
- Including solar PV panels at the factory can lower energy bills. The additional installation of batteries can also help lower peak demand and thus can bring the factory to a lower rate class, lowering electric bills.
- There may be tax and other government incentives available for building energy efficient housing or affordable housing, for making the factory more energy efficient, or for starting a factory in an economically depressed or rural area. Grants and incentives are listed in a prior section and should be thoroughly researched and utilized to lower overhead and production costs.

Examples of Affordable Housing Projects

McKnight Lane Park, Waltham, VT

In May 2016, the Addison County Community Trust (ACCT) and Cathedral Square developed a new 14-unit development in Waltham, VT. The duplex ZEM homes were designed by Pill-Maharam Architects and constructed by VERMOD Homes. More information can be found at: http://www.addisontrust.org/mcknight-lane.html

New York City Urban Infill Project

Vermod was commissioned to provide 13 Urban infill ZEM homes in New York City. The Habitat for Humanity homes will be built in 13 small lots scattered through Queens. The homes will then be sold to income-qualified buyers through a lottery. The homes will be delivered with all finishes and appliances in place and will be fitted with solar panels. Finishing the home on-site will take about one week and will result in minimal disturbance for neighbors.[25]

[25] https://vtdigger.org/2019/01/16/making-vermont-vermont-homes-will-move-new-york-summer/

Factory Case Studies

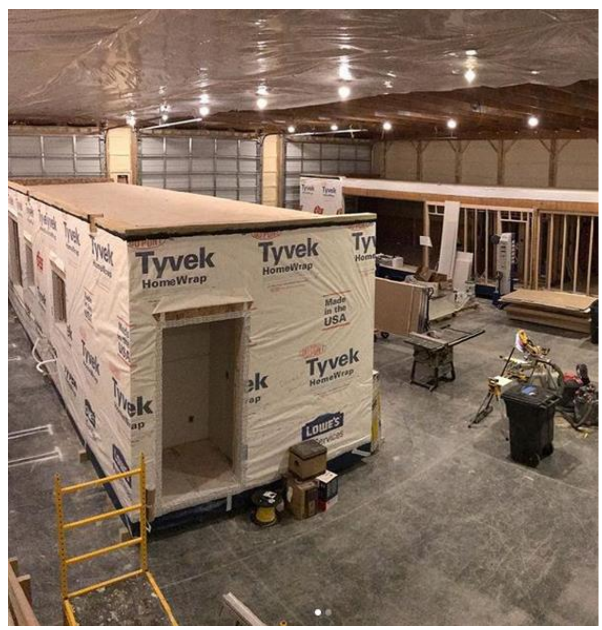
The following case studies provide examples of existing and potential ZEM factories, that illustrate the various approaches that can be taken in developing a ZEM factory business model.

Factory Start-up: Solar Factory in Geneva, NY

Factory Size and Location: *Start-up Bay Construction Factory in Geneva, NY.*

Approach and strategy*: Factory acts as developer as well.*

Solar Home Factory manufactures fully finished modular homes with net-zero or net-positive energy use. Solar Factory is currently developing the Lake Tunnel Solar Village in Geneva, New York — a development of 20 zero-energy homes of 650 to 1,000 square feet each. [26]



[26] https://www.laketunnelsolarvillage.com/; images from https://www.instagram.com/solarhomegeek/

Factory Start-up: Leaf Prefab Factory in Malone, NY

Factory Size and Location: *10,000 Start-up Bay Construction Factory in Malone, NY.*

Approach and strategy*: Bay construction using casters to move modules, access the underside, and move the modules.*

Figure 31: Leveling and tipping casters.

Tim McCarthy started a small ZEM factory in Malone, NY in 2018-- Leaf Prefab. Leaf Prefab builds both modules and panels.

After Leaf Prefab's first home was built at another factory location, the production was moved to a different, more suitable building. The building now consists of 10,000 square feet, rented at a very favorable cost. The adjacent 60,000 sq. ft. space is vacant and is available to Leaf Prefab for expansion if the factory were to grow.

The modules will be produced on casters, which will allow the modules to be moved around the factory floor, and rolled out the door onto a loading ramp and onto twin I-beam shipping frames for delivery to the customer. A much larger door than the existing loading door will be retrofitted into the building, which will allow modules to be simply rolled out for shipment.

Heavy duty leveling and tipping casters (costing around $140 each) will be used as a strategy to move the modules around the factory and to tip the modules to access the underside, to fully finish the underside of the first floor, or to access the bottom side of panels. Leaf factory is currently testing this tipping caster approach before implementing it throughout the production.

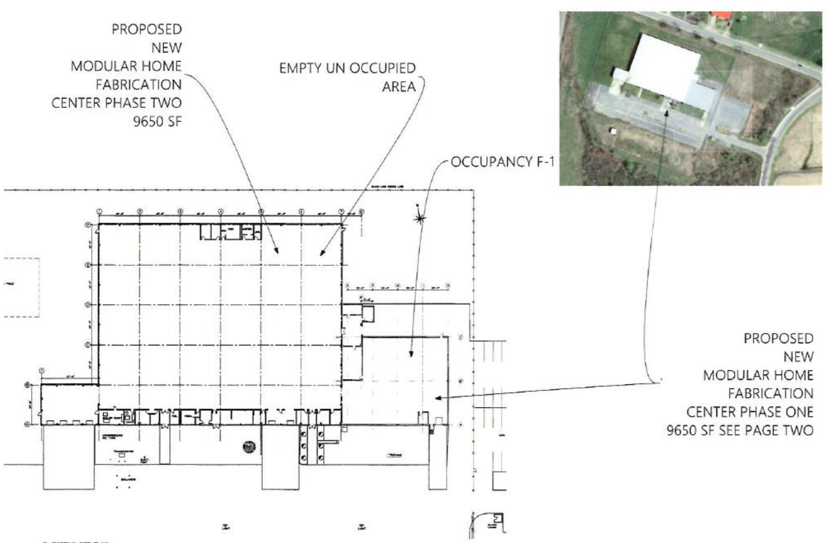


Figure 32: Leaf Prefab factory.

Vermod Factory, Wilder, VT - Lean Manufacturing Improvements

Factory Size and Location: *20,000 sq ft bay construction factory in Wilder, VT.*

Approach and strategy*: The factory exclusively builds ZEM homes, shipped to Vermont and neighboring states. The factory has sought to maximize efficiency through Lean manufacturing improvements.*

In 2013 Vermod started producing ZEM homes with a 10-homes pilot project. As of today, Vermod has set over 90 ZEM homes around the state and employs 15-20 local employees. Partnering with Efficiency Vermont's Zero Energy Modular (ZEM) Program, Vermod provides affordable housing for low- and moderate-income Vermonters with a special focus on replacing mobile/manufactured homes with ZEM. The case study at Vermod Homes demonstrates a bay style construction environment. Their specific example produces 20-30 homes a year. Their five-bay operation could be expanded to 50+ homes if demand increases and staffing is available.

In 2018, Vermod embarked on a LEAN manufacturing effort to improve the efficiency of their production. Vermod started as a construction business moving into a "factory" space with the intent to build multiple ZEM homes at a time. As a startup business, many systems were developed as needed without structure to replicate the process. The strength for Vermod was the knowledge of ZEM and construction in general. The challenge for Vermod was infrastructure, systems, discipline, and all other aspects associated with a startup. The first step in the journey to move from the current state towards the challenge defined earlier was to start looking for waste in the processes at Vermod.

- Using Lean Organizational techniques and visual systems, everything was sorted, what could be used was organized visually on shelves and labeled with Min/Max levels. Unnecessary items were disposed of appropriately. Space was reclaimed for staging received material for active projects.
- One project completed was the transformation of a saw used for cutting floor joists. This saw had been a permanently mounted tool located in one corner of the shop. The cuts were made and then moved to the bay to be installed. Vermod shop personnel rebuilt the saw base and made it mobile on big wheels so that the saw could be moved to the work area. With this new setup, the framing personnel do not need to leave the work area to get the raw materials and cut them for installation. This is just one example of how Vermod has installed their tooling and materials on rolling carts in order to bring them to the module being worked on.
- In order to reduce this waiting time Vermod began working on the hand-off process from the front office to the shop floor. Formal design review meetings began where the trades could all look over the prints looking for any conflicts with their work, and verify materials and look over the design for manufacturability. Only after a proper design review and proper sign-off of all parties shall a design be released to production. Upon release to production, a project will be assigned a bay 6 weeks out in order to allow long lead time materials to be ordered and received.
- Vermod does its best to stagger work in the bays so that it is at various levels of completion so that different crews are working in different bays at any given time. However, this has been a

challenge for Vermod. Financially, given the current workload, the decision was made to maintain the current staff level and limit production to three bays. The idea was to focus on the three bays, implement the Lean changes Vermod had been working on and getting really efficient as a three-bay operation before scaling up to the five bays.

- Before implementation of the lean manufacturing improvements, Vermod was experiencing an excessive amount of rework due to problems not being caught early in the process, such as sheetrock issues. The lean production focus became to follow a third-party standard across the board, with a focus on Quality at the Source: personnel at each process step make sure the steps before were completed without defect. If they find a defect, they pass this information back to the upstream process to mitigate future problems. Everyone is accountable and feedback is given in a constructive way with the goal of always improving the process. Vermod Homes has adopted a quality standard that aligns to third party inspection, which is required for out-of-state sales. When a modular home is built out of state, local inspectors require that a third-party inspection service act as that on-site inspector to ensure that the out of state build process meets all local codes and requirements. Many states within Vermod's delivery range, such as Massachusetts, Maine, New Hampshire, and New York, all require third party inspections. This process requires that Vermod send detailed drawings for all stages of production. These drawings are then reviewed and stamped to define the specific methods that will be used to produce the home. Then, the third-party acts as an on-site inspector at specific stages of production. The checking system that results allows the work to be validated as it's progressing and provides constructive feedback to the people responsible for catching and eliminating mistakes and rework.
- In order to minimize excessive design iterations with customers pre- and post-contract, and to give the customers a stronger starting point, the idea of the Book 1,2,3 designs was introduced. Each book is based on tiers of designs from income-qualified, minimal customization and size limitations in Book 1, to slightly bigger two-box designs with a little more customization in Book 2 to fully customizable homes in Book 3. Book 1 or 2 designs being less customizable require less of a deposit than the fully customizable Book 3. This initial education with the customer and clarification of design parameters helped to streamline the design process and decrease design time while the customer still gets what they want and can afford. Unlike traditional home building process, changes should not be made during the build process to keep timeline moving.
- Waste of Transportation comes from excessive transport of parts and materials around the plant. Vermod has some great systems to limit this. Each bay has a storage area at the end of the bay where all materials are stored upon receipt. Any time material is received that is job specific it is put in a bin and stored on those shelves at point of use. There is no need to move it more than once.

Efficiencies can be increased in several areas, for instance, by purchasing pre-fabricated materials from the supply chain, or building subassemblies of common building details. However, this low volume, high variability bay configuration still moves people to the work, instead of moving the work to the people. High efficiency operations can only be developed by significantly limiting the variability of model choices. In addition, the volume must be increased by a factor of 10 to achieve the kind of efficiencies that true flow manufacturing could offer. More details on the findings of the lean improvements at Vermod can be found in the full report, which can be requested from VHCB.org and VMEC.org.

Community College and Career Technical Educational Model

Factory Size and Location: *Proposed 10-20,000 sq. ft in Boulder, CO.*

Approach and strategy*: The factory will employ students and will provide an educational opportunity as they build ZEM homes for local, affordable housing needs.*

Figure 33: Potential locations for a 10,000 sq. ft crib construction factory at Arapahoe Ridge High School.

Several community schools, technical and vocational schools have expressed an interest in starting a Crib construction factory, where students could work on ZEM homes throughout the semester. The homes built in those factories will be designed by an architect firm in such a way that they can be zero energy ready. The homes will then be built by the students to meet all state and local regulations.

Students will learn to build all the components of a home indoors, and the house will ultimately be delivered to an affordable housing project locally.

Two examples of that type of projects are Boulder TEC, Boulder Valley School District in Colorado (led by Michael Bautista) and Smith Vocational in Massachusetts.

Building the homes in these small school-based facilities will have a few benefits:

- Educate students toward high efficiency construction and trades
- Replenishing the workforce with skilled trade
- Allow for partnerships with Habitat for Humanity, and donations of material
- Provide a student labor force at no direct labor costs
- Ability to get free materials and equipment from sponsorships, keeping upfront costs low
- Working through the school district opens doors for grant opportunities

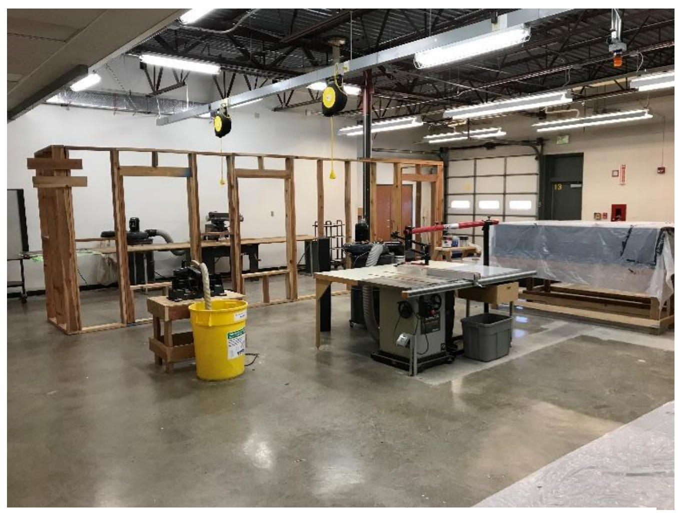


Figure 34: Teaching space at Arapahoe Ridge High School.

However, there are also some drawbacks to this approach:

- Factory production volume will be low, probably 1-2 homes per year
- Truck maneuvering for home delivery may be difficult on school grounds and will need to be carefully planned

Potential ZEM Factories:

St Regis Mohawk Akwesasne Homes, New York

Factory Size and Location: *To be determined*

Approach and strategy*: Opportunity for a tribal authority to own the factory as well as act as the developer of housing for tribal communities.*

The goal of the project is to "create an Eco-village called Akwesasne Homes to counter the housing shortfall, amplify community and cultural cohesion and be more resilient in the face of increasingly erratic economic, climate and pollution events facing the Akwesasne Mohawk tribal community." An initial plan calls for about 44 units and a building to house the Boys and Girls Club. This housing need could be fulfilled with ZEM homes, built in a factory owned by the St Regis Mohawk Akwesasne Tribe.

Disaster Recovery

Factory Size and Location: *To be determined.*

Approach and strategy*: Potential for ZEM homes to be used for disaster recovery, through one central factory producing ZEM homes to be deployed as permanent housing replacement following a natural disaster.*

From 2005 to 2007, Healthy Building Network (HBN) developed a business plan to build what they called the "Unity Homes". While the factory never came to fruition, it would have been located in Columbia, Mississippi, to provide rebuilding of low-income homes with quality ZEM homes following recent hurricanes. The factory had been planned for 86,250 square feet with 14 production stations that would have produced up to 4 modules per day, 500 houses per year by the third year of operations. Floor layout would have been as sidesaddle with staging and subassemblies on each side. Plant designs called for a 375' by 230' factory (Figure 35).

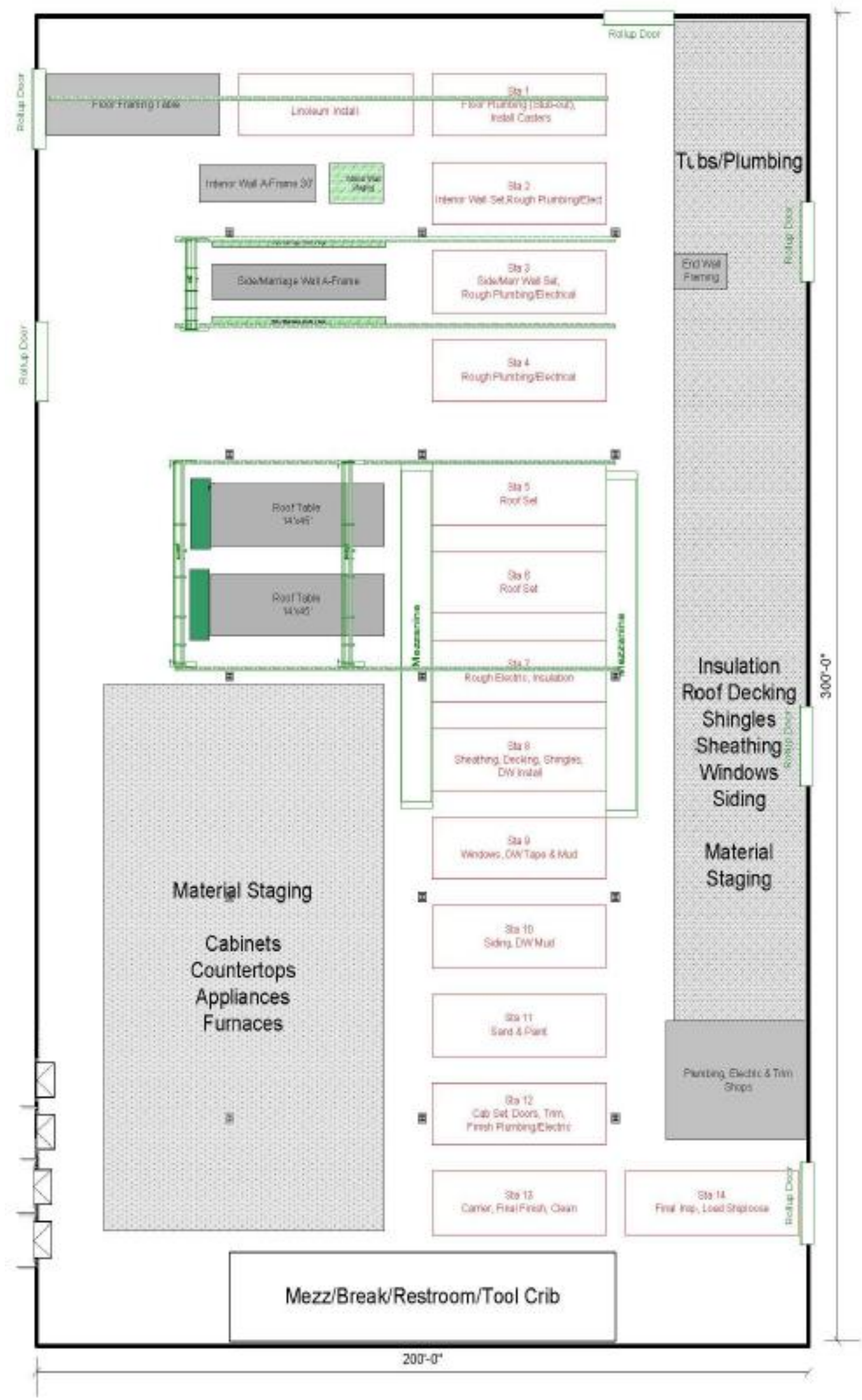


Figure 35: Healthy Building Network "Unity Homes" factory layout.

Conclusions

There is significant interest in and potential market for ZEM as an alternative to manufactured housing and single-family homeownership or rental, but the limited capacity for building ZEM homes is the most significant barrier to advancing this housing solution. This manual serves as guidance and resource for supporting the development of additional ZEM factories nationwide.

The development of a ZEM factory can take many forms, from a small, local, crib construction factory, to a large, state-of-the-art highly efficient factory serving a large area. Start-up may favor a crib construction design that involves less upfront capital, while factories with enough capital may choose a line-production layout that results in production efficiencies and lower production costs

In spite of their differences, ZEM factories will all share common attributes:

- Homes with high insulation, an air tight envelope, balanced ventilation, and minimal space conditioning
- No or low energy bills for the residents
- The creation of manufacturing jobs in rural areas
- Affordable, quality homes installed in partnership with affordable housing partners

Regardless of the factory business plan, size and layout the creation of supportive programs and financing sources from a state or federal agency would help support the development of the ZEM market for affordable housing.

Resources

- Volume 1: Market Analysis for Zero Energy Modular Homes in New York State http://www.veic.org/resource-library/volume-1-market-analysis-for-zero-energy-modular-in-new-york-state
- *Factory Design for Modular Homebuilding*, Michael A. Mullens, Constructability Press, 2011.
- Cantrell, R.A., Nahmens, I., Peavey, J., Bryant, K., Stair, M., *Pre-Disaster Planning for Permanent Housing Recovery, VOLUME 4: Basic Plant Design*, U.S., Department of Housing and Urban Development Office of Policy Development and Research, 2012
- Andrew Gianino, *The Modular Home*, Storey Publishing, 2005
- John Straube, Building America Special Research Project: High R-Value Enclosures for High Performance Residential Buildings in All Climate Zones, Building Science Press, 2010, https://buildingscience.com/sites/default/files/migrate/pdf/BA-1005_High%20R-Value_Walls_Case_Study.pdf

LEAN manufacturing resource*:*

- Raymond S. Louis, Integrating Kanban with MRPII: Automating a Pull System for Enhanced JIT Inventory Management, Productivity Press
- Ryan E. Smith*, Without A Hitch: New Directions in Prefabricated Architecture, Lean Architecture: Toyota Home Project,* University of Utah, https://scholarworks.umass.edu/wood/2008/

Appendices

I. Checklist for Factory Start-Up
II. Detailed Conceptual Equipment Costs
III. Building Material List
IV. Detailed Construction Steps Used at Vermod
V. ZEM In-depth Characteristics
VI. Build Timeline
VII. Labor Requirements

I. Checklist for Factory Start-Up

Manufacturing requirements (stations, equipment, labor)

- ❑ Floor Plan Space sufficient for desired production capacity and factory layout
- ❑ Factory Floor Plans offer room for expansion through production line re-design, or expansion
- ❑ Location: within 15 miles from major transportation route
- ❑ Ceiling Height: at least 24 feet to accommodate cranes and finished housing height
- ❑ Building structure strong enough to install and operate a crane, or does it need reinforcements
- ❑ Column spacing: at least 80 linear feet to maneuver work-in-process
- ❑ Loading docks and garage doors: 20 ft wide doors: at least one for incoming supplies, at least one for outbound modules
- ❑ Sufficient room for receiving, shipping, material staging, production, office space and break room.
- ❑ Hydraulic lift or sunken floor to finish the underside of first floor in the factory
- ❑ Electrical: 1,500-amp for equipment/ tooling (480-volt/240 volt, 3-phase)
- ❑ Heating equipment to heat the factory
- ❑ Water, sewer/septic for cleaning and workers
- ❑ Compressed air with dryer throughout the building
- ❑ Waste disposal and recycling system
- ❑ Qualified labor available locally

ZEM product (operations and sequencing)

- ❑ Ability to drywall all exterior walls and ceilings in one station/step, and then drywall soffits and partitions at a later step/station. Or ability to define the air and moisture barrier at a location other than the drywall.
- ❑ Ability of HVAC installers to install the soffits and the ductwork as one phase of work.
- ❑ Ability to access below first floor to finish floor
- ❑ Ability to finish all floors in the factory
- ❑ Ability to install HVAC in the factory, including ductwork
- ❑ Access to qualified set crew or GC
- ❑ Access to reliable vendors of the ZEM components

II. Detailed Conceptual Equipment Costs

Costs and Quantities adapted from *Pre-Disaster Planning for Permanent Housing Recovery, VOLUME 4: Basic Plant Design*, U.S., Cantrell, R.A., Nahmens, I., Peavey, J., Bryant, K., Stair, M., Department of Housing and Urban Development Office of Policy Development and Research, 2012, and professional experience. The costs presented below assume all new equipment, costs could be reduced by up to 40% by acquiring used equipment from idle or closing plants. Equipment costs will also vary regionally.

		Number of Units Needed				Costs Subtotals		
		Small, crib-build factory	**Small, line production, low-automation factory**	**Larger, Higher Automation Factory**	**Cost per unit**	**Small, crib-build factory**	**Small, line production, low-automation factory**	**Larger, Higher Automation Factory**
Standard Construction Tools	Floor jig	2	2	1	$9,000	$18,000	$18,000	$9,000
	Sabre saw	1	2	9	$250	$250	$500	$2,250
	Reciprocating saw	1	1	4	$250	$250	$250	$1,000
	Beam Saw	1	1	1	$150	$150	$150	$150
	Table saw	1	2	3	$4,200	$4,200	$8,400	$12,600
	Chop saw	1	1	3	$400	$400	$400	$1,200
	Miter/ radial-arm saw	1	1	11	$450	$450	$450	$4,950
	Wet/tile saw	0	0	1	$300	$0	$0	$300
	Router	2	2	8	$100	$200	$200	$800
	Sander	1	1	2	$400	$400	$400	$800
	Belt Sander	1	1	1	$1,000	$1,000	$1,000	$1,000
	Hot-melt glue system	0	0	1	$3,500	$0	$0	$3,500
	Air compressor pump	1	1	2	$9,000	$9,000	$9,000	$18,000

		Number of Units Needed				Costs Subtotals		
		Small, crib-build factory	**Small, line production, low-automation factory**	**Larger, Higher Automation Factory**	**Cost per unit**	**Small, crib-build factory**	**Small, line production, low-automation factory**	**Larger, Higher Automation Factory**
	Impact wrench	1	1	2	$200	$200	$200	$400
	Metal hand brake	0	0	1	$6,500	$0	$0	$6,500
	Ames mud-tool set	1	1	1	$4,000	$4,000	$4,000	$4,000
	Texture sprayer	1	1	1	$8,000	$8,000	$8,000	$8,000
	Ceiling Spraying equipment	0	0	0	$25,000	$0	$0	$0
	Nail/ brad guns	4	10	32	$250	$1,000	$2,500	$8,000
	Power drill	4	10	7	$100	$400	$1,000	$700
Insulation blowers	Blown-in fibergalss or cellulose machine	1	2	1	$10,000	$10,000	$20,000	$10,000
Carts, ladders, and scaffolding	Lumber cart with flip deck	0	0	1	$21,000	$0	$0	$21,000
	Push Cart	1	1	1	$6,500	$6,500	$6,500	$6,500
	Ladder	4	2	4	$150	$600	$300	$600
	Scaffold	0	1	1	$140,000	$0	$140,000	$140,000
	Safety harness, strap and Cable	0	2	2	$5,500	$0	$11,000	$11,000
Factory automation equipment	Face-framing machine (drill)	0	1	1	$11,500	$0	$11,500	$11,500
	OSB decking monorail	0	0	1	$25,000	$0	$0	$25,000

		Number of Units Needed				Costs Subtotals		
		Small, crib-build factory	**Small, line production, low-automation factory**	**Larger, Higher Automation Factory**	**Cost per unit**	**Small, crib-build factory**	**Small, line production, low-automation factory**	**Larger, Higher Automation Factory**
Lifting equipment	Diesel forklift (8,000 lbs)	1	1	4	$35,000	$35,000	$35,000	$140,000
	Hydraulic lifter			6	$9,000	$0	$0	$54,000
	1-ton bridge with Crane	0	0	1	$110,000	$0	$0	$110,000
	2-ton crane with bridge rails	0	0	1	$120,000	$0	$0	$120,000
	4-ton crane with bridge rails	0	1	1	$160,000	$0	$160,000	$160,000
Testing equipment	Di-electric tester	1	2	3	$1,500	$1,500	$3,000	$4,500
	Circuit continuity tester	1	2	8	$25	$25	$50	$200
	Breaker test/ torque screwdriver	1	2	4	$250	$250	$500	$1,000
	Air & water test/ 100-psi pressure gauge	1	2	4	$25	$25	$50	$100
	Gas tester/ mercury manometer	1	1	2	$90	$90	$90	$180
	HVAC duct-blaster kit	0	1	1	$1,500	$0	$1,500	$1,500
Delivery equipment	70’ 30 ton expandable trailers	5	5	6	$50,000	$250,000	$250,000	$300,000

		Number of Units Needed				Costs Subtotals		
		Small, crib-build factory	**Small, line production, low-automation factory**	**Larger, Higher Automation Factory**	**Cost per unit**	**Small, crib-build factory**	**Small, line production, low-automation factory**	**Larger, Higher Automation Factory**
	Trucks (pre-owned)	2	2	4	$50,000	$100,000	$100,000	$200,000
Subtotals	**Standard Construction Tools**	24	38	91	$77,050	$47,900	$54,450	$83,150
	Insulation blowers	1	2	1	$10,000	$10,000	$20,000	$10,000
	Carts, ladders, and scaffolding	5	6	9	$173,150	$7,100	$157,800	$179,100
	Factory automation equipment	0	1	2	$36,500	$0	$11,500	$36,500
	Material handling equipment	1	2	13	$434,000	$35,000	$195,000	$584,000
	Testing equipment	5	10	22	$3,390	$1,890	$5,190	$7,480
	Delivery equipment	7	7	10	$100,000	$350,000	$350,000	$500,000

III. Building Material List

Below is a partial list of products used at Vermod at the time of the writing of this report, and the Healthy Building Network's (HBN) assessment of the impact of that product on indoor air quality. Vermod is using HBN's recommended "step-up" approach: whenever feasible from a cost and factory process standpoint, Vermod uses an incrementally better, safer, and healthier product. While not all products listed below are highlighted in green, they are often better than the more common alternative.

The first step in sourcing healthy building materials is to understand what products are safe, where safer products exist, and what are the costs and the implications for the workflow of switching to a different product. Factories are also encouraged to buy the product that suits their needs now but write to the distributors or manufacturers advocating for a safer product that still meets their needs.

Hazard spectrum rankings below are an indication of what types of products are typically preferred within a product category based on common content and associated hazards. Product types in green are typically better options than those in orange or red, and product types in yellow are generally less preferable than green, but are better choices than orange or red. The full report is available upon request.

	Product	Product Type Hazard Spectrum Ranking *	Summary Guidance/Alternatives
Countertops			
	Formica laminate	Plastic Laminate	- Plastic laminate is not a top countertop choice from a health perspective. - Consider higher rated types of countertops like ceramic (made in the USA), solid surface, or engineered quartz. - For continued use of laminate check for availability of ULEF or NAF substrate options.[27]
Flooring			
	US Floors Solid Tongue and Groove Traditional Bamboo	Engineered Wood Floors (pre-finished) *Composite wood hazard spectrum:* NAUF	- This flooring is close to the top of our hazard spectrum ranking. Higher rated types of products are Linoleum and Solid Wood Floors (pre-finished). - Consider looking to see if there are bamboo flooring options available with lower formaldehyde emissions. - Prefer mechanical installation over adhesives.
	Country Home Collections Luxury Vinyl Tile	Unclear based on available information. Highest possible: New Formulations of Vinyl Floors (phthalate-free) Lowest possible: Traditional Vinyl Floors (with post-consumer recycled content)	- Vinyl floors of any kind are not a preferable material. Higher rated flooring options usable in wet areas include Ceramic Tiles (made in the USA/Lead-free) and Rubber sheet flooring (made without crumb rubber) - both come at a cost premium over vinyl. - If continued use of vinyl is unavoidable, verify with the distributor that there is no recycled content within the product and ask if it is free of orthophthalates. Or look for a different product that is verified to be free of post-consumer/unknown recycled content and free of orthophthalates.
Interior Paint			

[27] N o-added formaldehyde (NAF) or ultra-low emitting formaldehyde (ULEF)

	Benjamin Moore Ultra Spec 500-eggshell	APE-free, Low VOC Content, and Low VOC Emissions	- This paint product meets most of the targets that HBN has outlined for paint and is good choice of interior paint product. - An improvement would be a paint that is GS-11 certified (Benjamin Moore says this paint meets the requirements of GS-11, but it has not gone through third-party certification to verify this).
	Benjamin Moore Ultra Spec Vapor Barrier Primer	Low VOC Content	- Ask Benjamin Moore whether this product is APE-free and if it meets the requirements of the CDPH standard method for testing and evaluating VOC emissions.
Interior Wood Stain			
	Zero VOC LENMAR Waterborne Interior Wiping Wood Stain 1WB-1300	No hazard spectrum	- There does not appear to be a zero VOC version of Lenmar Waterborne interior wiping wood stain. - We don't currently have in-depth research into stains. SCAQMD regulations tend to be some of the most strict (but still achievable) in the country with regard to VOC content. Because of this, we recommend looking for a stain product that, at minimum, meets their requirements.
Insulation			
	SIP - BASF Neopor	Estimated: Graphite Polystyrene (GPS)	- Plastic foam insulation in general is not preferred. Within foam there is some polyisocyanurate insulation without halogenated flame retardants which is preferable. We aren't aware of SIPs currently available with this type of insulation.
			- Many higher-rated insulation products are not conducive to use in SIPs. There does appear to be at least one manufacturer that can provide SIPs using cork insulation, which is high rated, but likely adds a cost premium and a lower R-value than GPS per inch.
	Roxul Mineral Wool	Mineral Fiber Batts	- Roxul (now called Rockwool) mineral wool has at least one formaldehyde-free mineral wool batt. We suggest checking to see if this option would work for you. Owens Corning also offers some formaldehyde-free mineral wool batts.
Composite Wood			
	Weyerhauser Trus Joists TJIs	Unclear based on available information. Highest possible: ULEF (Ultra-Low Emitting Formaldehyde) Lowest possible: NAUF (no added urea formaldehyde)	- I-Joists are outside of the scope of HomeFree and are not required to meet CARB/TSCA requirements. - Applying the hazard spectrum we developed for interior composite wood products, based on the available information this product is at a minimum NAUF. We recommend asking the manufacturer whether they have emission testing results for their products and what sort of quality controls are in place to ensure the ULEF emission levels are met.
	Pacific Woodtech Corp Laminated Veneer Lumber	NAUF (no added urea formaldehyde)	- LVL is outside of the scope of HomeFree and is not required to meet CARB/TSCA requirements. - Applying the hazard spectrum we developed for interior composite wood products, based on the available information this product falls in the NAUF category. We recommending looking for ULEF or NAF options, or using solid wood where possible.
	3/4 OSB ARBEC (sheathing - subfloor)	NAUF (no added urea formaldehyde)	- For interior applications in particular, look for no added formaldehyde products (like those that use only pMDI) or ULEF products with regular test data to ensure consistently low levels of emissions.
Sheathing			

	ExoAir 120 + Advantech sheathing *Compared to* Georgia Pacific Forcefield	No hazard spectrum	- Neither option has full content disclosure. We recommend asking for a Health Product Declaration with all content characterized, screened, and identified to at least 1,000 ppm. - Based on the available information, the Forcefield product may be a better option from a health perspective, particularly for occupational concerns since there is nothing to wet-apply at the factory.
Cabinets			
	JS International and Tru Cabinetry	CARB Phase 2 (assumed based on US regulations)	- Legally, any cabinets made in or imported to the US at this point should contain composite wood products that meet CARB requirements. An improvement on this would be to choose products that have solid wood components like doors and drawer fronts, and those that have composite wood products that meet ULEF or NAF requirements.
Interior Doors			
	Brosco (interior)	Not a specific product - general recommendations provided	- Prefer solid wood products over composite (or solid veneers over composite facings). - When using composite wood (for solid core or composite veneer doors), specify materials that are NAF (No Added Formaldehyde) or ULEF (Ultra Low Emitting Formaldehyde) whenever possible.
			- Ask the manufacturer whether the door itself (not just the composite wood components) is free of urea-formaldehyde. - Prefer products that are factory-finished. - Avoid door knobs, hinges, and other hardware advertised as "antimicrobial."
Decking			
	CCA-Pressure Treated Wood	No hazard spectrum	- CCA (chromated copper arsenate) treated lumber can no longer legally be used for residential decking in the United States, though it is still available for some other applications. **Make sure that you are not actually using CCA treated lumber.** - If possible, prefer wood that doesn't need to be chemically treated - consider naturally rot-resistant, wood such as cedar, redwood, cypress, or fir. Acetylated lumber also avoids the use of preservatives and appears to be a good option. - Products treated with copper azole and ACQ are better options than arsenic treated products.
Roofing Membrane			
	RPI RE-FLEX EPDM Membrane RPI Royal Edge Bonding Adhesive	No hazard spectrum	- Verify with the manufacturer that this particular EPDM roofing membrane does not contain halogenated or antimony-based flame retardants. - The picture provided shows both the water-based and the low VOC solvent based adhesives. If you don't need both options for performance reasons, then prefer the water-based adhesive over the "Low VOC solvent-based adhesive."
Drywall			

	National Gypsum or USG Sheetrock Brand Gypsum Panels	No hazard spectrum	- Gypsum panels can contain large quantities of pre-consumer recycled gypsum or FGD - the amount depends on the exact product and manufacture location. Check with USG or National Gypsum on the amount of pre-consumer recycled content in the products you are using. - If possible, avoid pre-consumer recycled content (or prefer products with less) to avoid the release of mercury during manufacturing. - A pilot project has been working on closed loop gypsum recycling of cut off scrap from job sites. If the modular facilities have large quantities of cut off scrap, you may consider trying to participate in a pilot project to recover this material. Read more about the project here. We could connect you with them if interested in learning more about it.
	SHEETROCK DURABOND Setting Type Joint Compound and SHEETROCK Brand All Purpose Joint Compound	No hazard spectrum	- To reduce exposure to crystalline silica and other hazardous dust, consider using wet mud (ready-mix) versus dry material, where dust can be generated when mixing with water on site. - The largest exposure potential is likely during sanding operations. Use of wet-sanding techniques cuts down on the creation of dust when drywall mud is sanded - aside from removing the hazardous material, decreasing the amount of dust generated is the most effective protection. - Ask about the source of talc and whether it is verified to be from mines that are not contaminated with asbestos.
Sealants			
	Great Stuff Pro Window and Door Insulating Foam Sealant and Todol EZ Flo Gun Foam	One-part polyurethane spray foam sealant	- In general, we recommend the use of the SCAQMD Rule 1168 VOC content limits for sealants. - One-part polyurethane spray foam sealants are not preferred. If a foam sealant is desired, consider those that are not reacted on site, like an expanding polyurethane foam tape. - There are a couple of non-isocyanate spray foam sealants, but due to a lack of disclosure, we are unable to determine whether they are preferred to polyurethane spray foam sealants. If interested in these products, request HPD's. For smaller gaps, look for acrylic-based sealants with very low VOCs - options with ≤ 25 grams per liter (g/L) are available for many applications - making sure it is free of orthophthalate plasticizers.
	Adhesives		-

	Dow Great Stuff PRO Wall & Floor Adhesive	Polyurethane	- In general, we recommend the use of the SCAQMD Rule 1168 VOC content limits for adhesives. - Where possible, avoid the use of adhesives altogether by using mechanical installation methods like mechanical fasteners. - Next prefer solid adhesives, like peel-and-stick, to avoid the most hazardous content. - Within wet applied adhesives, prefer acrylic adhesives. Some acrylics may contain orthophthalate plasticizers, though this doesn't appear to be common - -- verify acrylic adhesives you source are free of orthophthalates.

*Hazard spectrum rankings are based on the most common formulations of product type. Specific product contents can vary considerably within a product type. Individual product contents must be fully disclosed for a robust review and comparison.

IV. Detailed Construction Steps Used at Vermod:

1. Lay out LVLs – 19oc
2. Set 1st LVL rim and nail on ledger board for TJIs
3. Set TJIs – fasten all together
4. Glue and screw 2nd LVL on outside
5. Square floor framing and install, glue and screw ¾" OSB
6. Lay out outer and inner wall on floor decking
7. Build outer wall on deck
8. Install fabric down center - stapled
9. Install upper sheathing and extend 12" above framing to capture SIPs when installed
10. Frame inner wall on deck
11. Stand walls and set 3" apart
12. 3/4" OSB for top plate to ensure 10" gap
13. Plumb, level and square walls
14. SIP panel installation (4'x14' panels with TJI embedded on one long axis – glued to next SIP panel
15. Sheetrock tunnel – glue sheetrock to studs
16. Mud and tape sheetrock
17. Install interior walls
18. Rough wire and plumb interior and exterior walls – includes panels and solar rough-in
19. Install interior walls sheetrock
20. Build soffits and sheetrock
21. Mud and tape all sheetrock
22. Install bottom course of exterior sheathing
23. Insulate exterior walls and install last section of sheathing
24. Tape all seams and rough openings
25. Window and door installation
26. Air seal and tape window and doors
27. Build eaves on outside
28. Install fascia and trim work
29. Install rubber membrane roof
30. Install all solar feet and rails and roof
31. Install all siding – metal, vinyl and/or wood
32. Paint inside
33. Install flooring – wood and vinyl
34. Trim out interior – kitchen, bathrooms, lighting, appliances, HVAC and all trim work
35. Jack the house up with hydraulic lifts
36. Finish plumbing, wiring, refrigerant lines
37. Install netting down middle of floor and glue and screw sheathing to TJIs along sides
38. Insulate floor systems
39. Install last section of OSB down middle
40. Tape and seal floor system
41. Lower down on trailer and deliver

V. ZEM In-depth Characteristics

Size Specifics of ZEM Housing

When designing ZEM homes, transportation size limits must be kept in mind:

- 12', 13', 13'9" are typical width, some manufacturers build to 14'9", and 15'9" but a police escort is required over 14', which increases transportation costs, especially over long distances.
- 60' are typical length of modules, some manufacturers build to 40' or 70'.
- Module height limit is usually 11', and is directed by federal, state, and local height limitations. This module height results in the load measuring 13'6" when sitting on top of the carrier, as the carrier is usually 2'6".

Foundations

- **Pier foundation**

A pier foundation system is the least expensive option and can reduce the overall foundation costs and installation time by several days. For sites with limited space for excavated material and utilities that run directly under the footprint of the home, piers are a great option to minimize site disturbance.

- **Crawlspace**

If the house is set on a conditioned crawlspace, the foundation should be properly insulated, air sealed, and built to avoid thermal bridges

- **Basement**

One of the more expensive options available for a foundation. If a ZEM house is placed on an insulated, conditioned, and ventilated basement, the first floor can be uninsulated.

First Floor Systems

Homes placed on an insulated, conditioned and ventilated basement can have an uninsulated first floor system. However, if a ZEM home is on an unconditioned space, the floor system must be insulated, air sealed, and made weather-tight in the factory, to maintain the benefits of modular construction. A ZEM home with an insulated floor system requires the following characteristics:

- Minimal thermal bridging;
- No ductwork and plumbing penetrations that would compromise insulation;
- Maximum air tightness through a defined and continuous air barrier; and
- Weather-tight and durable assembly.

Table 8 shows examples of ZEM home floor assemblies that have been used in the Northeast:

Table 8: First floor assembly options.

Structure	Insulation type	Underside Sheathing	R-value
9.25" TJI, 19" on center (oc)/ Solid Block Bridging	~9.25" Dense Pack Fiberglass at R4.3/inch	7/16" OSB with integrated water resistant and air barrier with taped seams on bottom of floor	R-40
9.25" Open webbed floor joists, 24"oc	~9.25" Dense Pack Fiberglass	7/16" OSB with integrated water resistant and air barrier with taped seams on bottom of floor	R-40
2'' x 12'' Floor Joists - 16''oc/ Solid Block Bridging	• (2) Layers of R-23 Roxul Insulation • Rim Joists @ 1st Floor Floor System with (2) Layers of 2" Rigid Foam	• 7/16" OSB with integrated water resistant and air barrier with taped seams on bottom of floor • Seal Edges with Low Expanding Foam for air sealing	R-46
2'' x 10'' Floor Joists - 16'' o.c. / Solid Block Bridging	• For conditioned and ventilated basement, so no insulation in the floor	N/A	

Exterior Wall

All wall assemblies should incorporate continuous insulation, a well-defined air and weather barrier and a system that manages moisture well. Continuous insulation can be achieved through a variety of approaches including double stud walls, or a single stud wall with exterior continuous insulation, or structural insulated panels (SIPs). In addition, a wide variety of insulation materials can be utilized to achieve the required R-values such as cellulose, mineral wool, wood fiber board, and blown-in fiberglass. In climates of the Northeast, the wall assembly's air barrier can be defined in several locations including:

- The gypsum wall board through the airtight drywall approach; or
- Exterior sheathing utilizing an OSB with integrated water resistant and air barrier with taped seams.

It is important that the wall assembly is designed to connect with the adjacent assemblies such as the floor or ceiling's air barrier. This ensures no gaps or penetrations are present at these transitions, so air leakage is prevented. While it's important to ensure high levels of air tightness and insulation, an exterior wall must also be able to manage moisture. It is important to evaluate the hygrothermal properties of the proposed wall system to prevent moisture from building up in components over time, which can lead to mold and mildew, and structural durability issues over the long term.

Drywall, is typically glued and/or nailed to the studs, rough opening perimeters and top and bottom plates, to achieve greater racking strength and sound-deadening, with all drywall seams landing on the studs and being sealed with tape and joint compound.

Table 9 shows examples of ZEM home wall assemblies that have been used in the Northeast:

Table 9: Exterior walls assembly options.

Structure	Insulation type	Exterior Sheathing	R-value
10" Exterior Walls. (2) 2x4 Walls Spaced 3" Apart Spaced 3" Apart - 24''oc - 1/2" OSB as Top Plate.	10" Dense-packed fiberglass insulation at 1.8/lbs per cubic foot, R-value of 4.3/inch	OSB with integrated water resistant and air barrier with taped seams and corners.	R-43
2x 6 Walls, 24"oc w/ continuous insulation	• Dense Pack Cellulose (R-21) • (1) or (2) 3" polyisocyanurate foam (R-17 each)	OSB with integrated water resistant and air barrier with taped seams	R-38 to R-59
2x8 stud framing 24"oc 2-1/2" @ 24"oc Interior open-built strapping layer for wiring chase	• Dense Pack Cellulose (R33) • 1-9/16" woodfiber exterior sheathing (R-6) • Service cavity can be insulated	7/16" OSB sheathing	R-39+
8" SIP	• BASF Neopor graphite infused expanded polystyrene	OSB with integrated water resistant and air barrier with taped seams	R-40

Roofs

- ### Low Pitch roofs

These are the most typical roofs, and conform to transportation standards. These roofs can be built completely in the factory, while still meeting the size restrictions for transportation.

- ### Hinged Roof System

In a hinged roof system, each section of the roof is fabricated into two or more components, which are hinged to the module and each other. Hinged roof systems are designed so they lie flat on top of the module during delivery, and once the module is on the foundation, the set crew uses the crane to lift and unfold the roof to its correct height.

- ### Site-Built Roofs

Another approach often utilized is to have roof trusses or panels delivered to the site for installation in the field. ZEM homes in MMH replacement projects will typically have the roof systems completed at the factory allowing for a turnkey product.

If a steeper pitched roof is desired, the ZEM home can still be delivered with a completed insulated and weather-tight flat roof assembly and roof trusses can be installed on site. A tilt-up, hinged roof assembly can also be integrated into the module in the factory and the roof can be erected on site with a crane and some additional panels to achieve temporary weather-tightness. These site-built roof systems still need to be air sealed, insulated, and made weather-tight on site increasing construction time and cost.

Multiple options are available for the roof system which will be determined by percent completion in the factory, ease of installation (labor hours), cost of components, and roof pitch. If the roof system will incorporate a steeper pitch, it is important to ensure the solar PV system can be oriented within 15 degrees of solar south with the ridge running east to west. It is also important to locate items such as vent pipes, dormers or chimneys on the north side of the roof, or outside of the PV array area.

Some of the roof assemblies that have been used for ZEM homes, in climates of the Northeast, include:

Table 10: Roof assembly options.

Structure	Insulation type	R-value
Parallel cord truss system, 2x4 top and bottom cords with cross bracing, spaced 24" on center.	Dense-packed with 14" of fiberglass with vented air space below roof deck.	R-60
12", 4' x 14' SIP panel. TJI joists every four feet that interlock with the opposing panel.	SIP panels with 12" Neopor expanded polystyrene insulation	R-60
Single Pitch, Shed-style Roof System with 9.25" TJIs or 2x10 rafters and continuous insulation	• Dense Pack Cellulose Insulation (R-40) • 4" Polyisocyanurate Rigid Foam installed on the exterior of 5/8" OSB with integrated water resistant and air barrier with taped seams	R-60
Single Pitch, Shed-style Roof System with rafters with continuous insulation	• 9.25" Dense Pack Cellulose Insulation	
Common Trusses 24"oc, 2x4 interior strapping @ 24"oc, Siga Majpell Membrane, 5/8" OSB Exterior sheathing	• Dense Pack Cellulose Insulation	R-60

Note: Building roofs as SIP can significantly save on ZEM factory construction time.

Windows

ZEM windows also incorporate insulated frames, triple glazing, low-E coatings, and argon gas between panes. There are several manufacturers nationally that provide windows that match these specifications. Some of the specifications that have been used for ZEM homes in the Northeast include U-factors of 0.12-0.21 and solar heat gain coefficient (SHGC) of 0.20-.50.

Another consideration with ZEM homes is passive solar design and ensuring overheating is avoided. When replacing manufactured and mobile homes, often solar orientation is not ideal and can involve the long access of the home running north to south. In this scenario, windows are specified to maximize the insulation value and reduce potential overheating with east and west facing glazing by integrating low SHGC windows. If the home's long access can be oriented east to west, homes can be designed to maximize glazing to the south (for example, 12% glazing to floor area ratio for a climate of the Northeast), and reduce the percentage on the north, east and west glass (for example, 2% glazing to floor area ration in the Northeast). At the same time, the design should consider the use of appropriately sided overhangs to minimize solar gains in the summer and maximize gains in the winter when the sun is lower in the southern sky.

HVAC and Hot Water

HVAC and domestic hot water equipment that have been successfully factory-installed in ZEM homes, in climates of the Northeast, have included the following components:

- A dedicated mechanical room, located inside the building envelope, housing the water heater, ventilation system, and battery storage. The mechanical room interior walls are insulated with acoustical batts to provide sound dampening.
- Balanced ventilation with heat or energy recovery to provide demand-controlled, and in some cases, conditioned (heated, cooled, and dehumidified air) ventilation through the entire home. Some ventilation systems can monitor CO_2 and VOC levels, and operates when specified thresholds are met. The main unit is typically installed in the mechanical room and is ducted throughout the home using 4 & 6 inch ducts located in a soffit chase installed inside the air barrier and thermal envelope. Soffits for the HVAC conduits in ZEM homes are often steel frame to ensure quality and fast installation (wood is often too warped and adds more construction time).
- A ductless cold climate heat pump installed in the main living area (multiple heads for larger homes). This operates in conjunction with the energy recovery ventilation unit and provides primary heating and cooling with the ventilation system mixes the air throughout the home. If installed at the factory, the external compressor must be mounted on the short side of the module, to avoid exceeding the module's width limitations. The indoor head needs to be installed on the inside of the same short wall as the exterior compressor.
- A heat pump water heater (HPWH) is typically specified, which reduces water heating costs by up to 70% when compared to electric resistance water heating. The HPWH is installed in the mechanical room, and then hot water is delivered throughout the home either directly into adjacent spaces when the mechanical room is close to a kitchen and/or bathroom or routed through the soffit chase inside the thermal envelope.
- The local exhaust and whole house ventilation is provided via the balanced ventilation system. The following average flow rates are achieved and based on the Passive House ventilation standard:
    - Exhaust (continuous)
        - 36 cfm in the kitchen
        - 24 cfm in the bathroom
        - 12 cfm in the powder room / laundry
    - Supply (continuous)
        - ~25 cfm supply per room

VI. Build Timeline

The time ranges presented in the table below reflect ZEM modular construction on a small scale in a crib factory. If a factory had enough demand for a large volume of ZEM homes and could produce these homes in a highly efficient and automated line production, rather than crib construction, that factory would see significantly shorter production times.

Table 11: Time to complete key tasks[28]

Module construction	Expected range for a ZEM factory
Cut to size (Mill)	80-300
Build floor	
Build windows/ door opening subassemblies	
Build partition walls	
Build side wall	
Build end walls	
Build marriage wall	
Set partition walls	
Set exterior and marriage walls	
Install rough electric in walls	
Air sealing, caulk, foam, tape	10-30
Build plumbing subassemblies & Install rough plumbing in wall and tubs and roof	10-50
Build subassemblies for roof	40-60
Build roof/ceiling	
Set roof	
Install rough electric in roof	
Sheath and install subassembly for roof & Insulate roof	
Shingle roof	
Prep/drop roof & wrap for shipment	
Insulation	20-60
Install fascia and soffit, Sheath walls, Insulate walls	10-20
Install windows & exterior doors	20-25
exterior painting	10-20
Install siding & trim	20-40
Hang drywalls on walls	20-100
Tape & mud drywall	
Sand & paint	20-40
Install cabinet & vanities	5-10
Fabricate & install kitchen countertops	5-20
Build finish plumbing subassemblies	2-10
Install finish plumbing	2-5
Install finish electric	3-80
Build interior door subassemblies	2-10
Install interior doors	2-10
Install molding	10-50
Install misc. finish items	5-10
Install flooring	5-40
Mechanical/AC	60-80
Solar	60-80
Load shiploose	5-10
Factory touch-up	10-40
Install plumbing in floor	5-10
Load module on carrier, Final wrap & prep for shipment, Build major shiploose subassemblies	2-10
Total factory hours per module	443-1,220

[28] Based on averages published in Factory Design for Modular Homebuilding, Michael A. Mullens, Constructability Press, 2011, and hourly values provided by Vermod.

VII. Labor Requirements

Table 12: Conceptual example of factory labor requirements (Source: adapted from HBN "Unity Homes" business plan)

	FTE required by activity		Trade
	1 module/day	2 modules/day	
Mill room	**1**	**3**	Carpenter and Carpenter helper
Framing	**4**	**7**	
Rough mechanical	**4**	**7**	
Electrical	1	2	Carpenter and Carpenter helper
Plumbing	2	3	
HVAC	1	2	
Roof build	**2**	**4**	Carpenter and Carpenter helper
Shingle or rubber membrane	**2**	**4**	Roofer
Siding	**2**	**4**	General construction helper
Inside Finish	**8**	**13**	General construction helper
Floor covering	1	2	Tile setter or general construction helper
Cabinet set	1	2	Cabinet maker
Trim and doors	1	2	
Final clean up	1	2	General construction helper
Material loading and close up	1	1	
Final electrical	1	1	Electrician and electrician helper
Final plumbing	0	1	Plumber
Install HVAC	2	2	
Drywall finish	**3**	**5**	Drywall installer, taper, and finisher
Back panel hanging	0	1	Drywall installer
Mudding/tape finish	2	3	Drywall taper
Sanding/painting	1	1	Drywall finisher and painter
Direct construction labor	**26**	**47**	
Receiving/ material handling	**1**	**2**	
QA inspection	**1**	**1**	
Maintenance	**0**	**1**	
Yard house loader	**1**	**1**	
General helper labor	**3**	**5**	
Engineering manager	**1**	**2**	
Purchasing manager	**0**	**1**	

	FTE required by activity		Trade
	1 module/day	2 modules/day	
Accounts payable and receivable	**1**	**1**	
Sales/Marketing	**0**	**1**	
Field Operations Manager	**0**	**1**	
Total management support staff	**2**	**6**	
President/ General Manager	**1**	**1**	
Production/ Plant manager	**1**	**1**	
Plant line supervisors	**1**	**2**	
Maintenance supervisor	**1**	**1**	
HR Director	**1**	**1**	
CFO/ Controller	**0**	**1**	
Sales/marketing manager	**1**	**1**	
Purchasing manager	**1**	**1**	
QA manager	**0**	**1**	
Total management staff	**7**	**10**	
Total operation employment	**38**	**68**	

Table 13: Direct labor rates for New York State[29]

Direct Labor Trade Type	Labor Rates
Carpenter	\$30.11/hr
Cabinet maker	\$20.00/hr
Carpenter helper	\$14.93/hr
Plumber	\$37.49/hr
Drywall installer	\$28.56/hr
Drywall taper	\$30.63/hr
Electrician	\$36.77/hr
Electrician helper	\$18.00/hr
Painter	\$16.55/hr
Tile setter	\$36.28/hr
Roofer	\$28.94/hr
General construction helper	\$16.54/hr
Truck driver	\$23.30/hr

[29] Source: Bureau of Labor Statistics, May 2017 State Occupational Employment and Wage Estimates, New York State, mean hourly wage: https://www.bls.gov/oes/current/oessrcst.htm