An Integrated Interior Infill System for Mass Customized Housing: Final Report

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Prepared by

UCF Housing Constructability Lab
University of Central Florida
Orlando, FL

Dr. Michael A. Mullens PE
Dr. Robert Hoekstra
Isabellina Nahmens

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Executive Summary

This report conceptualizes and assesses the viability of a new approach for the mass customization of housing. The approach seeks to enhance pre-fabricated modular building systems by incorporating the open building concepts of shell/infill layering and disentangling. Concepts are explored in the context of a mid-rise, multi-family urban housing project, the housing type expected to become dominant in the U.S. as baby boomers retire. The report includes the schematic design of the larger system, the identification/design of selected components, and the assessment of needed changes to existing processes including factory manufacturing, on-site construction and ongoing remodeling.

Research results suggest the new methodology is an efficient homebuilding approach that better meets the challenges and opportunities of the future by providing tailored living environments that can more gracefully accommodate changing activities, needs, and technologies. More specifically, results indicate that the approach is feasible, although changes in materials and construction processes are necessary. Innovative materials and components provide the structure necessary to apply open building concepts. Primary building components recommended include open-web ceiling joists and factory-built integrated interior infill (I^3) components used to construct interior walls. The I^3 components include movable framed interior walls, commercial open-office walls and cabinet walls. The latter two elements are part of highly engineered, vendor-supplied wall systems. Innovative utility solutions complement the new building components, disentangling utilities from structural systems and other utilities. Utility solutions include a high velocity forced air distribution system that uses 4” mini-ducts, centralized wiring runs in the ceiling of each module, a surface-mounted baseboard wiring system, wireless controls for ceiling fixtures, flexible PEX freshwater plumbing lines, and wireless communications (telephone/cable/data).

Although these innovative components cost more than their conventional counterparts, they are likely to reduce factory manufacturing and on-site construction effort. The primary reason for incorporating open building concepts in modular homebuilding is to simplify remodeling. Remodeling efforts will be greatly simplified with the new system:

- The continuous finished floor permits walls to be relocated without affecting flooring.
- The I^3 wall design coupled with disentangled utility strategies (e.g., surface-mounted baseboard wiring system for wall outlets and wireless communications) permit walls to be easily added, removed, or relocated. Only minor repairs for the floor, ceiling, and wall interfaces may be required.
- The combination of open-web ceiling joists and the miniducts used by the high velocity HVAC system effectively eliminate soffits in the unit.
- The combination of open-web ceiling joists, wireless ceiling fixture controls, centralized wiring paths, and spare circuits greatly reduce the effort and minimize damage when adding or relocating ceiling fixtures.

This research has several limitations. First, it focuses on specialized modular homebuilding technologies that are suitable for mid-rise applications - steel framing and concrete floor decks. This technology is not used in mainstream modular homebuilding in the U.S. A second shortcoming is the lack of quantitative data that allows costs to be better understood when considering design alternatives and tradeoffs. A final shortcoming is the focus on existing components that can address open building needs. Future research should address these shortcomings. The same open building concepts and design solutions should be explored to assess how they can apply to more conventional wood frame modular homebuilding technologies used for single family and low-rise multi-family applications. Costs should be more thoroughly examined and estimated, permitting tradeoffs between first cost and remodeling flexibility. Finally, new and more innovative designs should be considered for all components that can facilitate the integration of open building concepts into modular homebuilding. Prime examples include I^3 wall, surface-mounted wiring, HVAC, and structural components.

This research yielded several additional products. An important element of this study was an analysis of the current modular production process to assess its efficiency and identify opportunities for introducing lean production concepts into the operation. Recommendations were presented to factory management and a follow-up kaizen rapid improvement event was organized and executed. This new homebuilding approach was also the topic of a paper presented at the NSF sponsored U.S.-India Symposium on Urban Housing and Supporting Infrastructure.

1. Background and Research Objective

We are entering an era where one size no longer fits all, or even a few. We are entering an era where One Size Fits One (Heil et. al 1997). Market studies indicate that the home buyers of tomorrow – the baby boomer and GenX population - are sophisticated, financially enabled consumers (Larson 2000) who want choice and tailored solutions in homes that:

- Closely reflect their values and needs.
- Can accommodate increasingly complex activities and work patterns.
- Can easily adapt over time as family size, financial and health conditions change.
- Can accommodate rapidly evolving technologies and services in the home.

It is clear that current approaches to housing meet none of these expectations. Most new homes and apartments are low-grade, low-tech, inflexible, disruptive to upgrade, high maintenance, and ill-designed. Few are tailored to the unique and changing needs of its occupants, and architects play no significant role in the creation of most places of living. The housing industry itself is decentralized, resistant to change, wary of new technology, labor intensive, inefficient, and unresponsive. It is decades behind other industries in taking advantage of new materials, technologies and processes.

1.1 Mass Customization

Mass customization is an emerging production paradigm that seeks to design and manufacture customized products at mass production efficiency and speed (Pine 1993). A mass customization strategy encompasses the dynamics and trade offs among three factors (Figure 1.1): product design, supply chain design, and production system design (Guruswamy et al 2004). It is in the overlapping of these factors that trade-offs between product variety, mass efficiency and time to market occur. The role of these factors in the development of a mass customization strategy is discussed in the following sections.

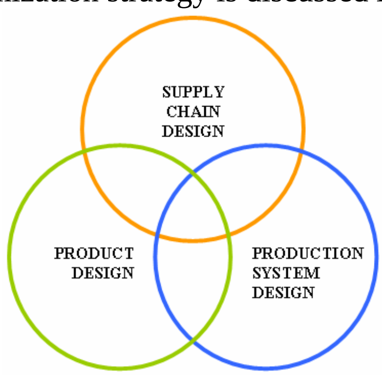


Figure 1.1. Mass customization factors

1.1.1 Product Design

Before considering a mass customization strategy, the product should be customizable (Da Siveira, Borentein and Fogliatto 2001). The adaptability of a product to customization largely depends on its architecture - the assignment of functional elements to the physical building blocks of the product (Ulrich and Eppinger 2004). Architectural considerations that can facilitate customization include:

- Product platform - a set of product elements and interfaces that are common to different final models (Gilmore and Pine 1997, Muffatto 1999).
- Modularity - the tightness of coupling between components and the degree to which the rules of system architecture enable or prohibit the mix-and-match of components (Schilling 2000).

Product customization can take place by adding options to a common platform or by mixing and matching modules to achieve different product characteristics (Mikkola and Larsen 2004). The motivation behind both approaches is to make it easier to create product variety and achieve customization.

1.1.2 Supply Chain Design

The implementation of mass customization strategy affects the entire enterprise. It is imperative that the strategy be reflected in the design of supply chain, from sourcing to final distribution (Chandra and Kamrani 2004). Supply chain configuration involves determining the location of suppliers, component warehouses, manufacturing facilities, distribution centers and establishing flows among supply chain members (Chandra and Grabis 2004). Outsourcing selected elements of the supply chain can sometimes provide greater flexibility. Outsourcing candidates include components (Mikkola and Larsen 2004) and logistics (Gooley 1998).

A critical decision is determining how production will be linked with actual demand (Fisher 1997). The decouple point is defined as the point in a supply chain where a specific customer order is associated with a specific product (Ulrich and Eppinger 2004). Ideally, operations upstream of the decouple point operate in a make-to-stock mode and fill inventories of partially completed goods, while operations downstream of the decouple point operate in a make-to-order mode and produce good associated with specific customer orders. This approach buffers the upstream operations from unpredictable fluctuations in end customer demand. Use of the decoupling point in housing supply chains has been suggested by Naim and Barlow (2002).

Postponement is a powerful strategy to improve supply chain performance in the production of customized products (Whang and Lee 1998, Feitzinger and Lee 1997). Postponement or late configuration seeks to delay product differentiation to later in the supply chain (Bowersox and Morash 1989), locating the decoupling point closer to the customer. Postponement can be used in manufacturing to delay customization to final assembly, labeling or packaging. It can also be shifted from manufacturing to distribution. For example, Honda-Europe configures body kits, alarms, and trim accessories in distribution centers, based on customer orders.

Information technology can be a powerful integrating force across the supply chain, providing a common source of information on sales, inventory levels, supplier orders, and shipping status. It can facilitate customization by providing efficient and accurate exchange of product requirements between customer and manufacturer and between manufacturer and supplier.

The homebuilding supply chain is unusually large and complex (Mullens and Hastak 2004). Product suppliers provide a wide range of stock materials (e.g., insulation, roofing) and custom components (e.g., trusses, cabinets), with delivery times ranging from hours to months. Managing the product side of the supply chain involves ensuring specified materials are on-site when needed (and not before), staged in the proper location, protected from theft and damage, and, of course, provided at the overall best value to the homebuyer. The services side of the homebuilding supply chain presents an even greater challenge. Most homebuilders who build more than 50 homes per month perform no construction work (Bashford 2004). Instead, they rely on 25-30 independent trade contractors who actually build the house. Difficulties arise in coordinating the numerous independent contractors with a series of complicating factors: multiplicity of interactions between contractors, workflow variability in a long, sequential production system, and repetition of this problem across multiple homes simultaneously under construction. Mullens and Hastak (2004) suggest that the supply chain might be simplified by 1) creating value-added partnerships or simply adding additional value at a supplier or 2) increasing cooperation or better integrating suppliers, perhaps through technology (Bernhold 2004).

1.1.3 Production Process

While researchers have explored approaches to determine optimum product customization levels (Ho and Tang 1998), customization's impact on the manufacturing process is not well understood (MacDuffie et al 1996). Product design and supply chain initiatives that support mass customization will almost certainly impact manufacturing. For example, designing and outsourcing large-scale, modular, integrated components will have a profound effect on fabrication, sub-assembly and final assembly processes.

Davis (1989) states that mass customization is facilitated by production processes that are flexible and integrated. Qiao et al (2004) find that flexible manufacturing systems can support mass customization, producing more part varieties and handling manufacturing requirement changes. A flexible manufacturing system typically consists of computer numerically controlled (CNC) machines, linked by an automated material handling and storage system, all under the control of an integrated computer control system. Flexible manufacturing systems typically have flexibility in four dimensions: volume, manufacturing processes, product mix, and delivery (Koste and Malhotra 1998). This flexibility allows companies to satisfy demands for a relatively diverse range of products with a small to medium batch size.

Originating with the Toyota Production System (Ohno 1988), the philosophy of lean production (Womack and Jones 1996) focuses on eliminating all waste in manufacturing processes. A lean manufacturing system is lean because it uses less of everything compared to traditional manufacturing systems. Lean production is based on five fundamental principles: 1) identify what the customer values, 2) identify the value stream (the steps necessary to create value for the customer) and challenge all wasted steps, 3) produce the product when the customer wants it and, once started, keep the product flowing continuously through the value stream, 4) introduce *pull* between all steps where continuous flow is impossible, and 5) manage toward perfection. Lean is very efficient in an environment of high and stable demand. However, Qiao et al (2004) argue that the efficiency of lean is diminished in an environment where product mix changes irregularly and drastically and where downstream processes require randomly customized parts on flexible schedules to be supplied from their predecessor processes on short notice. Under these conditions, they argue that extra inventory, equipment, and labor are needed to compensate for product and order variations. Chandra and Grabis (2004), however, argue that lean manufacturing can be an effective strategy for customized products with stable demand. A number of lean principles support mass customization. Minimizing set-up times and reducing lot size increases the opportunity for continuous flow. Cellular manufacturing (Bedworth, Henderson, and Wolfe 1991) with its flexible workplace and flexible workforce enable the efficient production of a family of products on the same line.

Factory configuration plays an important role in production flow, particularly when there is considerable product variation. Queueing availability and the flexibility for work to migrate upstream/downstream can mitigate some of the inefficiencies resulting from high product variation (Mullens, 2004). Information technology can enable better planning and management under conditions of high product variation.

1.1.4 Intersecting Mass Customization Strategies

Intersecting strategies for successfully achieving mass customization are well known for many consumer products. For example, a closer look at the automobile industry reveals three trends: 1) product design - the standardization of the chassis, engine components, sensing, wiring harnesses, etc. across an entire product line, 2) supply chain design - the use of "tier 1" suppliers who replace thousands of assembly line parts with integrated component assemblies, and 3) production system design - the mass customization of body parts, finishes, accessories, and other elements that customers want tailored. Both Ford and BMW, responding to market pressures, have announced plans to move their production systems toward batch quantities of one. The use of integrated modules has resulted in 30% reduction in design and labor cost and a 16% reduction in material cost – while improving quality and accommodating customization and production flexibility.

Barlow et al (2003) find that the applicability of these intersecting strategies to complex products like housing is less well understood. They describe the mass customization strategies used by five of Japan’s leading homebuilders, all industrialized. For example, Toyota Home manufactures small standard modules that are shipped to the construction site where they are assembled to create a custom home.

Several mass customized homebuilding strategies are emerging at the intersection of product design, supply chain design and production system design. Building systems - wood/steel frame trusses, wood/steel frame panels, structural insulated panels (SIPs), pre-cast concrete panels, insulated concrete forms, and “modular” homebuilding – use factory-made modular components to speed the assembly of new homes on the construction site. Suppliers are increasingly able to use flexible manufacturing innovations to gain production economies, even with greater demands for customization (Mullens and Toleti 1996). The most popular building systems use the same components and design as their site-built counterparts, but effectively consolidate or shorten the supply chain by the delivery of factory-made sub-assemblies to the construction site. Modular homebuilding is an increasingly popular approach to industrializing the homebuilding process. Modular homebuilders produce about 3% of the single family and low-rise multi-family homes built in the U.S. (Traynor 2002). In 2001 their 12% growth made them the fastest growing segment of the housing market. Modular homebuilders use three-dimensional sections or modules that are typically 95% finished when they leave the factory (Carlson 1991). After transport to the construction site, modules are lifted by crane and assembled on a permanent foundation. The resulting home meets conventional code and zoning requirements and is typically indistinguishable from nearby conventional site-built housing. Mullens (2004) examined the production challenges faced by modular manufacturers, identified applicable state of the art research in manufacturing systems and lean construction, and proposed future research directions to bridge the gap between current research and industry needs. He proposed that the greatest challenge is developing methodologies to maximize production capacity and increase quality, while expanding production flexibility to deliver the widening product mix and customization demanded by homebuyers. He suggested that the real underlying challenge is to identify and manage floating bottlenecks caused by the great variability in process times and identifies four interrelated research areas: module design, process and material handling technology, factory configuration, and shop floor control.

Open Building is an innovative, postponement-like strategy that spans product design, supply chain design and production process design. Open Building divides the total process and product of house construction into two decision levels: shell and infill (Habraken 1976, Kendall 2004). The shell is the result of design decisions specific to the site, constrained by local regulations and conventions, geo-technical and environmental conditions. Generally, the shell includes the foundations, building structure and envelope, stairs, and main mechanical/electrical/plumbing systems. The infill is the set of design decisions and products – decoupled from the shell - needed to make a shell habitable and less difficult to alter later without disturbing the shell. This approach makes it possible for a builder to offer, in a particular shell design, a variety of interior layouts, equipment and finish choices; and it allows the builder to defer these decisions (and their costs) until the point of sale without risk. At the same time, it enables individual buyers to act on their preferences and budgets, initially and over time. The benefits of Open Building extend beyond simple postponement, enabling more efficient remodeling and retrofitting during the life of the house. The infill can be subsequently updated as homeowner needs change (e.g., aging in place or family expansion/contraction) or a new homeowner brings a new set of needs.

Several supply chain innovations may facilitate Open Building strategies. Likely opportunities include product bundling and kitting to support infill construction, factory production of larger, standardized, interchangeable infill components and the use of multi-skilled infill installation teams.

1.2 Research Objective

The objective of this research is to conceptualize and assess the viability of a new approach for the mass customization of housing. The approach seeks to enhance pre-fabricated modular building systems by incorporating the open building concepts of shell/infill layering and disentangling. The result is an efficient homebuilding approach that better meets the challenges and opportunities of the future by providing tailored living environments that can more gracefully accommodate changing activities, needs, and technologies.The scope includes schematic design of the larger system, the identification/design of selected components, and the assessment of changes to existing processes including manufacturing, construction and remodeling.

Section 2 describes the research context. The schematic design of the overall system is outlined in Section 3. Sections 4 through 6 outline needed changes to the current production, construction and remodeling processes respectively. Section 7 summarizes the effort, draws conclusions, identifies research limitations, and proposes future research.

2. Research Context – Multi-family Mid-rise

As baby boomers retire, it is likely that multifamily housing will become the dominant new housing type in the U.S. This research explores the new mass customization approach in the context of the multi-family, mid-rise residential project shown in Figures 1.2, 1.3, and 1.4. The project consists of a parking garage at ground level, 9 residential levels, and a social room on the top level (Figure 1.2). Residential levels are constructed from a total of 126 modules, 14 modules per level. Each living unit is formed from two, three, or four modules stacked horizontally and/or vertically. Each module is 10' 0' high x 13' 9" wide x 42' l" long (584 square feet). Residential levels are configured as 44 living units including a total of 12 townhouses on levels one and two and a total of 24 one-story condos and 8 two-story condos on levels three through 9.

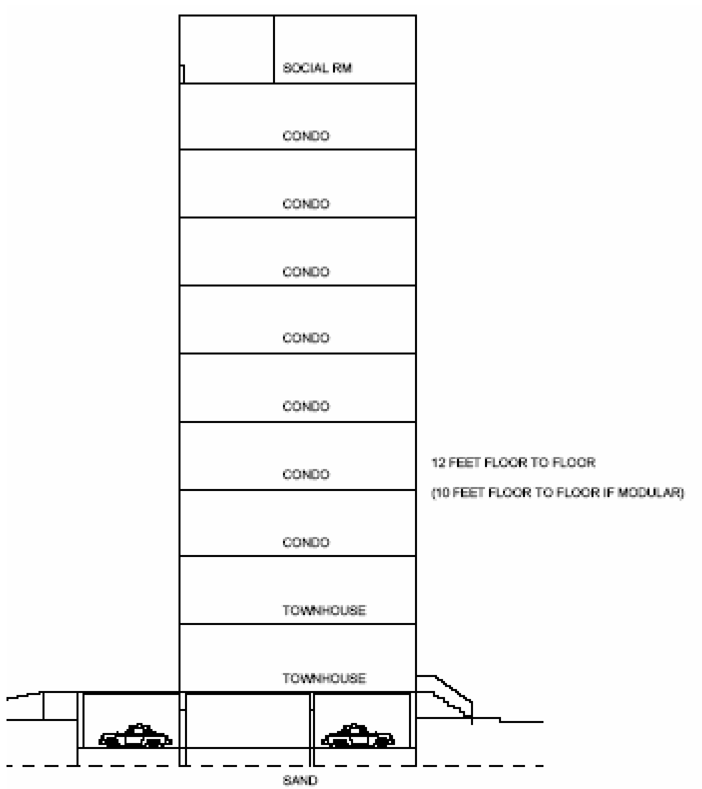


Figure 1.2 Multi-family mid-rise residential application: elevation view (Larson 2004)

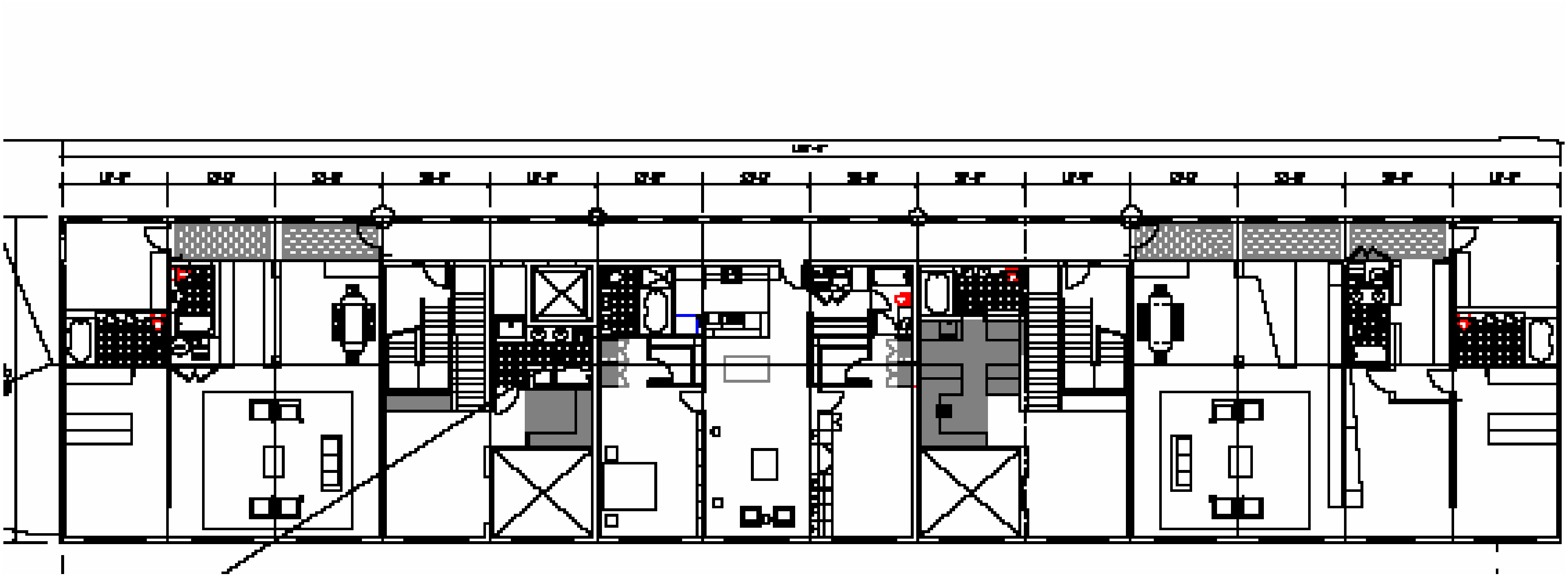


Figure 1.3 Multi-family mid-rise residential application: plan view of typical condo-level floor (Larson 2004)

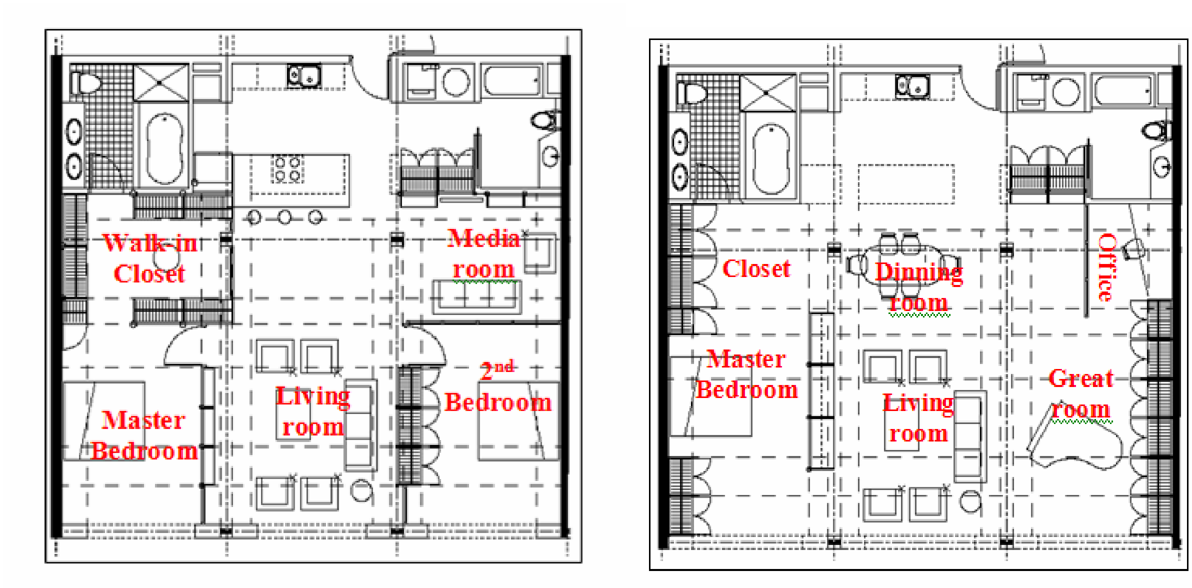


Figure 1.2 Multi-family mid-rise residential application: alternative floorplans for typical 3-module condos (Larson 2004)

3. Open Building Concepts for Modular Homebuilding

This section describes an innovative building system that integrates open building concepts into conventional modular homebuilding. The resulting system is composed of three major sub-systems: open framing, integrated interior infill and disentangled utilities.

3.1 Open Framing

The open framing system is composed of four major elements: chassis, floor, exterior walls, and ceiling. Together, these elements create an environment that is highly conducive to both structural longevity and interior adaptability, two of the fundamental goals of open building. Each element is described in the following sections.

3.1.1 Chassis

A structural chassis is used as the stackable backbone of each module (Figure 3.1). The chassis has the following features:

- Structural steel box beams (approx. 4"x12") are used as the perimeter rim joists of the floor.
- Structural steel I-beams (approx. 6") located on 6' centers span the rim joists transversely and serve as floor joists. Additional blocking provides rigidity.
- Structural steel box beams (approx. 3.5" square cross-section) are used as vertical posts at each of the four corners of the module and in the middle of each of the two long sides.
- Maximum module width is 20'. New York City allows this wide load with a special permit, escort vehicles and shipment between midnight and 6 AM. Note that this is

much wider than the 13'9" allowed in most other jurisdictions. Some jurisdictions also allow 14'-16' loads with a special permit and escort vehicles.

- Maximum module length is 44', limited by the width of the current chassis bay in factory.
- Maximum module height is 10'10", limited by overhead road clearance. (see discussion in Section 3.1.4).

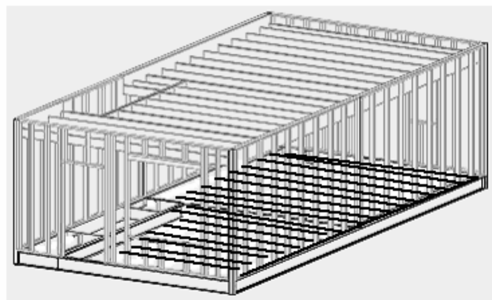


Figure 3.1. Typical chassis framing (13'9" w x 42' l x 10'10" h), shown with exterior wall and ceiling subassemblies installed.

Initial construction – The chassis is assembled in the factory on a specialized multi-station sub-assembly line adjacent and parallel to the main assembly line. Chassis assembly is the first operation in the construction process. After the chassis enters the main line, the floor is poured, all other major sub-assemblies (e.g., walls and ceilings) are added and then finished. After modules are completed in the factory, they are transported to the construction site where they are stacked using a crane and welded to form a monolithic structure.

Remodeling – It is assumed that remodeling will not affect the chassis.

3.1.2 Floor

The floor system is built on the chassis.

- A corrugated metal pan sits on the floor joists and is used to support the poured concrete floor.
- A monolithic reinforced concrete floor (approx. 3" deep) is poured on the corrugated pan. The rim joists serve as the sides of the form.
- No utilities penetrate the floor except drains, which penetrate only when necessary. Where several different bath/kitchen floor plans are available, optional drainage lines are provided to facilitate future remodeling.
- Finished flooring consists of tile in the bath and hardwood flooring elsewhere. To facilitate the flexibility sought in open building, the hardwood flooring is installed as a continuous surface throughout the unit.

Initial construction – Prep work for the concrete floor, including installation of the corrugated metal pan, other formwork, and steel reinforcement, is completed in the factory on the first station on the main line. The concrete floor is also poured at this station. Finished flooring is also installed in the factory, where practical:

- In all permanently enclosed rooms that are completely contained in one module (e.g., tile in the baths)
- Completely throughout at least one module (the seed module) to which all other finished flooring will be added after set. This is normally the module containing the kitchen, which allows cabinetry to be set and the kitchen completed in the factory.

When possible, finished flooring is installed on the main line after drywall is finished and painted and before cabinets and the surface-mounted baseboard wiring system (see Section 3.3.4) are installed.

Remodeling – It is assumed that remodeling will not affect the concrete floor slab. Where several different bath/kitchen floor plans are available, optional drainage lines will be provided to facilitate future remodeling. Most remodeling will not affect the finished flooring, since bath walls are assumed fixed and the integrated interior infill elements (conventionally framed interior walls, commercial open-office wall systems, and cabinet wall systems – described in Section 3.2) are readily movable on top of the continuous finished floor.

3.1.3 Exterior Walls and Façade

Exterior walls built with light-gauge steel framing (approx. 2"x 6") sit between the structural steel posts of the chassis. They serve as the building envelope, the demising walls and also support the ceiling. The interior surface is finished drywall. Insulation includes fiberglass batt in the wall cavity and expanded polystyrene (EPS) sheets on the exterior. Additional drywall sheets may also be installed on the exterior for fire protection. There will be limited options for façade and window type, size, and location designed to complement exterior design (Figure 3.2).

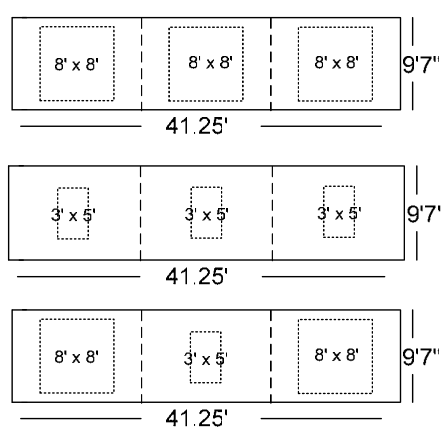


Figure 3.2. Examples of window options for 3-bay condo

Initial construction – Exterior walls are framed and drywalled on a specialized sub-assembly line that is adjacent and parallel to the main assembly line. The same sub-assembly line produces framed interior walls (see Section 3.2.1). Drywall is installed on both sides (when needed) of exterior/demising walls, except for wet sections, which may require utilities inside walls. To permit drywall installation on the second side, fiberglass batt insulation is also installed as required. Walls are installed in the factory (even when the units are not pre-sold) to weatherproof the building and provide a finished look. Exterior walls are set on the second station on the main assembly line, after the concrete floor has been poured and has cured. Ceiling set immediately follows. Additional interior and exterior sheathing materials, insulation and windows/doors are installed later on the line and drywall is finished. Marriage lines (between modules) are finished after the modules are set on the site.

Remodeling – It is assumed that remodeling does not affect exterior walls. However, an option might be to have lift-out sections of the wall that contain all possible window configurations. These sections will need to provide the interfaces that preserve the energy efficiency and consistent look of the building's visual aesthetics.

3.1.4 Ceiling

Conventional ceiling systems for steel frame modular construction use light gauge steel joists (approx. 2"x8" C-channel) covered with finished drywall. Joists extend transversely between rim joists consisting of inverted L-channel (angles). Joist hangars serve as an interface between rim joists and transverse joists. The ceiling system mounts inboard of and is supported by the perimeter walls using the horizontal flange of the rim joists. When a perimeter wall is not used in a specific design, a steel beam mounted on the module's steel posts may be used to support the ceiling. A critical disadvantage of using steel C-channels for ceiling joists arises when utilities must run lengthwise through the ceiling. There are several options:

- Run utilities through the joists, utilizing punchouts and drilling/reinforcing additional holes as required. This option is time consuming, expensive and does not facilitate future remodeling. It is also difficult, if not impossible, to run larger, more rigid components (e.g., forced air ducts and sprinkler systems) through the joists.
- Create a soffit below the ceiling to carry utilities. This option is not architecturally desirable since it lowers the ceiling in the affected area and may still limit the placement of ceiling-mounted fixtures (both in the original design and remodeling).
- Create a cavity between the ceiling and the floor chassis of the next higher level module. This also reduces the typical ceiling height (8'11") of the standard steel frame building system. New York transport regulations permit a maximum load height of 10'10" – the floor chassis rim joist is 12" high, the floor is 3" (above the rim joist) and the ceiling joist height is 8".
- Open-web ceiling joists allow utilities to be run lengthwise through the ceiling frame without extensive fabrication or loss of ceiling height.

It is assumed that open-web ceiling joists (Figure 3.3) will be used to facilitate running utilities lengthwise through each module while minimizing loss of ceiling height. Utility routing is described in Section 3.3. Finally, note that if ceiling height is not critical (e.g., it can be lowered) or building height is not critical (e.g., it can be extended), the same utility routing concepts described below can be used with C-channel joists and a cavity between the ceiling and upper floor chassis. Related notes are given in Attachment 1.

Initial construction – Ceilings (complete with unfinished drywall) are assembled in the factory on a specialized multi-station sub-assembly line adjacent and parallel to the main assembly line. After exterior walls are set on the line, the ceiling is hung from the walls. After the ceiling is set, wall and ceiling drywall is finished on the line.

Remodeling – It is assumed that remodeling will not affect framing in the ceiling.

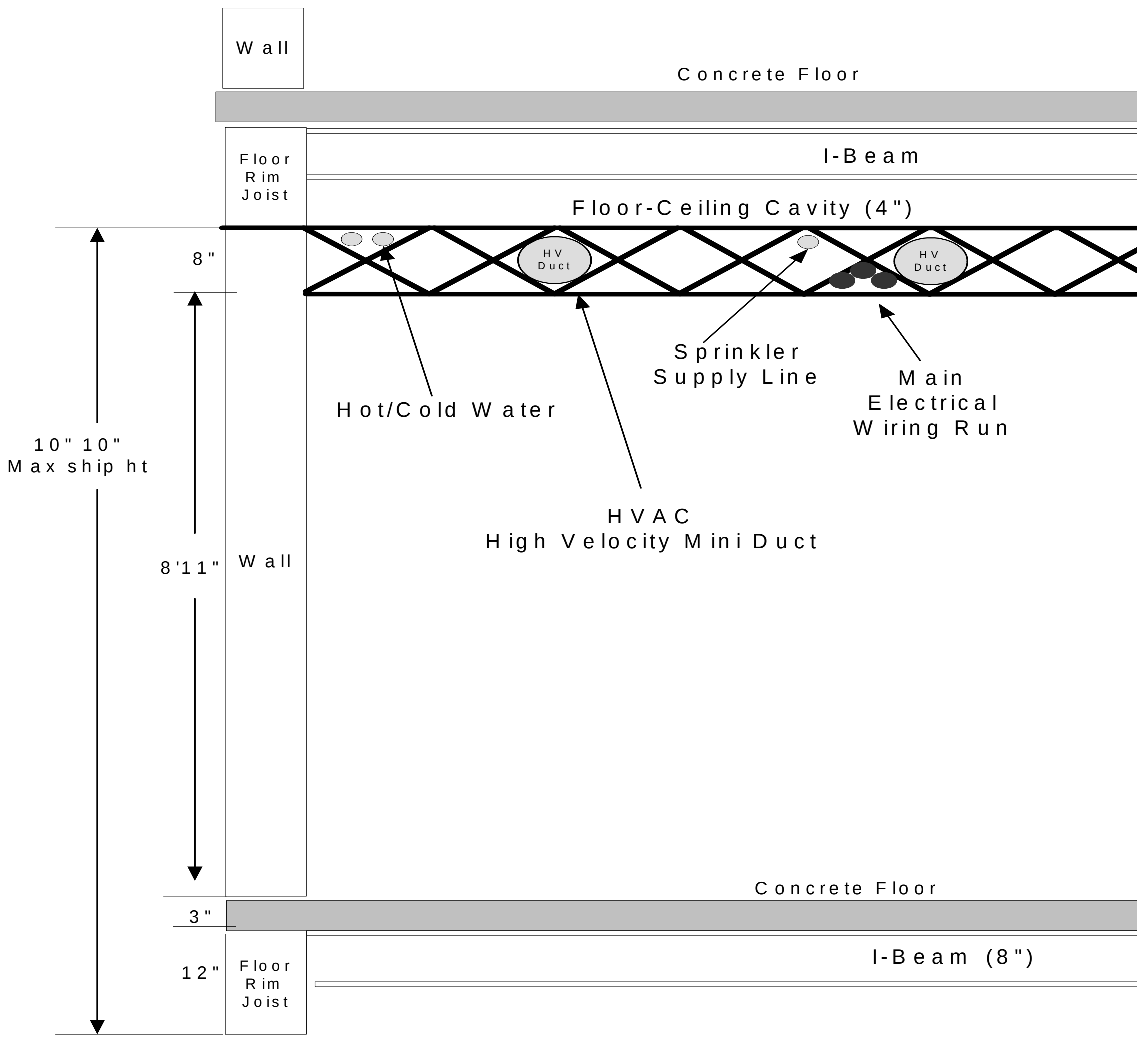


Figure 3.3. Typical module with open-web ceiling joists: elevation view (also see Attachment 1)

3.2 Integrated Interior Infill System

The integrated interior infill (I^3) system consists of partitioning components such as conventionally framed interior walls, commercial open-office wall systems, and cabinet wall systems. I^3 components are designed to be easily installed, removed and relocated. To facilitate installation and remodeling, I^3 components are installed on top of the continuous finished floor. All I^3 components are vertically adjustable, allowing them to fit snugly against the floor and ceiling. Utility strategies (Section 3.3) disentangle utilities from I^3 components. These I^3 components are described below.

3.2.1 Conventionally Framed Interior Walls

The most common I^3 component is the conventionally framed interior wall. The wall will have the following features:

- Conventional 2”x4” light gauge steel framing.
- Finished drywall on both sides.
- Supported by jack screws that allow vertical adjustment.
- Installed on top of continuous finished floor. Cushions on feet of jack screws prevent floor damage.
- Top plate of wall attached to ceiling joists using screws (this may limit transverse walls to same grid as ceiling system).
- No utilities embedded in walls. (see Section 3.3)

Initial construction – Conventionally framed interior walls are framed and drywalled on both sides on a specialized sub-assembly line that is adjacent and parallel to the main assembly line. The same sub-assembly line produces exterior walls. Adjustable jack screws are installed on the bottom plate of each wall while it is on the framing table. Walls are installed in the factory. Walls are loaded into the module at the second station of the main assembly line, after the concrete floor has been poured and has cured, and before the exterior walls have been set. After setting the ceiling, the interior walls are set upright. Since a wall will eventually rest on the finished floor (which has not been installed yet), it is temporarily supported by large wedges that keep it positioned firmly in place against the ceiling until the finished flooring is completed (later in the factory or on site). The top plate of the wall is attached to the ceiling joists from overhead, by driving screws down from the ceiling. Drywall is finished immediately after walls are set. Finished flooring is installed in the factory, where practical:

- In all permanently enclosed rooms that are completely contained in one module.
- In at least one module (the seed module) to which all other finished flooring will be added after set. This will normally be the module containing the kitchen, which will allow cabinetry to be set and the kitchen completed in the factory.

When finished flooring can be installed in the factory, it will be installed on the main line after drywall is finished and painted, and before cabinets and the surface-mounted baseboard wiring system (Section 3.3.4) are installed. Flooring is installed under the interior walls by iteratively repeating the following process: 1) flooring is installed under part of the infill wall, 2) adjustable jack screws in that area are extended to remove weight from the supporting wedges, and 3) wedges in that area are removed. Finished flooring that cannot be installed in the factory is installed after module set on the construction site – after all remaining drywall work is completed (the marriage line between modules) and before the remaining I^3 components (shipped inside the module as shiploose) are set in place. An alternative to factory installation of interior walls is discussed in Attachment 3.

Remodeling – Conventionally framed interior walls are easily removed by uninstalling the baseboard wiring system (Section 3.3.4), removing drywall from the top of one side of the wall and removing the screws that attach the wall to the ceiling (note that if crown molding is used, wall-ceiling mounting brackets may be hidden under the molding). The adjustable jack screws are then backed off, allowing the panel to be lowered. The wall can be reinstalled elsewhere, if required, using the original installation procedure and only minor drywall repairs.

New framed interior walls are framed and drywalled on site, due to limitations in moving larger pre-assembled panels through the elevator and doors. After framing, installation of the new wall parallels original installation on the construction site (described in Attachment 3).

3.2.2 Commercial Open-Office Wall Systems

Commercial open-office wall systems can also serve as I^3 components. One example is the DoubleWall and I-Line product lines offered by Steelcase (www.steelcase.com). The Steelcase DoubleWall system is a set of engineered components that are used to configure reusable, adaptable walls (Figure 3.4). Walls are configured from internal steel posts and steel wall plates. Posts have telescopic extensions to accommodate field adaptability from location to location. Pre-finished, laminated steel wall plates are available in a variety of factory finishes including paint, vinyl or marker board. The plates can also be painted in the field. Joints between plates are nearly invisible, making the walls appear conventional. The DoubleWall system uses a unique post and panel connection for quick and easy installation, eliminating the need for additional clips and fasteners. Floor and ceiling tracks are used to attach walls to the structure. Attachments do minimal damage to the ceiling grid, carpet or floor. Base trim completes the system. Although wiring is typically run in the wall cavity, the surface-mounted baseboard wiring system (described below) is used in this application. The DoubleWall system can be supplemented with Steelcase I-Line panels that offer greater variety of finishes including fabric, wood, and glass.

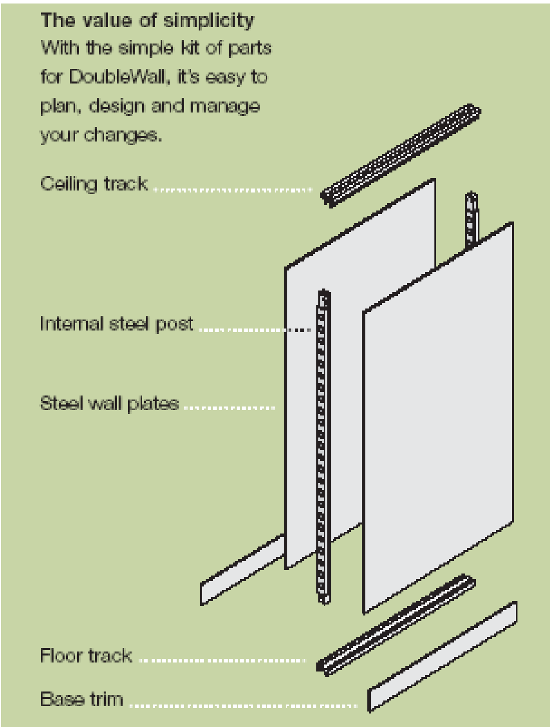


Figure 3.4. Typical commercial open-office type wall system: components (left) and finished application (right) (Steelcase)

Initial construction – Commercial open-office wall components are speced for each unit and ordered from the supplier. Components are shipped to the factory. Walls are installed in the factory wherever the finished floor can be installed. When finished flooring can be installed in the factory, it will be installed on the main line after drywall is finished and painted, and before cabinets and the surface-mounted baseboard wiring system (Section 3.3.4) are installed. Wall components are then loaded into the module and installed.

Walls that cannot be installed in the factory (because the finished flooring in that area cannot be installed), are installed on site after the modules are set and the finished floor is installed. The baseboard wiring system is then installed. Wall components are treated as shiploose, and loaded into the module at the last station in the factory, after all other work is completed.

Remodeling – Commercial open-office walls are easily removed by uninstalling the baseboard wiring system (Section 3.3.4), removing the wall components (posts and plates) and then removing the floor and ceiling tracks. Wall components can be reinstalled elsewhere, if required, using the original installation procedure. Components for new walls can be ordered from the supplier and used to build the new walls. It should take less time and less mess to install new commercial open-office walls than the conventionally framed interior walls that require drywall finishing.

3.2.3 Cabinet Wall Systems

Cabinet wall systems can also serve as reusable, adaptable I^3 components. One example is the furniture cabinets offered within the Merrilat Masterpiece product line (Figure 3.5). Furniture cabinets are assembled from engineered wood components, available in a limited number of heights and depths (e.g., 12”, 18”, 21” or 24” depth) to provide dimensional coordination. Different components can be specified to produce a variety of cabinet configurations, including flat panels, open shelving, closed shelving with doors and drawers. Further customization is possible by specifying solid wood or veneer, wood species and finish (stains, paints and glazes).

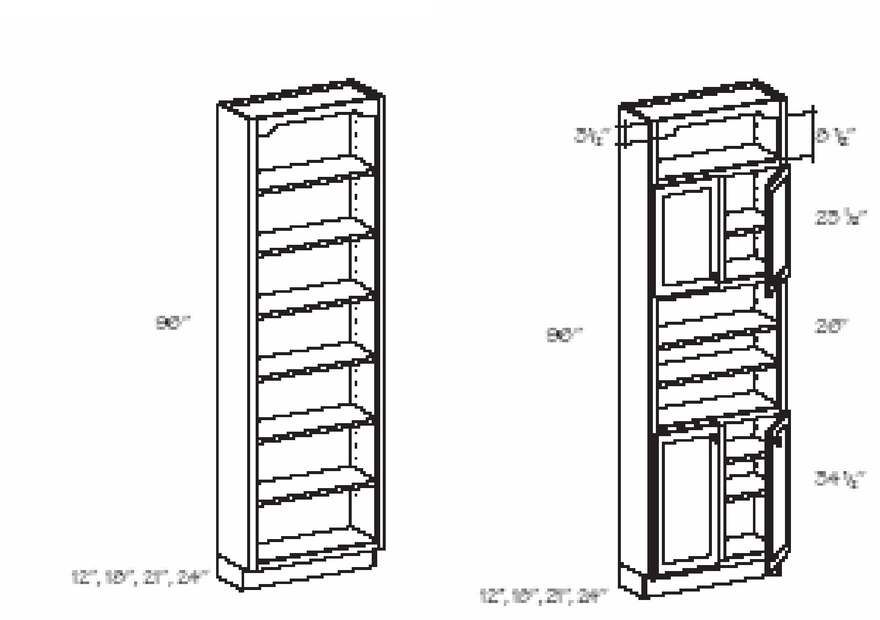


Figure 3.5. Merillat cabinet wall components: bookshelf (left) and furniture base and wall 96" (right) (www.merrilat.com)

Initial construction – Cabinet wall components are speced for each unit and ordered from the supplier. Merillat has implemented an award winning lean production system in several of its plants and is able to offer a one-week delivery time (Welch 2001). Components are shipped to the factory. Cabinet walls are installed in the factory wherever the finished floor can be installed. When finished flooring can be installed in the factory, it will be installed on the main line after drywall is finished and painted, and before cabinets and the surface-mounted baseboard wiring system (Section 3.3.4) are installed. Cabinet wall components are then loaded into the module and installed.

Cabinet walls that cannot be installed in the factory (because the finished flooring in that area cannot be installed), are installed on site after the modules are set and the finished floor is installed. The baseboard wiring system is then installed. Cabinet wall components are treated as shiploose, and loaded into the module at the last station in the factory, after all other work is completed.

Remodeling – Cabinet walls are easily removed by uninstalling the baseboard wiring system (Section 3.3.4) and removing any attachments to the adjoining walls and ceiling. Wall components can be reinstalled elsewhere, if required, using the original installation procedure. Components for new walls can be ordered from the supplier and used to build the new walls.

3.3 Disentangled Utilities

Each unit is provided with electricity, water, natural gas and telephone/data/cable service. Interior climate is maintained by a forced air HVAC system utilizing natural gas fired hydronic heating and electrical powered cooling. This section describes a strategy for disentangling these services, both from each other and from the I^3 components.

3.3.1 Utility Infrastructure

Several elements form the core of the utility infrastructure for a module (Figure 3.6): 1) the main vertical utility chase that houses the main risers for all utility supply lines and drain lines/vent stacks, 2) smaller vertical utility chases that house remaining drain lines/vent stacks, 3) a utility closet where each living unit is connected to the main supply lines, and 4) the corridor utility soffit that serves as the spine connecting the utility closet to all modules comprising the living unit.

The main vertical utility chase houses the main risers for all utility supply lines for a stack of living units. It also houses as many drain lines/vent stacks as possible, given the floor plan. Smaller vertical utility chases will house remaining drain lines/vent stacks. The vertical chases run through all living units in the stack, from ground level to roof. Ideally, all vertical chases will be located adjacent to the corridor, allowing access from the corridor for connection and maintenance without entering the living unit.

A utility closet (one in each living unit) will be located adjacent to the main vertical utility chase. The closet lies alongside and is accessible from the main corridor. The utility closet will house: 1) the main connection for fresh water, 2) the hot water heater, 3) a fresh water distribution manifold, 4) the main connection for natural gas, 4) a natural gas distribution manifold, 5) the main connection for electricity, 6) the electrical panel, 7) the HVAC air handler, 8) the main connections for telephone/data/cable and 8) wireless hubs for telephone/data/cable.

A soffit located along the living side of the main corridor (or a lowered ceiling across the entire corridor) will distribute utilities from the utility closet to each of the modules comprising the living unit. Most utilities (electrical wiring, flexible pex water lines, rigid gas lines and rigid main sprinkler lines) will likely fit within a ceiling cavity above or immediately adjacent to the soffit and will not need to run through the soffit. This will require slots to be cut in the non-structural ceiling rim joists, allowing utilities to run between modules. Utility hangars will be used to further organize these lines. The larger HVAC plenum will not fit in a ceiling cavity and will run through the soffit.

The utility closet and the corridor utility soffit will be considered part of the living unit and must have fire rated walls/ceilings/doors/access panels separating them from the corridor and vertical utility chases.

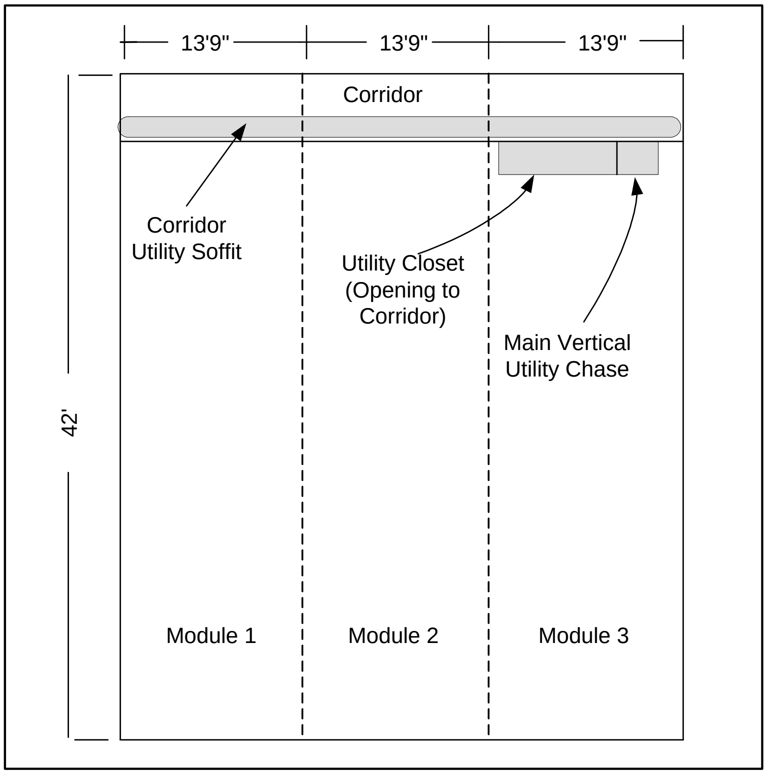


Figure 3.6. Utility Infrastructure

Initial Construction – The vertical utility chases, utility closet and corridor utility soffit will be constructed and outfitted with equipment in the factory. Panels for each of these elements will be assembled in the wall framing area and installed on the main line. All panels except the soffit will be installed as part of wall set. Soffit panels will be installed over the HVAC plenum after it is installed immediately following ceiling set.

After the necessary modules have been set, intermodule utility connections will be made for the HVAC, gas and sprinkler systems. Since these connections will be made from the top, they must be made immediately to prevent delays in setting the next level. Note that this urgency can be mitigated by cutting away the drywall on the soffit near the marriage lines and making the connections from below (note that drywall finishing will be required at the marriage line of the soffit regardless. Since electrical circuits and fresh water pex lines are home run, they must be pulled from each module to the utility closet near their respective panel/manifold. Since these pulls will be made from the top, they must be made immediately to prevent delays in setting the next level. After the necessary modules have been set, main utility supply and drainage risers will be installed in the vertical utility chases, from the ground to the top level of the complex. After the risers have been installed, final supply and drainage connections for each living unit will be made. If all vertical chases are located adjacent to the corridor, access for connection and maintenance can be from the corridor without entering the living unit. Note that lowering the ceiling in the corridor may require constructing the ceiling as two components. If the corridor ceiling cannot be supported by the walls using a longer hanger, this may require additional posts to support the corridor ceiling. Another option might be to use a drop ceiling in the corridor.

Remodeling – It is assumed that the utility infrastructure is permanent, with the exception of equipment in the utility closet (e.g., hot water heater, air handler, electrical panel, and wireless hubs).

3.3.2 HVAC System

To facilitate utility disentangling and conserve valuable ceiling height, a high velocity forced air distribution system will be used. The system will be controlled via wireless thermostat. The high velocity air handler will be located either in the utility closet or at one end of the corridor utility soffit. A sealed combustion high efficiency gas water heater (also in the utility closet) sends super-heated hot water to a fan coil located at the air handler. Combustion air and exhaust gases are vented through the main vertical utility chase. An air conditioning condenser mounted on the roof supplies refrigerant to a cooling fan coil at the air handler. The refrigerant supply and return lines reach the utility closet through the main vertical utility chase.

As shown in Figure 3.7, the supply plenum will extend from the air handler, up and into the utility soffit, and through the soffit for the full width of the living unit. Four inch mini-duct supply lines (2” supply plus 2” insulation – Figure 3.8) will branch from the top of the supply plenum and run up and through the open-web ceiling joists to supply registers located in the ceiling. Mini-duct supply lines must be a minimum of 10’ and a maximum of 25’ long to function properly. To prevent mini-ducts from entangling with other systems, they will be mounted/strapped near the top chord of the ceiling joist (Figure 3.3). The return will be located inside the living unit in an open hallway adjacent to the air handler in the utility closet. Interior doors in the living unit (e.g., bedroom doors) will be cut-away from the bottom to allow adequate return air flow for pressure equalization.

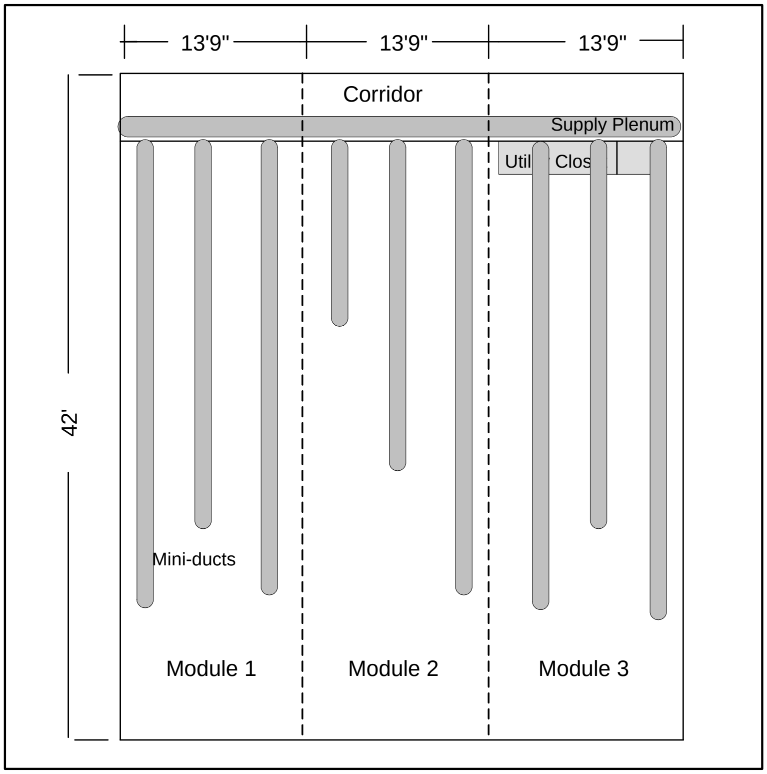


Figure 3.7. High velocity HVAC duct system

Figure 3.8 High velocity duct (left) and finished installation (right) (Spacepak)

If a conventional lower velocity air handler is used, larger ducts are required throughout the system. To accommodate the larger ducts in the ceiling system, an open-web ceiling joist will be used with a centrally located rectangular cavity for running conventional rectangular ducts. This cavity will displace the centrally located electrical conduit, which will need to be moved up and outboard to either side of the duct.

Initial Construction – Supply plenums, branches, miniduct runs, and registers are installed in the factory. Local miniduct runs are installed and holes are cut for registers while the ceiling is on the ceiling cart. Immediately after ceiling set, plenums and branches are installed in what will become the corridor utility soffit. Local miniduct runs are then connected to each branch. Registers are installed after drywall finishing and painting are completed. On site, intermodule plenum connections are made from the top after all modules on the same level for the unit are set.

Remodeling – Initial design of the duct system comprehends relatively fixed spaces (baths, kitchens) as well as flexible spaces (bedrooms, living areas). The duct system design accommodates possible rearrangements within the flexible spaces including the movement and addition of interior walls. By providing a maximum number of registers and locating them to yield generous airflow over a completely open space, there is a high probability that airflow will be adequate for most desired changes. If necessary, existing registers can easily be moved and duct length can be shortened or lengthened (by splicing). In the worst case, new duct lines can be added by splicing into the supply plenum in the corridor and then fishing the new duct through the open web ceiling joists to the new register location. Note that several holes may need to be cut in the ceiling drywall to fish the new duct.

3.3.3 Ceiling Electrical System

Ceiling-mounted fixtures are controlled by wireless RF signals. As shown in Figure 3.9, electrical power wiring for ceiling mounted fixtures run up from the electrical panel located in the utility closet, through the corridor utility soffit, through the open-webs of the ceiling joists, to electrical boxes for ceiling fixtures. All wiring is enclosed in flex conduit. All wiring serving a module runs together from the panel, through the soffit, and in a main wiring run through the center of the module (through the lowest openings in the open web ceiling joists as shown in Figure 3.3). Wiring primarily powers ceiling fixtures throughout the module. When a circuit reaches the ceiling cavity where its next electrical box is located, it exits the wiring run by making a 90 degree turn and running through the cavity to the box. The wiring run also contains wiring dedicated to fixtures in the wet area as well as the baseboard wiring system (Section 3.3.4). A single feeder line may provide power for several distributed fixtures. Additional wiring and pull cords run the length of each main wiring run, allowing more flexible remodeling.

The same strategy can be used to provide power to power poles in open spaces and to stand-alone walls not connected to powered perimeter walls.

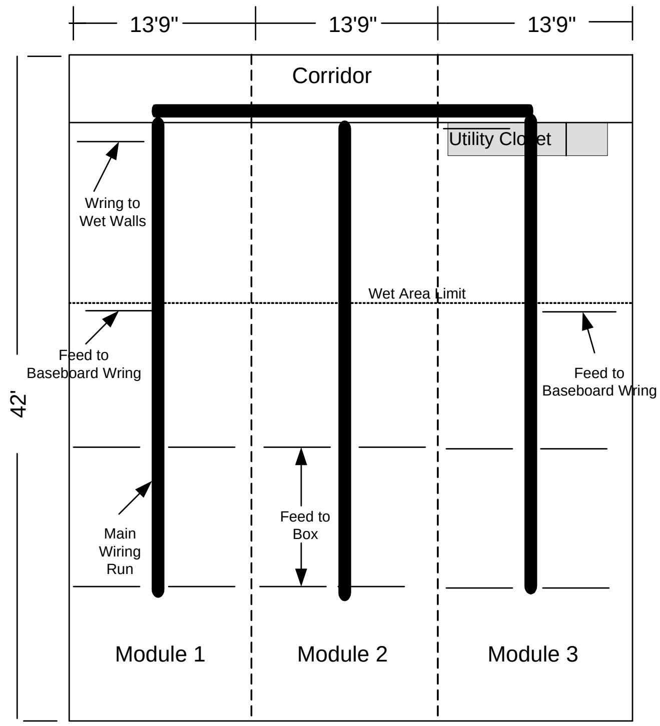


Figure 3.9. Electrical system in ceiling

Initial Construction – Ceiling electrical is wired in the factory, including the installation of soffits, boxes and fixtures. Boxes are installed in ceiling panels on the ceiling framing jig. Holes for boxes are cut in ceiling panels on the ceiling cart. Wiring is pulled through the ceiling panel on the ceiling cart. As part of this process, excess wiring for each module required to reach the main electrical panel is coiled for shipment. Ceiling fixtures are installed after drywall finishing and painting is completed on the main line. After all modules on the same level for the unit are set, the coiled flex conduit is extended through the corridor utility soffit and connected to the electrical panel. These final on-site wiring runs are accomplished from overhead and from the corridor.

Remodeling – Additional ceiling fixtures may be added at any time by locating a circuit in the area with additional capacity, locating the closest box and tapping into the circuit at the box. If no circuit is available, one of the unused circuits in the main wiring run can be used. Accessing the circuit will require cutting a hole in the ceiling drywall near the wiring run and in the same cavity as the new fixture. The wiring can then be fished through the cavity to the new box. For additional flexibility, pull cords are placed in the main wiring run to facilitate running new wire.

3.3.4 Surface-Mounted Baseboard Wiring System

The national building code for residential construction requires the installation of electrical outlets every 6 feet of wall on any wall more than 2 feet long. For high rise residential construction, it also requires that all high voltage electrical wiring be run in conduit.

With the exception of wet areas (e.g., kitchens, baths, utility room), wiring for electrical wall outlets is run in a surface-mounted baseboard wiring system (Figures 3.10 and 3.11). The system consists of a raceway that houses individual wires, a snap-on cover, quarter-round trim and integrated surface-mounted outlets.

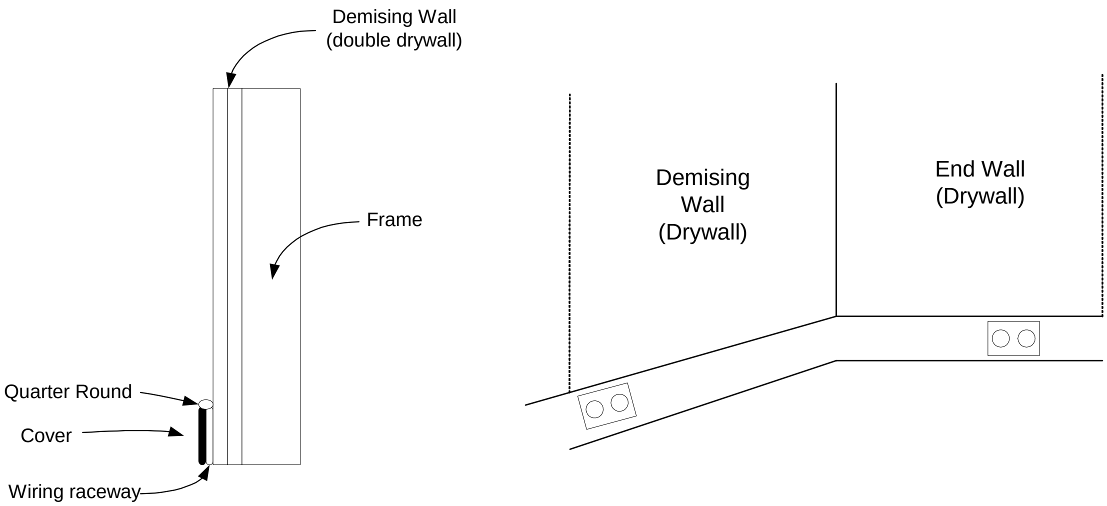


Figure 3.10. Surface-mounted wiring system – side and front views

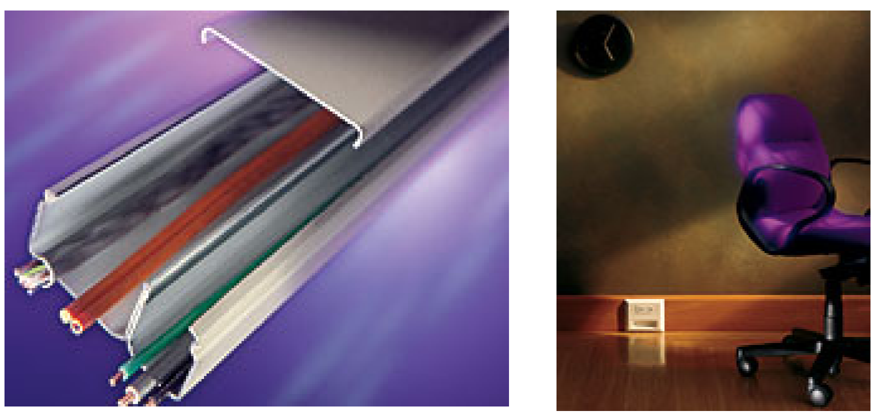


Figure 3.11. Surface-mounted wiring system components (left) and finished installation (right) (Wiremold)

Wiring reaches the surface-mounted system through the demising walls of the end modules using the same path as wiring to ceiling mounted fixtures. This wiring runs up from the electrical panel located in the utility closet, through the utility chase located in the corridor, through the open-webs of the ceiling joists (Figure 3.3), turn (Figure 3.9) and run across to their respective demising walls and then down through the walls to the origination of the surface-mounted system. Once entering the surface-mounted system, the flex conduit is no longer needed.

3.3.4.1 Demising and End Walls

Wiring for all wall outlets (except those in wet walls and stand-alone walls) run through the surface-mounted system originating in the two demising walls.

Initial construction – The entire surface-mounted system is factory installed on the demising and end walls of the unit's end modules. Wiring to accommodate the surface-mounted system is pulled while the ceiling panel is on the ceiling cart. This wiring is run alongside the other ceiling wiring (Figure 3.9) and then turns near the end of the wet area and runs through a ceiling cavity to the side of the ceiling. Excess wiring required to extend down the demising wall to the beginning of the surface-mounted system is coiled. After the ceiling is set on the production line, this wire is run down through the wall to the entrance of the surface-mounted system and enters a junction box. The surface-mounted raceway, wiring and outlets are installed and the system cover and quarter-round trim added after: 1) drywall finishing and painting and 2) installation of the finished floor and I^3 components (where possible). Note that spacing for the flooring is maintained under the surface-mounted system when the system is installed before the finished floor. To reach the end walls of inboard modules, extra wiring is coiled at the end of the end walls on the end modules. After set, an electrician performs the intermodule connections.

An option to install all of the surface-mounted system on-site after set is described in Attachment 2.

Remodeling - Outlets may easily be added, removed or relocated on the surface-mounted wiring system. Additional capacity is provided on each original circuit to allow a limited number of outlets to be added. Additional circuits are provided to accommodate further needs. If even more capacity is required, a new circuit can be pulled from the main wiring run in the ceiling to the surface-mounted system.

3.3.4.2 Integrated Interior Infill Walls

All I^3 walls (conventionally framed interior walls, commercial open-office wall systems, and cabinet wall systems) use the same surface-mounted wiring system (Figure 3.12).

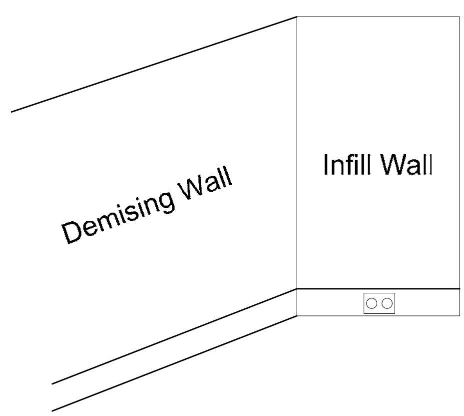


Figure 3.12. Front View

Initial construction – The surface mounted wiring system is factory installed on all I^3 walls that are installed in the factory on a finished floor. Installation of the wiring system occurs at the same time that the system is installed on the demising and end walls, after the finished floor is installed and the I^3 walls are set.

The wiring system for other I^3 walls is installed on site after the modules are set, the remaining drywall finish work is completed, the finished floor is installed, and all remaining I^3 walls are set. Surface-mounted wiring components are shipped to the construction site as ship-loose material in the modules. Wiring for intersecting I^3 walls are pre-installed in the surface-mounted system on the end modules and coiled at the intended intersection. Note that the surface-mounted system on the demising wall prevents an I^3 wall from directly abutting the demising wall. Overhanging drywall or a trim piece is used to cover this narrow gap.

For cabinet wall systems, the surface-mounted wiring system is mounted on the toe kick panel. Since the surface-mounted system is 5 ¼ inches and the toe kick is 4 ½ inches, a narrower wiring system must be identified or the toe kick raised (e.g., extending a jack screw on the cabinet base). A second possible option is to mount the outlet boxes in the toe kick panel and run wire in conduit through the space in the cabinet bottom frame. Using this option, holes would be drilled in the sides of the cabinet base to run wire.

Remodeling - I^3 walls may be added, removed or relocated without affecting wiring in other walls. To remove walls, the affected circuit is terminated or cut/spliced in the wiring chase on the feeder wall. To add walls, one of the unused circuits is tapped. If even more capacity is required, a new circuit is pulled from the main wiring run in the ceiling to the surface-mounted system.

3.3.4.3 Stand-alone I^3 Walls

Electrical outlets on a stand-alone I^3 wall are also mounted in a surface-mounted wiring system. Since a stand-alone wall is physically isolated from the contiguous surface-mounted wiring system by either open space or doorways, they are powered through the ceiling wiring system. The wiring extends along the main wiring run, then turns and runs through a cavity to the stand-alone wall, and then down through the wall to the surface-mounted system.

Initial construction –Wiring for stand-alone I^3 walls is pre-installed in the ceiling, running to the point of intersection with the wall, where it penetrates the ceiling and is coiled. After the wall is set (either in the factory or on site), the wiring is run down through the wall to the entrance of the surface-mounted system and enters a junction box. The surface mounted system is then installed as described in the previous sections depending on the wall type.

Remodeling – Stand-alone I^3 walls are added, removed or relocated without affecting other wiring. To remove walls, the affected circuit is terminated or cut/spliced in the ceiling. To add walls, a new circuit is pulled from the main wiring run in the ceiling to the surface-mounted system.

3.3.4.4 Wet Walls

Most wet areas are considered to be part of the permanent shell and will not be the focus of flexible infill strategies. A key driver of this assumption is the relative inflexibility of waste water drainage systems. Furthermore, wall outlets mounted in wet areas (e.g., kitchens, baths, utility) are typically mounted at counter level. Therefore, the advantages of the surface-mounted wiring system are limited. Wiring for wall outlets in wet walls extends through the main wiring run in each module and down through the walls to counter-level circuits connecting the outlets.

Initial construction - All counter-level outlets and supporting wiring is installed in the factory. Boxes are installed in wall panels on the wall framing jig. Holes for boxes are cut in wall panels after drywall has been installed on the wall drywall jig. Wiring to accommodate a counter-level circuit is pulled while the ceiling panel is on the ceiling cart. This wiring extends through the main wiring run, turns (Figure 3.9) and runs to the end or side of the ceiling panel. Excess wiring required to extend down the end or side wall and to the circuit is coiled. This wire is run and the remaining circuit wiring completed after the ceiling is set on the main production line. Outlets are installed after drywall finishing and painting is completed on the main line.

Remodeling – Although wet areas are considered to be part of the permanent shell, adding, removing or relocating electrical outlets is not difficult thanks to easy access to the counter-level circuit. If more capacity is needed, new wiring can be pulled from the main wiring run in the ceiling to form a new counter-level circuit.

3.3.5 Plumbing

3.3.5.1 Fresh Water and Natural Gas

Fresh water and natural gas flows through flexible lines (PEX for water and copper for gas) home run from manifolds in the utility closet, up to and through the corridor utility soffit, through the open-webs of the ceiling joists (Figure 3.3), and down through walls to fixtures and equipment installed in the unit. A sealed combustion high efficiency water heater located in the utility closet provides fresh hot water as well as super-heated water to a fan coil at the air handler.

Initial Construction – All plumbing runs are installed and connected to fixtures/appliances in the factory. Flexible lines are installed in the ceiling on the ceiling cart. Excess tubing required to reach the manifolds are coiled for shipment. After all modules on the same level of the living unit are set, the coiled tubing is extended through the corridor utility soffit and connected to the manifold. These final connections are from overhead and from the corridor.

Remodeling – Drainage considerations limit future rearrangement of plumbing fixtures. All feasible rearrangement can be handled through existing plumbing in the walls. Gas lines to ranges may be moved by running inside cabinetry.

3.3.5.2 Drainage Lines and Vent Stacks

Drainage lines from each sink, toilet, bathtub and shower runs to the closest vertical utility chase, where it is connected to a drainage riser. Vent stacks must be located within 5’ of each drain, and, if possible, the stacks are placed in the vertical chases. Only when necessary are drainage lines run through the concrete floor. Where several different bath/kitchen floor plans are available, optional drainage lines are provided to facilitate future remodeling.

Initial Construction – All drain lines (and if necessary vent stacks) are installed and connected to fixtures/appliances in the factory. Drain lines that must be located in the floor are installed in the plumbing station after the floor is framed and before concrete is poured to form the floor. Vent stacks that must be located in walls are installed on the main line after walls are set and before drywall installation. After the necessary modules have been set, drainage risers and vent stacks are installed in the vertical utility chases, from the ground to the top level of the complex. After the risers have been installed, final drainage and vent stack connections for each living unit are made. If all vertical chases are located adjacent to the corridor, access for connection and maintenance can be from the corridor without entering the living unit.

Remodeling – Drainage considerations limit future rearrangement of plumbing fixtures. However, original equipment can be easily upgraded with newer equipment with comparable drainage layouts. If extra drainage lines are provided to accommodate different bath/kitchen floor plans, then remodeling can be facilitated.

3.3.6 Sprinkler System

A sprinkler system is required for living units with a ceiling height over 9'. The sprinkler system is run from the utility closet (where it is connected to the main supply riser) up to a main supply line in the corridor utility soffit. Branch lines extend from the main supply line and run the length of each module. Each branch line is located near the center of the module (offset slightly from the electrical conduit) and is mounted near the top of the open-web ceiling joists (Figure 3.3). Short local runs extend down to ceiling height where the sprinkler heads are mounted. Rigid pipe (e.g., steel) is used. If necessary, a short local run may extend widthwise across the module (over the mini-ducts, if required) to accommodate wall layout.

Initial Construction – The sprinkler system is installed in the factory. The main supply line and branch line for each module is installed in the ceiling on the ceiling cart. Holes for the sprinkler heads are also cut on the cart. Sprinkler heads are installed on the main line as part of finish plumbing, after painting. After all modules on the same level of the living unit are set, the main supply lines are connected. These final connections are from overhead and from the corridor.

Remodeling – Most wall relocation requires no change in the sprinkler system. If a sprinkler head must be added, it may be connected to a branch line and extend down to the ceiling. This may be done with only minor drywall rework.

3.3.7 Telephone, Data and Cable

Telephone, data and cable signals are distributed wirelessly through wireless hubs located in the utility closet. As an option to wireless communication, telephone, data, and cable wiring may be run parallel to electrical wiring serving the surface-mount baseboard wiring system.

Initial Construction – Wireless hubs are installed in the utility closet at the factory.

Remodeling – Rearrangement does not impact wireless communications.

4. Modular Production Process

This section describes the conventional factory-based modular manufacturing process and the changes anticipated to incorporate the proposed open building system concepts. The description is based on findings from an intensive three-day study of production activities in a modular manufacturing plant (Manufactured Housing Research Alliance, 2005). The plant layout is shown in Figure 4.1, and a high level process map is shown in Figure 4.2. The map includes each high level activity, the physical location(s) within the plant where the activity was observed and a time line indicating the production cycle during which the activity occurred. During the study, the plant operated at a rate of four modules per week, with an equivalent cycle or TAKT time of 10 hours per line move. This production rate is 40% of the maximum production rate of the factory.

The detailed description that follows in Attachment 5 includes the following information for each manufacturing activity:

- Activities – the detailed production steps observed.
- Labor – estimated personnel and labor hours per module based on observations. Many estimates are not available or incomplete and may understate actual times.
- Cycle time – estimated clock time (start to finish) per module based on observations. Many estimates are incomplete and may understate actual times.
- Materials – raw materials and purchased components.
- Tools and equipment – hand tools and larger equipment.

Two additional analyses were developed for the manufacturing process. First, a lean production analysis was performed to assess process performance and identify opportunities for introducing lean production concepts into the operation. Recommendations were presented to factory management (Attachment 6) and a kaizen rapid improvement event is planned to kick-off a lean production campaign.

It should be noted that the activity descriptions have been modified for this discussion to reflect a mid-rise residential application, instead of low-rise housing typically produced at the plant. Design features affected include:

- The use of a poured concrete floor deck (for fire protection) instead of a wood floor deck.
- The use of soffits as required to house forced air HVAC duct runs and sprinkler lines. Low rise modular construction in the area typically uses no forced air distribution system (relying instead on package units when cooling is required) or duct installation in the basement. Sprinklers are not required in low-rise housing.
- The addition of utility chases needed to house utility risers serving all floors of the building.

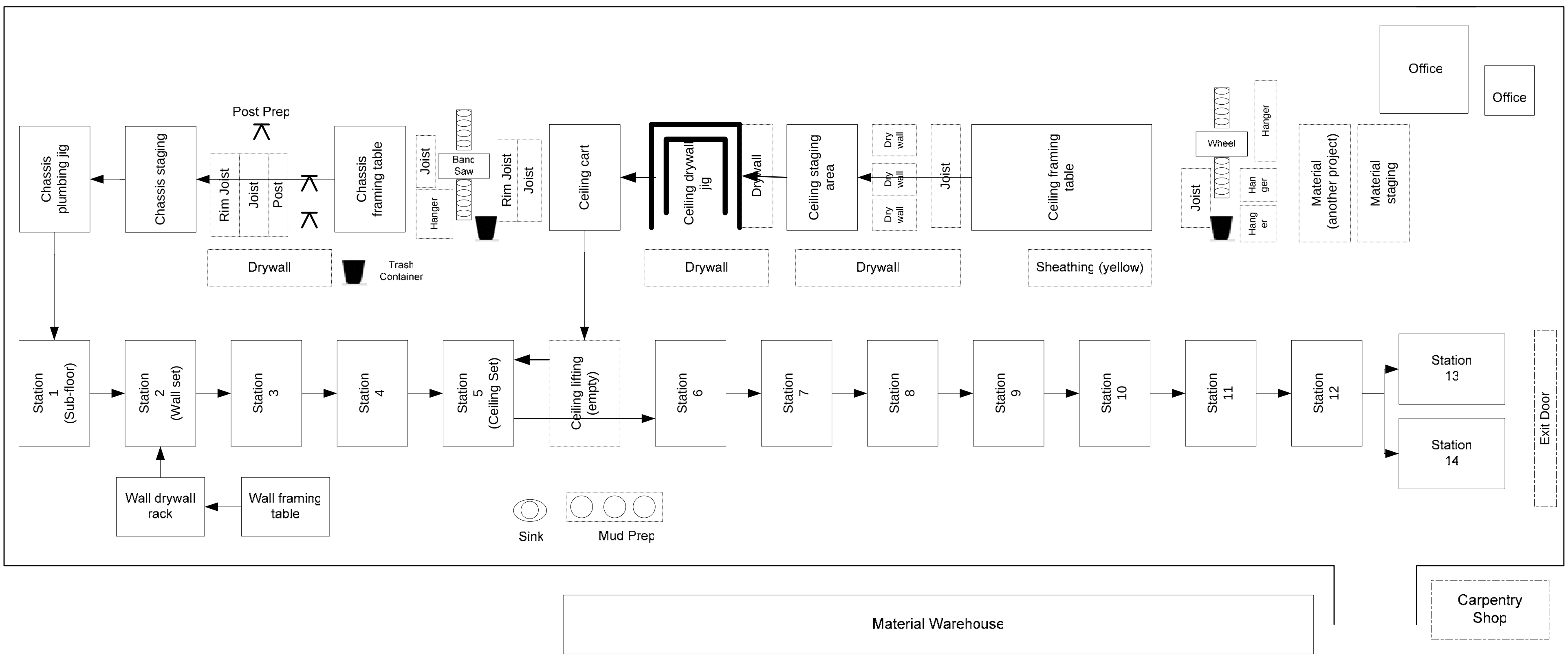


Figure 4.1. Layout of Factory

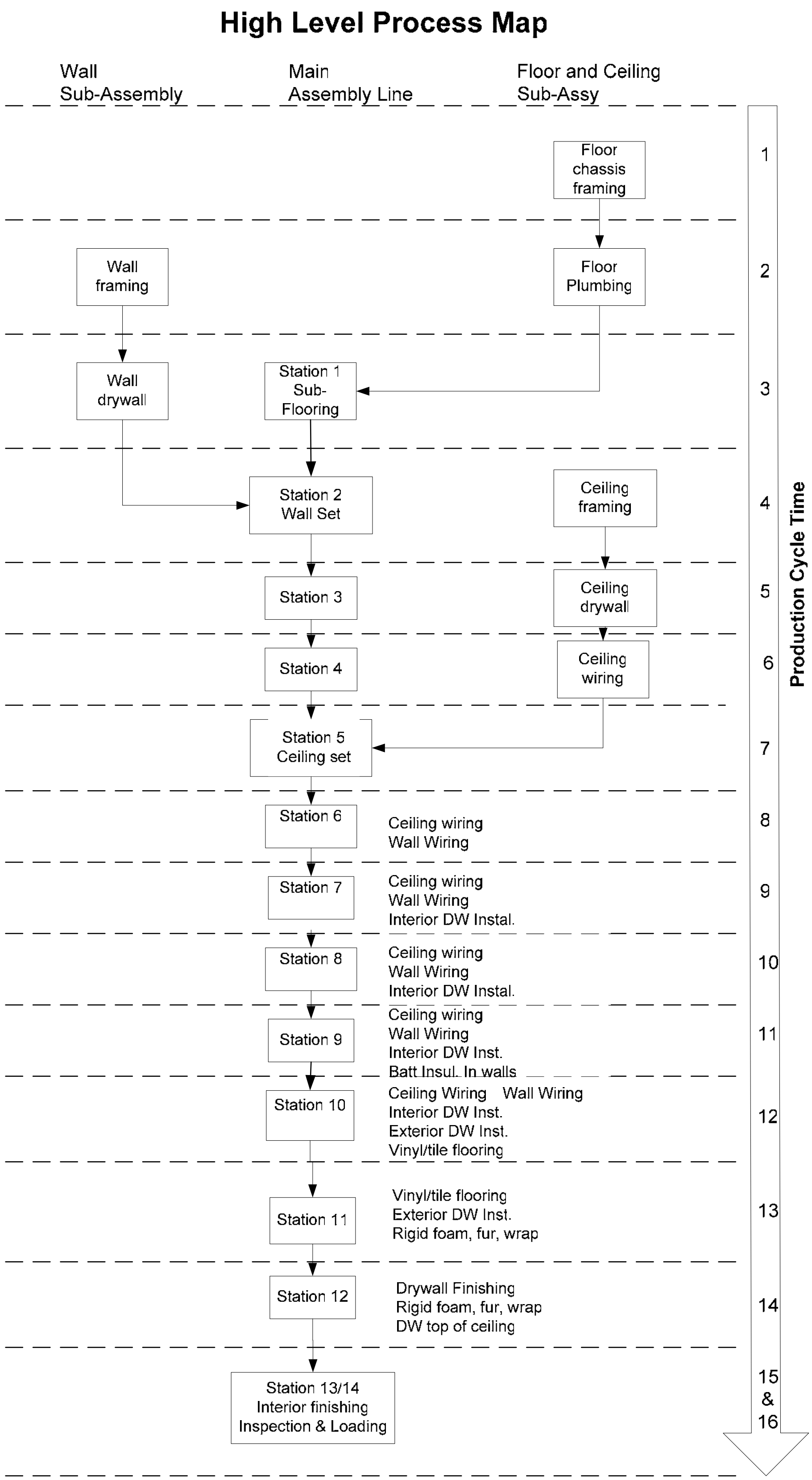


Figure 4.2. High level process map of production process

5. The Impacts of Open Building on the Construction Site

This section describes impacts on the construction site that result from incorporating open building concepts into conventional modular homebuilding. Module transport to the construction site and set (by crane) on the site are not changed. Finished flooring that cannot be installed in the factory is installed after module set on the construction site and after all remaining drywall work is completed. The use of a continuous finished floor throughout the non-wet portions of the unit cause most floor installation to be moved to the construction site. Note that all conventionally framed interior walls are pre-set and finished in the factory before the finished flooring is installed. Flooring is installed under these walls by iteratively repeating the following process: 1) flooring is installed under part of the wall, 2) adjustable jack screws in that area are extended to remove weight from the supporting wedges, and 3) wedges in that area are removed.

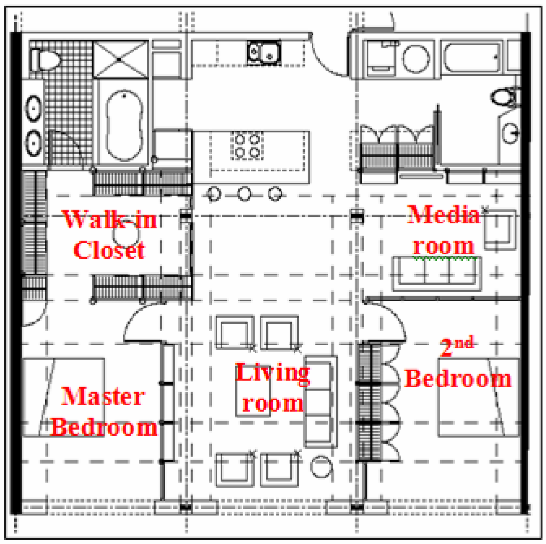
Other I^3 walls (commercial open-office and cabinet walls) that cannot be installed in the factory because finished flooring in the area is not installed, are installed on site after the modules are set and the finished floor is installed. The baseboard wiring system is then completed for the unit. Wall components are treated as shiploose, and loaded into the module at the last station in the factory, after all other work is completed. Note that it is extremely important that shiploose such as flooring and I^3 components be organized to facilitate installation and prevent damage to factory-finished surfaces.

Intermodule connections for telephone, data, and cable are not required for the new building system. Instead, service technicians or the new owner will install wireless hubs in the utility closet.

6. The Impacts of Open Building on Remodeling

Remodeling lets a unit meet the evolving needs of the current homeowner or, if a unit is sold, meet the needs of the new homebuyer, increasing the value of the unit and extending its useful life. Even modest remodeling projects in a conventional home require considerable effort and expense. This section examines how a modular unit that incorporates open building concepts can affect remodeling effort. Two scenarios are considered for the analysis: 1) conventional design concepts are used and 2) the open building concepts described in Section 3. are incorporated into the design.

For the purposes of this analysis, it is assumed that all remodeling changes are made in inside the unit, in non-wet areas. No changes are made in the external corridor, the utility infrastructure (utility closet, corridor utility soffit, vertical chases) or in wet areas inside the unit. Using these assumptions, remodeling involves removing, relocating, adding and refinishing the following elements: walls, doors, cabinets/bookshelves, flooring, electrical outlets, ceiling electrical fixtures, electrical controls/switches, HVAC registers, and telephone/data/cable outlets. Two possible floorplans (Figures 6.1 and 6.2) are selected from a large portfolio of potential plans to serve as examples in the analysis. The two bedroom plan is suited for two individuals or a small family. It is a conventional layout with multiple closed spaces, with ample use of walls and doors to separate functions and occupants. The remodeled one bedroom plan is more suited to a single professional or a couple. It is open, featuring a single large living/dining/great room. Wet areas are assumed to be essentially the same for both plans.



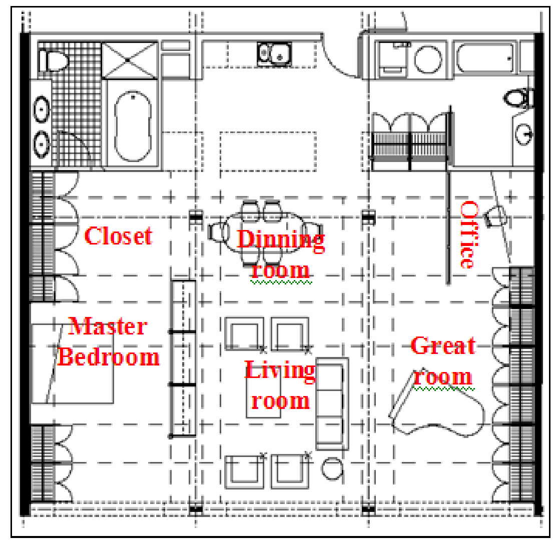


Figure 6.1- Two bedroom closed floorplan   Figure 6.2- One bedroom open floorplan (Larson 2004)

6.1 Structural Changes

Remodeling requires no structural change in either scenario. This is largely due to the structural framing system used in conventional steel-framed modular homebuilding, which provides the clear spans necessary for flexible infill. When supplemented with open web ceiling joists to disentangle and organize utilities (see Section 6.3), it provides an ideal environment for open building. The use of a continuous finished floor in the open building scenario permits walls to be relocated and even removed without creating unfinished areas under relocated walls and possible flooring mis-matches that necessitate patching or complete replacement.

6.2 Infill Changes

In the conventional scenario, the removal and relocation of framed walls and doors requires minor demolition and subsequent construction of new wall elements. Some drywall finish repair is likely on remaining walls. These framed walls also extend behind all cabinetry and shelves, requiring additional effort when these elements are removed or relocated. Removal and relocation of cabinets and shelves are not difficult, if they are freestanding. However, if they are built into their backing wall, relocation may not be possible and new built-in elements may need to be constructed. Adding new shelves or cabinets under this scenario involves specifying and ordering the components, constructing a new backer wall (framing, drywalling and finishing), and then assembling the cabinets or shelves.

In the open building scenario, walls are not used behind cabinetry and shelves, eliminating wall-related activities from remodeling efforts. The cabinet walls themselves, including freestanding cabinets and shelves, are also easily removed and relocated. The remaining flat walls are configured from several I^3 elements, either conventionally framed interior walls or commercial open-office wall systems. If open-office components are used, walls are easily disassembled and the components reused as required to form new walls. Only minor repairs for the floor and ceiling tracks are required. If additional components are required, they are specified and ordered. If conventionally framed interior walls are used, the process is more involved. Drywall is removed from the top of one side of the wall and the screws that attach the wall to the ceiling are removed (note that if crown molding is used, wall-ceiling mounting brackets may be hidden under the molding). The adjustable jack screws are then backed off, allowing the wall to be lowered. Some drywall finish repair is likely on remaining walls. The wall can be reinstalled elsewhere, if needed, using the original installation procedure and only minor drywall repairs. If new framed interior walls are needed to complete the remodeling, they are framed, drywalled and finished on site, comparable to similar activities under the conventional scenario.

6.3 Utility Changes

All utilities except plumbing are affected by remodeling.

6.3.1 HVAC Changes

Under the conventional scenario, conventional (large diameter) HVAC ducts are installed in a soffit located around the perimeter of the unit (Figure 6.3). In general, if the unit is transitioning from a closed to a more open design, remodeling changes to the HVAC system are less likely, since existing register locations should provide adequate airflow throughout the more open unit. Even if previously open areas are closed around the perimeter (e.g., the media room is subdivided into an office), new registers can easily be installed by branching from the main duct run and installing a new register in the bordering soffit. However, if remodeling involves a transition from an open design to a more closed design (e.g., a new room is desired in the center of the unit – especially a larger unit), then significant remodeling effort is required under the conventional scenario. If a new duct run is needed to reach the register in the new room, it must be installed along with a soffit enclosure. The new duct/soffit must negotiate from the perimeter soffit, around/through existing walls, to the new room. The new soffit effectively lowers the ceiling and creates an unsightly protrusion. It also creates a potential obstacle for later remodeling efforts, which may necessitate building a more complex wall around the soffit or even demolishing the soffit and installing yet another new duct/soffit path.

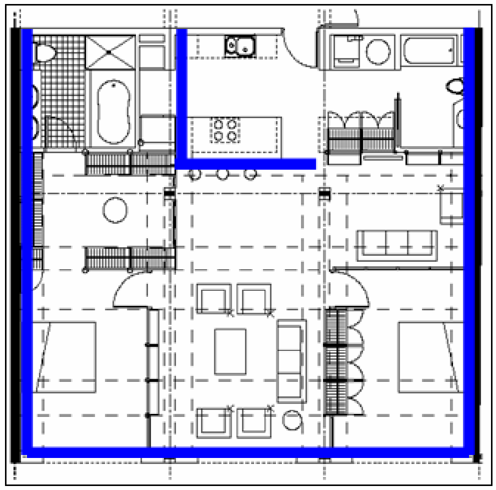


Figure 6.3 Interior soffits housing HVAC ducts: conventional scenario (Larson 2004)

Under the open building scenario, no changes to the high velocity (mini-duct) HVAC system are expected. If remodeling involved a transition from an open design to a more closed design (e.g., a new room is desired in the center of the unit), then significantly less effort is required than under the conventional scenario. Under the open building scenario, an existing miniduct serving the affected area would be redirected to the new register in the new room. This should be easily accomplished by fishing the miniduct through the open web ceiling joists from the old register to the new, splicing additional length if required. If this is not possible, a new miniduct can be run from the plenum in the corridor to the new register. A hole is cut in the corridor utility soffit to install the branch in the plenum and fish the duct. Minor drywall repair is required to complete the change.

6.3.2 Electrical Changes

6.3.2.1 Electrical Changes for Ceiling Fixtures

The remodeling effort involves removal, relocation and/or addition of new ceiling fixtures. Under the conventional scenario, adding a new ceiling fixture involves installation of a new box, running power wiring and running control (switch) wiring. The degree of difficulty depends on the location of a circuit with additional capacity. If the circuit has a box in the same ceiling cavity as the new fixture, then power wiring is easily fished from that box to the new box. Associated drywall damage and repair is limited. If the circuit does not have a box in the cavity, then ceiling drywall is cut and holes drilled through each light gauge steel joist between the two boxes so that wiring can be run. Associated drywall damage is major. If no existing circuits have capacity or are close enough to utilize, then a new circuit must be run from the panel. This requires even more cutting and drilling and subsequent repair to ceiling/wall drywall. The perimeter soffit may also be used as a path for this wiring. To complete the installation, a new switch(es) and the associated control wiring are also installed. This involves installing the switch in a wall and running wire through the wall and up into the ceiling to the box. Like the power wiring, the extent of the effort required for installing control wiring is largely dependent on the location of the box relative to the switch, and involves cutting drywall and drilling holes through steel framing in the walls/ceiling as required to run wire between the switch and the box. If remodeling requires the removal, relocation and/or addition of walls, control switches and the associated wiring in these walls must also be relocated.

Adding a new ceiling fixture under the open building scenario is much simpler. The new ceiling fixture is added by locating a circuit in the area with additional capacity, locating the closest box and tapping into the circuit at the box. Wiring is fished between boxes through the open ceiling joists. If no circuit is available, one of the unused circuits in the main wiring run in the module can be used. Accessing this circuit involves cutting a hole in the ceiling drywall near the wiring run and in the same cavity as the new fixture. The wiring is then fished through the cavity to the new box. For additional flexibility, pull cords are placed in the main wiring run to facilitate running new wire. Wireless controls are used in the open building scenario, eliminating the need for control wiring – a significant advantage over the conventional scenario.

6.3.2.2 Electrical Changes for Wall Outlets

When remodeling involves removal, relocation and/or addition of walls, wall outlets and their associated wiring are affected. Under the conventional scenario, adding a wall involves adding wall outlets at least every 6 feet and running the wiring to support these outlets. Boxes are installed and wiring is run through punchouts in the framing studs before drywall installation and finishing. To power the new outlets, an existing circuit on an adjoining wall or ceiling that has additional capacity must be found or a new circuit must be run from the panel. If an existing circuit is available, the connection occurs at an existing box or by adding a new box/cover plate at a convenient location in the circuit. If a circuit is available in an adjoining wall, this connection requires relatively little effort: minor drywall cutting, running wiring through stud punchouts, and minor drywall repair. If the circuit is only available in the the ceiling, then ceiling drywall is cut and holes drilled through each light gauge steel joist between the connection point and the new wall. Associated drywall damage is major. If no existing circuits have capacity or are close enough to utilize, then a new circuit must be run from the panel. This requires even more cutting and drilling and subsequent repair to ceiling/wall drywall. The perimeter soffit may also be used as a path for this wiring.

Under the open building scenario, wall outlets may easily be added, removed or relocated using a surface-mounted wiring system. After erecting a new wall from I^3 components, the surface mounted system is installed. Installation is the same regardless of the wall type (framed interior wall, commercial open-office wall, or cabinet wall). First, the raceway is installed on the base of the wall. Wiring is connected to a circuit with additional capacity inside the raceway on an adjoining wall and then the wiring and the outlets are installed inside the new raceway. Finally, the cover and trim are added to complete the installation. Note that the original installation is designed to facilitate these changes:

- Additional capacity is provided on each original circuit to allow a limited number of outlets to be added.
- Additional circuits are provided throughout the original surface-mounted system to accommodate future needs.

If even more capacity is required, a new circuit can be pulled from the main wiring run in the ceiling to the surface-mounted system. This latter option will take considerably more effort.

6.3.3 Sprinkler Changes

If a sprinkler head must be added in either scenario, it is connected to a branch line and extend through the ceiling cavity and down to the ceiling. This is done with only minor drywall rework.

6.3.4 Telephone/Cable/Data Changes

Under the conventional scenario, when remodeling involves removal, relocation and/or addition of walls, wiring for telephone, cable and data is often affected. Rewiring to accommodate these changes is comparable to the rewiring required for wall outlets.

Under the open building scenario, wireless communications are used for telephone, cable and data. Therefore, rearrangement of walls has no impact on communications systems.

7. Summary, Conclusions and Recommendations for Future Research

This research has explored the feasibility and utility of incorporating open building concepts in modular construction in a mid-rise residential application. The approach is feasible, although changes in materials and construction processes are necessary.

Innovative materials and components provide the structure necessary to apply open building concepts. Primary building components recommended include open-web ceiling joists and factory-built I^3 interior wall components. The I^3 components include movable framed interior walls, commercial open-office walls and cabinet walls. The latter two elements are part of highly engineered, vendor-supplied wall systems. Innovative utility solutions complement the new building components, disentangling utilities from structural systems and other utilities. Utility solutions include high velocity HVAC with mini-ducts, surface-mounted baseboard wiring system, wireless controls for ceiling fixtures, flexible PEX freshwater plumbing lines, and wireless communications (telephone/cable/data). While these innovative components cost more than their conventional counterparts, they greatly reduce the effort required for construction and remodeling.

Conventional modular manufacturing and construction processes are modified to accommodate open building concepts. In the modular factory, some process changes require extra effort.

- Additional electrical circuits and pull lines are installed to ease the addition of ceiling fixtures and wall outlets during remodeling.
- Alternate drainage layouts are provided in wet areas to simplify likely remodeling efforts.
- Factory-framed interior walls utilize adjustable legs that are installed in the wall framing cell.
- Factory-built framed interior walls are set in a two-stage process after the ceiling is set. The first stage involves temporarily wedging the wall from the floor and attaching it to the ceiling. The second stage involves installing the finished floor

under the wall, then extending the legs to permanently support the wall and removing the wedges.

Other process changes in the modular factory require less effort.

- Vendor-supplied I^3 wall components do not require framing or finishing. They are also easier to set than conventional interior walls. However, they do require that the finished floor be completed before set. Since the finished floor is installed after drywall finishing is complete, this may extend finishing operations.
- Framed interior walls and most exterior wall surfaces are drywalled on both sides in the wall framing cell, eliminating most drywall handling and installation on the main line. This allows critical path operations such as drywall finishing to begin earlier on the main line. Most batt insulation is also installed in the framing cell.
- It is much easier to run HVAC miniducts through open-web ceiling joists than hang conventional ducts below the ceiling and enclose them in a soffit. Eliminating soffits from the interior of the unit eliminates the need for framing, installing and finishing the soffits. In addition, most of the miniduct installation can be moved off the main line to the ceiling assembly cell.
- It is much easier to pull power wiring through open-web ceiling joists than through light gauge steel joists – conduit does not pull easily through the light gauge steel punch-outs and drilling is often required.
- Wireless electrical controls for ceiling fixtures eliminate the need to install related switch boxes and wiring in the walls and ceiling.
- Wireless communications eliminate the need to install related boxes and wiring in the walls and ceiling.
- It is much easier to run flexible PEX freshwater plumbing lines through open-web ceiling joists than through floor joists that require extensive hanger systems and some drilling.
- The installation of sprinkler lines is moved off the main line to the ceiling assembly cell.
- The surface-mounted baseboard electric system makes it easier to install outlet boxes and run wiring.

Modular finishing processes on the construction site are also changed to incorporate the open building concepts. Most of these site process changes involve the continuous finished floor and the I^3 wall components that are installed on top of the floor. Although most changes will extend finishing time on site, this time is considerably shorter than the corresponding time saved in the factory.

- The continuous finished floor that extends throughout the non-wet portions of the unit prevents most flooring from being installed in the factory. This work migrates to the construction site and is completed after all remaining drywall work is finished. Since all factory-built framed interior walls are pre-set and finished in the factory, some flooring may need to be installed under these walls on the construction site, increasing installation time.
- Other I^3 walls (commercial open-office and cabinet walls) that are not installed in the factory because their finished flooring is not installed, are installed on site after the finished floor is installed. The baseboard wiring system is then completed.

- Intermodule connections for telephone, data, and cable are not required. Instead, service technicians or the new owner installs wireless hubs in the utility closet.

The primary reason for incorporating open building concepts in modular homebuilding is to simplify remodeling.

- The continuous finished floor permits walls to be relocated without affecting flooring.
- The I^3 wall design coupled with disentangled utility strategies (e.g., surface-mounted baseboard wiring system for wall outlets and wireless communications) permit walls to be easily added, removed, or relocated. Only minor repairs for the floor, ceiling, and wall interfaces may be required.
- The combination of open-web ceiling joists and the miniducts used by the high velocity HVAC system effectively eliminate soffits in the unit. Even a worst case remodeling situation involving a transition from an open design to a more closed design (e.g., a new room is desired in the center of the unit) is readily accommodated in the open building scenario. The same situation is much harder to accommodate using conventional design strategies where soffits are involved.
- The combination of open-web ceiling joists, wireless ceiling fixture controls, centralized wiring paths, and spare circuits greatly reduce the effort and minimize damage when adding or relocating ceiling fixtures.

In conclusion, open building concepts can be incorporated in modular homebuilding to greatly simplify both the initial production and continued remodeling of modular housing. This simplicity will come at a cost. More design effort will be required to incorporate open building concepts into each project. The innovative components that allow open building concepts to be realized are also more expensive than their conventional counterparts.

This research has several limitations. First, it focuses on specialized modular homebuilding technologies that are suitable for mid-rise applications - steel framing and concrete floor decks. This technology is not used in mainstream modular homebuilding in the U.S. A second shortcoming is the lack of quantitative data that allows costs to be better understood when considering design alternatives and tradeoffs. A final shortcoming is the focus on existing components that can address open building needs. Future research should address these shortcomings. The same open building concepts and design solutions should be explored to assess how they can apply to more conventional wood frame modular homebuilding technologies used for single family and low-rise multi-family applications. Costs should be more thoroughly examined and estimated, permitting tradeoffs between first cost and remodeling flexibility. Finally, new and more innovative designs should be considered for all components that can facilitate the integration of open building concepts into modular homebuilding. Prime examples include I^3 wall, surface-mounted wiring, HVAC, and structural components.

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Attachment 1
Notes About Structural Members
(from Modular Manufacturer)

1. For shipping quite a distance, manufacturer would prefer the module height at about 10'7" to allow for 3" clearance for the tongue that is used for lifting and alignment.

2. If the module is 14' or less wide, the manufacturer can make up some of that room by using a 6" ceiling joist. (See comment below regarding beam protection and depth of ceiling materials)

3. The manufacturer is working on a system to allow for 2-hour rated beams being protected by the ceiling/floor assembly. This building will require 2-hour ratings for all steel members. This ceiling will most likely be about 1-1/4" - 1-3/4"

4. Depending on the span of the floor rim joists, the manufacturer may be able to use a 10" member instead of 12". (Up to about 20 feet for a 14' wide module assuming a W10x22 could be a safe assumption, with a depth of 10.17".)

Attachment 2
Alternative for Installing All of the Surface-Mounted Wiring System On-Site

Several issues may lead the builder to install all of the surface-mounted wiring system on the site after setting the modules, instead of installing the system on the demising and end walls of the unit's end modules in the factory. For example, it may be desirable to install the surface-mounted system over the finished floor. Since much of the floor is installed on site after set, the surface-mounted system would need to be installed on site. It may also be desirable to install all of the surface-mounted system at the same time. Since some of the system must be installed on walls that are erected after the finished floor has been completed (on site), the surface-mounted system would need to be installed on site. If this alternative is selected, the following process might be used.

Wiring to accommodate the surface-mounted system will be pulled while the ceiling panel is on the ceiling cart in the factory. This wiring will run alongside the other ceiling wiring and then turn near the end of the wet area and run to the side of the ceiling panel (Figure 3.9). Excess wiring required to extend down the demising wall to the beginning of the surface-mounted system will be coiled. After the ceiling is set on the production line, this wire will be run down through the wall to the entrance of the surface-mounted system and enter a junction box. After the modules are set on site, floors are installed, and interior walls are erected, the surface mounted raceway, wiring and outlets will be installed and the system cover and quarter-round trim added.

Attachment 3
Alternative for Installing Framed Interior Walls on Site

If it is not practical to install finished flooring under framed interior walls that are already set (using wedges and the iterative installation process described above), it will be necessary to install and finish all framed walls after the finished floor is completed on site. If necessary, the following process might be used.

Interior wall panels are framed and drywalled (one side only) on a specialized sub-assembly line that is adjacent and parallel to the main assembly line. The same sub-assembly line produces exterior walls. Adjustable jack screws are installed on the bottom plate of each wall while it is on the framing table. Walls are not installed in the factory. Instead, they are loaded into the module as shiploose. Loading occurs in the second station of the main assembly line, after the concrete floor has been poured and has cured, and before the exterior walls have been set. Like the other I^3 components (specialty walls and freestanding cabinet systems) that are also loaded as shiploose, the framed interior walls are set after modules are set on the construction site and the finished floor is installed. After tilting each framed interior wall up into position, the adjustable jack screws are extended, forcing the top plate against the ceiling. The top plate is then attached to the ceiling joists using screws from below. Drywall is then installed on the open side of the wall and the drywall is finished. Finally, the baseboard wiring system is installed.

Attachment 4.
Miscellaneous Notes

Utilities

1. How do we get wiring to appliances in open area? Our approach is to run through ceiling and down poles. Could have poles that also provide storage or lighting track. Could run wiring in floor along marriage lines, even if they are open walls initially. Then cut into chase and place box, if needed later. Could lay out grid with unused wiring initially, or even place outlets.
2. Provide floor level drainage for all waste water. No step up allowed, because this will be step away from universal design (roll in shower for wheelchairs). This means that shower and some tub drains may need to be run through floors (cast into floor) and thus be fixed. This drain will need to run to vertical utility chase where it will be attached to riser. Some flexibility might be created by providing some type of flexible drainage fixture to accommodate difference between standard tub and garden tub (or possibly shower) – maybe 6" flexible location. Future drains might also be cast in the floor for this purpose or to accommodate the addition of a shower in a bath that initially only has a tub.
3. Code says that vent stacks must be located within 5' of drain. Can we run horizontal for some distance? Are there other technologies (e.g., bladders) that can reduce or eliminate need for stacks?

Miscellaneous

Long term - How do we allow the demising walls, ceilings to be flexible so that we can redefine living units in discrete whole modules. How can utility riser systems accommodate this? How can floors be made more flexible to make living unit reconfigurable?

Attachment 5

Details of Modular Production Process

1. Ceiling Framing

Activities:

1. Position and align components (3 standard length and 1 short component) that form each ceiling hanger (side ceiling rim joist) on ceiling framing table. Note that the short component was cut from a standard length hanger component. (10 min. to position and align each side)
2. Weld 4 components together to form each of 2 ceiling hangers.
3. Clamp ceiling hangers to ceiling framing table.
4. Measure and mark location of joist hangers. (12 min.)
5. Trace lines at the locations marked.
6. Weld joist hangers to each ceiling hanger - 22 joist hangers per side. (Total time: 60 min)
7. Place joists on joist hangars and clamp.
8. Weld joists to joist hangers. Note that a double joist is used at the center of the ceiling and is welded after the 1^{st} joist is welded to the joist hangers.
9. Measure and mark position of metal strip on each ceiling hanger.
10. Weld metal strip on each ceiling hanger. (20 min./ 2 metal strips)
11. Measure and mark locations for blocking - 4 blockings per ceiling.
12. Weld blocking hangers to joist and then blocking to blocking hangers. (8 min./blocking)

Labor: 1 welder; 5 labor hours
Cycle time: 5 hours
Material: rim joists (heavy gauge steel with special x-section), joist hangers (galvanized angles), joists (light gauge steel c-channel), hanging strips
Tools/Equipment: ceiling framing table, clamps, welding torch and supporting equipment, crane, saw, electric drill

Changes Anticipated for Open Building:

- Light gauge steel joists replaced by open web joists

2. Ceiling Drywall Installation

Activities:

1. Place drywall on overhead ceiling drywall jig. Note that drywall is not measured or cut. (24 labor min.)
2. Place deadman support to prevent drywall from sagging.
3. Using the crane, lift and position ceiling frame on top of drywall. (40 min.)
4. Remove spreader bar from ceiling frame using crane.
5. Rearrange deadman supports.
6. Measure and mark location of joists to aid attachment with screws.
7. Attach drywall to ceiling frame using electric screwdriver using 6 screws per joist.

Labor: 1-2 drywall workers; 2.5 labor hours
Cycle time: 2.5 hours
Material: drywall, screws
Tool/Equipment: electric screw driver (drill w/ manual screw feed), ceiling drywall jig, bridge crane, spreader bar, deadman supports

Changes Anticipated for Open Building:

- No changes required.

3. Ceiling Wiring

Activities:

1. Move ceiling assembly from ceiling drywall jig to ceiling cart using crane equipped with spreader bar.
2. Measure and position electrical boxes for ceiling fixtures. Attach to joists using electric screwdriver.
3. Drill holes for wiring through ceiling joists and rim joists as required; note that holes for running primary wiring are pre-punched in the joists.
4. Position wiring cart containing spools of flex conduit at end of ceiling assembly.
5. Pull wiring through punched holes in joists.
6. Coil extra wiring as required to run down walls to electrical boxes and panels and to connect to other modules. Use drawings. (Total wiring time: 83 clock min.)

Labor: As many as 3 electricians worked on ceiling at one time; labor hours depended on module level and where wiring was done (see Table 1).

Level	Ceiling Cart (on floor)	Main Line (after set)
1	7.5	9.3
2	2.5	2.6

Table 1. Labor hours required for pulling wiring in ceiling

Cycle time: See Table 2

Level	Ceiling Cart	Main Line
2	2.5	1.3

Figure 4.1. Layout of Factory

Table 2. Cycle time (hours) required for pulling wiring in ceiling

Location: Ceiling cart (optimal location since it is on floor with no falling hazard and ability to walk on drywall); station 9 last station observed
Material: Various types of wire in conduit on spools, electrical boxes for ceiling fixtures
Tool/Equipment: screw driver (drill w/ manual screw feed), wiring cart (holds four spools of wire), ceiling cart, crane, spreader bar

Changes Anticipated for Open Building:

- HVAC Activities:
  - High velocity HVAC ducts are installed in predetermined paths through the open web ceiling joists to serve the interior of the unit – instead of being installed after ceiling set in a soffit mounted below the ceiling .
- Wiring Activities:
  - Wiring in flex conduit is pulled through pre-determined paths in the open web ceiling joists. Pulling wiring through open web joists is much easier than pulling through punchouts in light gauge steel joists.
  - No holes need to be drilled in open web joists to accommodate wiring.
  - Additional circuits and a pull line are added in each module to facilitate addition of ceiling fixtures and wall outlets.
  - Wiring for telephone, data, and cable are not required, since wireless technologies will be used.
- Plumbing activities:
  - Fresh water lines made of pex tubing are pulled through pre-determined paths in the open web ceiling joists – instead of installed in the floor in the plumbing station.
- Sprinkler activities:
  - Rigid sprinkler pipes are installed through pre-determined paths in the open-web ceiling joists - instead of installed after ceiling set in a soffit mounted below the ceiling.

4. Floor Chassis Framing

Pre-assembly activities:

1. Cut rim joists to size and cut and screw strips of drywall to inside of each rim joist. Screw placement appeared random. Drywall located near station was wavy, so worker walked down the main line to get and cut drywall strips. (40 labor min.)
2. Measure and cut blocking.
3. Weld metal plate with holes onto top end of each post - 6 posts per floor chassis assembly. (20 labor min./6 posts)

Assembly Activities:

4. Lift, position and clamp 4 rim joists (1 on each side) onto chassis jig. Workers had to search about 10 min. for clamps.
5. Measure and mark locations of joist hangers along the rim joists.
6. Lay joist hangers on floor close to marked locations.
7. Tack weld hangers onto rim joists.
8. Place and clamp corner posts onto rim joists. (16 labor min./4 posts)

9. Place and clamp squaring jigs from middle of each post down to rim joist - 2 per post. (30 labor min.)
10. Stitch weld rim joist corners and posts to rim joist. (27 labor min./post).
11. Use crane to lift and position pre-assembled double drywall and joist.
12. Manually move, position and clamp pre-assembled double drywall and joist to rim joist. (2 labor min./side)
13. Stitch weld at the inside corners the rim joist and sub-assembly. (4 labor min./corner)
14. Nail sub-assembly to rim joist - about 16 nails per side.
15. Measure and mark the inner side of rim joists for the locations of hangers.
16. Tack weld hangers to the inner side of the rim joist. (10 labor min./8 hangers) The chassis has 16 floor joists supported by 32 hangers.
17. Measure and mark location of middle posts.
18. Place middle posts onto rim joists.
19. Use level to square posts and install 2 post jigs per post and clamp.
20. Spot weld 2 middle posts (35 labor min./2 posts)
21. Finalize welding.
22. Remove fixtures and clamps.
23. Position joists on the joist hangers.
24. Place jigs to prevent joists from sliding.
25. Weld joists to hangers. (44 labor min.)
26. Measure and mark location of blocking.
27. Tack weld joist hangers to joists, at each side of the blocking location. Weld blocking to joist hangers.
28. Tack weld metal strips to the bottom of rim joists.
29. Weld plate with holes and plates to the front of the chassis assembly. (32 labor min.)

Labor: 2 welders - good dynamic; divided work - each worker responsible for specific pre-assembly activities and during assembly each one was responsible for one side of the chassis
Cycle time: 12 hours
Material: rim joists, joists, joist hangers (galvanize angles), nails, drywall, galvanized blocking, strips, posts
Tools/Equipment: Clamps, post jigs, level, nail gun, crane, band saw, welder

Changes Anticipated for Open Building:

- No changes required.

5. Plumbing Station (This activity was not observed)
Activities:

1. Tack weld support hangers to joists, at each end of pipe supports. Weld pipe supports to support hangers.
2. Install fresh water and waste water piping.

Changes Anticipated for Open Building:

- Fresh water lines are not installed in the floor – instead they are installed through the ceiling and the wet walls.

- Alternate drainage lines are installed when flexibility is desired to accommodate predetermined alternate bathroom layouts.

6. Window/Door Opening Framing

Activities:

1. Get framing information from drawings. (sub-assembly configuration and dimensions)
2. Measure and cut-to-size components; note that door frames use wood framing.
3. Place components on small sub-assembly framing table.
4. Measure and mark the location of component, position and secure with clamps.
5. Attach components using electric screwdriver.
6. Remove frame from table and stage near wall framing table.

Labor: 1 person (wall framer, ceiling framer, or drywall installer as available)
Cycle time:
Tools/Equipment: tape measure, grinding wheel, clamps, small sub-assembly framing table with jigs, electric screw driver (drill w/ manual screw feed), welding equipment, electric saw (for wood only)
Materials: Metal framing components (studs), wood framing components (for doors)

Changes Anticipated for Open Building:

- No changes required.

7. Wall and Soffit Framing

Activities:

1. Get framing information from drawings. (panel configuration and dimensions)
2. Measure and cut-to-size steel tracks used for top and bottom plates – tracks were purchased in 10' lengths, requiring a cut to one track per plate to obtain desired overall length.
3. Position and weld tracks together to form top and bottom plates.
4. If necessary, measure and cut studs to size. Studs used for first floor walls do not require cutting. Studs used for second floor walls require cutting to obtain the desired roof slope for drainage. These studs are usually cut in batches of the same length and staged.
5. Place studs, plates and door and window opening sub-assembly frames on framing table.
6. Measure and mark the location of each stud and sub-assembly on the plates, position and secure with clamps.
7. Attach studs and sub-assemblies to plates using electric screwdriver.
8. Get location of electrical boxes from drawings.
9. Measure and install electrical boxes.
10. Mark drywall installation requirements on frame.
11. Remove frame from table and stage behind drywall installation rack.
12. Construct soffit frames for both the interior of the unit and for the corridor.

Labor: 2 people; 15 labor hours
Cycle time: 7.5 hours
Tools/Equipment: tape measure, grinding wheel, clamps, framing table with jigs, electric screw driver (drill w/ manual screw feed), welding equipment, electric saw (for wood only)

Materials: Metal framing components (studs, tracks), wood framing components (for doors), electrical boxes, screws

Changes Anticipated for Open Building:

- Vendor-supplied I^3 interior wall elements do not need to be framed.
- Frames for the factory-built I^3 framed interior walls are shorter to accommodate the adjustable jack screws that serve as support legs against the finished floor. Studs are purchased at the correct length for these walls.
- Jack screws are attached to the bottom plate of the framed interior walls as a first step in the framing process, before the studs are attached. Jack screws are attached at three locations on the bottom plate – right side, left side, and middle.
- Electrical boxes will not be installed on wall frames (except for wet walls) since the baseboard surface-mounted wiring system is used.
- Soffit frames are not required for the interior of the unit.

8. Wall Panel Drywall Installation

Activities:

1. Get panel frame from staging behind drywall installation rack.
2. Verify location of drywall by noting indications on frame and position frame on drywall installation rack.
3. Measure frame, including window/door openings and electrical boxes.
4. Measure, mark and cut drywall using utility knife.
5. Position drywall on frame and attach using electric screwdriver; note that drywall is installed on one side only to allow wiring installation on main assembly line.
6. For exterior demising walls – repeat Activities 4.-5. to install a second layer of drywall for fire ratings.
7. Use crane to move wall from rack onto wall panel staging cart.

Labor: 1 person; 6.5 labor hours
Cycle time: 6.5 hours
Tools/Equipment: tape measure, drywall installation rack, electric screw driver (drill w/ manual screw feed), utility knife, drywall cutter
Materials: Drywall, screws

Changes Anticipated for Open Building:

- Drywall is installed on both sides of framed interior walls, since no utilities are installed inside walls.
- Drywall is installed on both sides (when needed) of exterior/demising walls (except wet sections), since no utilities are installed inside walls. To allow drywall installation on the second side, fiberglass batt insulation is also installed as required. Batt insulation is normally installed on the main line after wiring is installed.
- Cut-outs for electrical boxes on all walls (except wet walls) are not needed, since no utilities are installed inside walls.

9. Sub-Flooring - Station 1

Activities:

Move floor chassis to main line:

1. Push module from framing bay to main line.
2. Lift module, re-orient wheels and set on main line.

Straighten chassis:

3. Check that chassis is square.
4. Pull or push middle post until chassis is square.

Prep and pour concrete:

5. Install corrugated steel sheets over floor joists to support concrete.
6. Install rebar, wire mesh, and inserts.
7. Install wood forms on rim joists.

Labor: 2 people; 15 labor hours
Cycle time: 7.5 hours
Tools/Equipment: tape measure, nail gun, staple gun, coping saw, circular saw
Materials: Plywood decking, flooring underlayment, nails, staples

Changes Anticipated for Open Building:

- No changes required.

10. Wall Set - Station 2

Activities:

1. Measure and mark wall locations.
2. Locate and attach temporary wood jigging components to secure exterior wall location.
3. Stage drywall sheets inside module for later use.
4. Locate bathtub in module.
5. Check wall numbers on panels to locate in module.
6. Place all interior wall panels and soffit frames in module using crane.
7. Attach interior panels that do not connect to exterior walls using crane.
8. Lift and position each exterior wall panel in module using crane and attach using nail gun.
9. Position each interior wall in module and attach.

Labor: Same 2 people as Station 1; 15 labor hours (2 operators have total of 30 labor hours per module)
Cycle time: 7.5 hours
Tools/Equipment: tape measure, nail gun, staple gun, screw driver (drill w/ manual screw feed), circular saw, crane
Materials: Bathtub, nails, screws, staples

Changes Anticipated for Open Building:

- No drywall is staged in the module for later installation on interior walls and soffits (except corridor utility soffit), since drywall is installed on both sides of the wall in wall framing (possible, since no utilities are installed inside framed interior walls) and since soffits are eliminated on inside of unit (since all utilities are located in the ceiling).

- Framed interior walls are still placed inside the module at this station, but the walls are not set until after ceiling set (because they must be attached to the ceiling instead of the floor).
- No soffit frames for the interior of the unit are staged in the module, since all utilities are located in the ceiling.

11. Ceiling Set and Duct/Sprinkler/Soffit Installation

Activities:

1. Roll ceiling cart from framing bay into the empty location on the main line (after station 5).
2. Rig ceiling assembly to spreader bar. (25 labor min.)
3. Attach crane hook to spreader bar. (5 labor min.)
4. Lift ceiling assembly and set on module. Workers had to wait 2 min. until ceiling assembly stopped swinging before dropping it onto module. Exterior walls had to be forcibly spread before lowering the ceiling. (24 labor min.)
5. Cut out section of ceiling hanger for middle post.
6. Remove spreader bar from ceiling assembly and place on ceiling cart.
7. Remove crane hooks from spreader bar.
8. Move ceiling cart from the main production line back to the framing bay.
9. Attach ceiling to top plate of walls using electric screwdriver.
10. Install HVAC ducts and sprinkler lines below ceiling in corridor and in interior of unit.
11. Install soffit frames around HVAC ducts and sprinkler lines below ceiling in corridor and in interior of unit.

Labor: 3 workers. Note that some waiting/idle time occurred until all 3 workers were ready
Cycle time: 1 hour
Tools/Equipment: spreader bar, crane, 2 rolling scaffolds, screw driver (drill w/ manual screw feed)

Changes Anticipated for Open Building:

- Framed interior walls are set immediately after ceiling set. Walls are tilted up, positioned, and wedged firmly against the ceiling using large wedges between the concrete floor deck and the wall bottom plate. Note that the jack screws are not extended to support the wall until the finished floor is laid later in the factory or on site. The wall is attached to the ceiling from above, by driving screws down through the ceiling joists into the wall top plate.
- HVAC ducts and sprinkler lines are not installed below the ceiling in the interior of the unit. Instead, they are installed in the ceiling while the ceiling is on the ceiling cart. Note that since the corridor utility soffit is still required to run the HVAC plenum and main sprinkler line, these still need to be run after the ceiling is installed. Connections between these main lines and the branch lines already installed in the ceiling are completed at this station.
- Since the ducts and sprinkler lines are not installed below the ceiling in the interior of the unit, no soffit frames are installed.

12. Installing electrical panel, boxes and wiring in walls

Activities:

- Install panel – did not observe
- Install electrical boxes in walls: junctions, switches, outlets
    1. Measure and mark locations for boxes.
    2. Cut hole using manual drywall saw.
    3. Attach box using electric screwdriver.
- Run wiring in walls
    4. Wait until wiring in ceiling is completed
    5. Drill holes in top plates and through ceiling drywall (from underneath at floor level).
    6. Climb to top of ceiling and pull wire through holes into walls.
    7. Return to lower level and complete pulling wire.

Labor: 4 electricians, seldom working on same module at same time; 14 labor hours Level 1 module and 8 labor hours Level 2 module
Cycle time: cycle for Level 1 was 18.8 hours; cycle for Level 2 was (7.3-14 hours; caused by electricians moving around, not focusing on same module, waiting for ceiling wiring to be completed
Tools/Equipment: tape measure, manual drywall saw, electric screw driver (drill w/ manual screw feed)
Materials: Electrical boxes, electrical panel, misc. electrical components, wall studs (to mount panel box)

Changes Anticipated for Open Building:

- The installation of electrical boxes and wiring for wall outlets are done in wet walls only. The baseboard wiring system is used in all other walls. The feeder line from the ceiling to the baseboard wiring system is installed in demising walls and stand alone walls.
- The installation of boxes, switches and wiring to control ceiling fixtures is not required, since wireless controls are used.
- The installation of boxes and wiring for telephone, data, and cable are not required, since wireless technologies are used.
- Fresh water lines made of PEX tubing are pulled from the ceiling down into the wet walls – instead of through the floor.

13. Interior Drywall Installation

Activities:

1. Wait until wiring in interior walls is completed and soffit framing is installed around HVAC ducts and sprinkler lines.
2. Measure wall sections and soffits requiring drywall.
3. Cut drywall to size using utility knife or hand saw (drywall was loaded into module at Station 2).
4. Carry drywall to point of use.
5. Position vertically using wooden jig and attach using electric screwdriver.

Labor: 1 person; 1.3-8.3 labor hours (no module completed in 2.5 days of observation)

Cycle time: 1.3-12 hours (no module completed in 2.5 days of observation - affected by same issues as wiring in walls)
Tools/Equipment: Tape measure, manual drywall saw, utility knife, electric screw driver (drill w/ manual screw feed), wooden jig to lift and hold drywall in place while attaching
Materials: Drywall (4’x8’ sheets)

Changes Anticipated for Open Building:

- No drywall is installed on interior walls on the main line. All interior drywall (both sides) is installed in the wall framing area, since no utilities are installed inside walls.
- No drywall is installed on soffits located inside the unit, since these soffits have been eliminated.

14. Exterior Drywall Installation

Activities:

1. Wait until wiring and batt insulation are installed in exterior walls.
2. Measure wall sections requiring drywall.
3. Cut drywall to size (if required) using utility knife or hand saw (operator pre-stacks drywall on cart and positions in main aisle closest to point of use).
4. Carry drywall to point of use.
5. Position vertically using wooden jig and attach using electric screwdriver (3 min. average to carry, position and attach one 4x12’ sheet – lower screws only – accessible from floor) (Another 2.5 minutes/sheet to attach upper screws using rolling scaffold).
6. Cut excess drywall from top of module using hand saw.
7. For exterior demising walls - Apply 2nd layer of drywall (Activities 2-6).

Labor: 1 person; 10 labor hours (not complete; does not include 3.3 hour repair)
Cycle time: 6.8 hours (not complete; does not include 3.3 hour repair; affected by same issues as wall wiring)
Tools/Equipment: Tape measure, manual drywall saw, utility knife, electric screw driver (drill w/ manual screw feed), wooden jig to lift and hold drywall in place while attaching
Materials: White drywall (5/8”x4’x10’ sheets) – Exterior walls, 1st layer on 1st floor; White drywall (5/8”x4’x12’ sheets) – Exterior walls, 1st layer on 2nd floor; brown drywall (5/8”x4’x12’ sheets) – Exterior walls, 2nd layer; yellow drywall (5/8”x4’x8’ sheets) – waterproof used for 2nd layer on demising walls

Changes Anticipated for Open Building:

- No exterior drywall is installed on exterior/demising walls (except wet sections). This drywall is already installed in the wall framing area, since no utilities are installed inside walls.

15. Drywall Finishing (Taping 1,2)

Activities:

1. Wait until interior drywall has been installed.
2. Install corner bead.
3. Mix mud.

4. Apply mud using pallet and trowel.
    a. Apply 1st coat (watered down pre-mix compound) with tape on seams. (6.5 labor hours)
    b. Allow to dry (2 hours or overnight).
    c. Apply 2nd coat (dry mix compound). (17 labor hours)
    d. Allow to dry (90 minutes).
    e. Apply finish coat (pre-mix). (8.5 labor hours)
    f. Allow to dry.
5. Sand (1.3 labor hours)

Labor: 2 person; 33 labor hours
Cycle time: 17 hours
Tools/Equipment: pallet, trowel, sanding pole
Materials: Drywall mud, sandpaper

Changes Anticipated for Open Building:

- Less drywall finishing is required since: 1) soffits on the interior are eliminated and 2) some I^3 wall components do not require finishing.
- Drywall finishing can begin earlier on the line, since drywall is already installed on both sides of interior walls when they are set and soffits on the interior of the unit have been eliminated.

16. Foam Insulation, Furring, Wrapping
Activities:
1. Wait until exterior drywall has been installed.
2. Get rigid foam insulation from warehouse, position on wall and attach using electric screwdriver. (4.8 labor hours)
3. Get OSB sheets from staging area along main aisle, cut into furring strips (and larger elements) and attach using electric screwdriver. (5.7 labor hours)
4. Get Tyvek house wrap, position on wall and attach using staple gun. (.5 labor hours)

Labor: 1-2 persons; 11 labor hours
Cycle time: 16 hours
Tools/Equipment: electric screw driver (drill w/ manual screw feed), staple gun
Materials: OSB sheathing, rigid foam insulation, Tyvek housewrap, screws, staples

Changes Anticipated for Open Building:

- This operation can begin earlier on the line, since exterior drywall is already installed on the wall (except for wet areas) when it is set.

17. Wood & Tile Flooring Installation
Activities:
1. Clean kitchen/bath floor.
2. Apply adhesive with trowel.
3. Position and adhere wood/tile squares.
4. Grout tile.

Labor: 1 person
Cycle time:
Tools/Equipment: Trowel, utility knife
Materials: Vinyl/ceramic tiles, flooring adhesive, grout

Changes Anticipated for Open Building:

- The use of a continuous finished floor throughout the non-wet portions of the unit cause most floor installation to be moved to the construction site to be completed after module set.
- The flooring that is installed in the factory is installed later in the process (after drywall finishing and paint), since a higher quality finish is desired.
- Where framed interior walls are used, they are pre-set and finished before the finished flooring is installed. Flooring is installed under these walls by iteratively repeating the following process: 1) flooring is installed under part of the wall, 2) adjustable jack screws in that area are extended to remove weight from the supporting wedges, and 3) wedges in that area are removed.

18. Drywall Installation on Top of Ceiling (first level only to support housewrap)
Activities:
1. Stack drywall on top of ceiling.
2. Carry and position on ceiling joists and attach using electric screwdriver

Labor: 2 person; 7 labor hours
Cycle time: 3.5 hours
Tools/Equipment: electric screw driver (drill w/ manual screw feed)
Materials: drywall sheets, screws

Changes Anticipated for Open Building:

- No changes required.

19. Finishing
Activities:
1. Sand drywall compound manually using pole as extension. (1.5 labor hours)
2. Molding, doors & trim. (3 labor hours)
3. Spackle nail holes in trim. (1 labor hour)
4. Clean – primarily sweeping. (1 labor hour)
5. Mask unpainted surfaces. (1.25 labor hours)
6. Paint using pressured paint system. (1 labor hour)
7. Install kitchen cabinets, sink and countertop. (1.5 labor hours)
8. Install windows (2 labor hours). All windows were installed with the exception of the front window, which was used for access. The front window was installed after most of the interior finish work was complete.
9. Remove masking materials and touch up. (.75 labor hours)
10. Install closet doors. (1.5 labor hours)
11. Assemble/install bath vanity. (.5 labor hours)

12. Install medicine cabinet.
13. Install bullnose tile in bath. (.75 labor hours)
14. Install wire frame closet shelves. (1.5 labor hours)
15. Install locksets. (1 labor hour)
16. Install commode.
17. Install plumbing fixtures.
18. Hang light fixtures and install switch plates. (2 labor hour)
19. Caulk molding, trim, windows, countertops.
20. Install grills on registers

Labor: As many as six persons working in the module at the same time; 22 labor hours
Cycle time: 7 hours
Tools/Equipment: manual sand block with pole extension, miter saw, pressurized paint system (fed from a five gallon bucket located outside of the unit), level, caulking gun
Materials: sandpaper, molding, trim, doors, spackling compound, vacuum cleaner, masking tape, masking paper, paint, cabinets, vanities, sinks, countertops, nails, windows, closet doors, medicine cabinet, bullnose tile, grout, wire frame closet shelving, locksets, commode, baseboard radiators, water heater, plumbing fixtures, light fixtures, electrical cover plates, caulk

Changes Anticipated for Open Building:

- I^3 components such as commercial open-office system components and cabinet walls are installed after the finished floor is installed in the area. When this can be done in the factory, it is moved near the end of the line as part of finishing.
- Kitchen cabinets, which are normally installed as part of finishing, are also installed over the finished floor.
- The surface mounted baseboard wiring system is installed on demising walls as well as on I^3 walls where finished flooring is factory installed.

20. Inspection and Loading
Activities:

1. Load onto carrier and secure. Performed as part of the move from Station 12 (last sidesaddle station) to either Station 13 or 14 (parallel shotgun stations).
2. Load shiploose materials.
3. Final clean.
4. Final inspection.
5. Repair non-conformances.

Labor:
Cycle time:
Tools/Equipment: crane with spreader bar for lifting module
Materials: Shiploose materials

Changes Anticipated for Open Building:

- Shiploose materials include new I^3 components.

Attachment 6

Lean Production Analysis:
Top 10 Recommendations

Production activities in a modular manufacturing plant were observed continuously from 7:00 AM 2/16/2005 until noon 2/18/05. During the visit, the plant operated at a rate of four modules per week, with an equivalent cycle or TAKT time of 10 hours per line move. This production rate is 40% of the full production rate of the factory. A more detailed description of each high level production activity is given in Section 4. above.

An important element of this study was to analyze the current modular production process to assess its efficiency and identify opportunities for introducing lean production concepts into the operation. The concepts summarized in Table 1 were presented to factory management on 6/23/05). Follow-up efforts to organize kaizen rapid improvement events are planned for Fall 2005.

Recommendation	**Cost**	**Savings**
General plant operations		
1. Order the workplace	Low	Medium
2. Rationalize material staging and replenishment	Low	Low-Medium
3. Purchase right-sized materials	Low-medium	Medium
4. Reduce welding	Medium	High
5. Use the right tool for the job	Low	Low
6. Use jigs	Low-medium	Low
7. Spread line activity by moving work upstream	Low-medium	Medium-high
8. Expedite electrical processes	Low	Medium-high
9. Create sub-assembly cells	Low-medium	Low-medium
10. Re-engineer roof slope	Medium	Medium

1. Order the workplace

The 5Ss – sort, set in order, shine and inspect, standardize and sustain – are an important foundation of any lean effort. Their goal is to establish order and allow visual management in each workplace throughout the plant.

Sort

The first principal is to sort out what is not needed. For example, the ceiling framing workstation had material from previous projects staged in the area. These materials impeded the routine flow of work and increased travel distances for workers who had to move around it. They were also potential trip hazards.

Each operator should thoroughly inspect their workplace, red-tagging unneeded items. All red-tagged items should then be removed.

Set in order

After unneeded items are removed from the workplace, the remaining items can be organized to improve efficiency. For example, operators were observed searching for equipment: clamps at the ceiling framing and floor framing workstations, electric drill and deadman supports in the ceiling drywall workstation.

Material and equipment that supports production should be organized along three dimensions: what, how many and where. To fix the location of equipment and material, tape can be used to designate their home position on the floor and labels can be used for identification. A shadow box can be used to locate tools and jigs. Colored tape can be used as a visual reminder to replenish an item. The objective should be transparency. Workers should immediately be able to find all necessary items and out-of-standard situations should be obvious to everyone.

Shine and inspect

The workplace should be well maintained. Examples include:

A. Operators were observed using poorly maintained equipment: band saw blades in the ceiling framing and floor framing workstations were dull, increasing cutting time (Figure 1); grinding wheel in the wall framing was also dull (Figure 2); clamps on the wall framing table were loose, increasing assembly time and reducing quality; the drywall installer used a malfunctioning electrical screw driver, which increased attachment time.

Figure 1. Dull band saw (floor framing)

Figure 2. Grinding wheel with dull blade (wall framing station)

B. The operator was attaching insulating foam sheets with screws using a manual feed drill because the power stapler normally used was broken (Figure 3). The drill was used for the entire three day study period.

Figure 3. Installing foam sheet using screws

Operators should regularly inspect their equipment using an inspection checklist. They should be able to recognize tool and equipment wear and perform routine maintenance when required. More extensive equipment maintenance should be completed by others in a timely manner, with suitable back-up equipment available for use during this period.

Standardize

There appeared to be little standardization throughout the production process. Design drawings were often unavailable, incomplete or incorrect. No standard work instructions documenting materials, tools/equipment, and methods were posted. The result was substantial variations in production methods, inefficiencies, and rework. Wall framing and electrical seemed to be particularly plagued by inadequate shop drawings, resulting in lengthy discussions to resolve design details and substantial rework. Examples of waste included:

A. When two operators lifted a ceiling frame on top of the jig, they noticed that insufficient drywall had been pre-positioned on the jig. They had to relift the frame and position additional drywall (Figures 4,5).

Figure 4. Re-lifting ceiling frame

Figure 5. Positioning additional drywall

B. When wall panels were set on the main line, workers noticed that window framing (Figure 6) was incorrectly sized. To repair the problem, workers had to tear out the drywall, rebuild the window opening to the correct dimensions, and then re-install drywall. A follow-up investigation indicated that the framers did not have a complete set of drawings.

Figure 6. Window frame in wall

C. As wall panels were set on the main line (Figure7), workers sometimes noticed that wall dimensions were incorrect. Line workers with the help of wall framers had to rebuild the panel before set. A follow-up investigation indicated that dimensions on the drawings were either incomplete or incorrect.

Figure 7. Lifting wall panel before set

D. In an effort to expedite the installation of electrical wiring in walls, wall framers tried to install electrical boxes while walls were on the framing table. Since framers did not have drawings showing the location of boxes, boxes were installed in the wrong location (Figure 8), causing later disruption on the main line. Framing activities were also disrupted during follow-up discussions with electricians.

Figure 8. Incorrect location markings for electrical boxes

E. Framers identify and mark panels (Figure 9) to indicate which side should have drywall installed first. Incorrect marking contributed to drywall being installed on the wrong side of the frame twice. In each case, drywall was removed and reinstalled on the correct side.

Figure 9. Labeled wall frames staged for drywall installation

F. Operators installed the wrong type of drywall (Figure 10) on the exterior of marriage wall. Rework required 4.25 labor hours.

Figure 10. Operator reworking drywall

G. Two incorrect closet doors were installed, requiring removal and replacement.

H. Drywall finisher productivity was roughly half typical industry rates (Figure 11).

Figure 11. Drywall finishing

A standard work plan should be documented for each major activity and posted prominently in the appropriate workstation(s). The plan should utilize graphics (e.g., pictures, drawings) whenever possible to communicate instructions. When multiple floor plans are produced for the same project, a unique work plan should be developed for each floor plan. When module variation (including customization) is allowed, the variation will be described in the traveler – the paperwork that accompanies the module through the process. The standard work plan should specify precisely how to efficiently fabricate, assemble and/or finish the module. It should include the sequence of manufacturing steps and the details of each step: 1) the materials (with dimensions) and their location, 2) the tools and equipment and their location, 3) the method – how the work will be performed, and 4) the logistics - who, where, when and at what rate the work will be performed. When the production rate changes during a project, the TAKT time or line cycle time will change, necessitating a change in these logistics and an update of the standard work plan. For example, an increase in production rate will require a reduction in line cycle time which will require an increase in labor which will require specific labor assignments within an activity to be rebalanced.

Sustain

Involvement is the key to sustain 5S improvements. Management should empower workers, set expectations, provide resources and hold workers accountable for their workplace.

2. Rationalize material staging and replenishment

Materials were often staged far from their point of use. Materials should be located as close to their point of use as practicable. Examples include:

A. Material staging locations in the floor framing workstation are not efficient . Stage rim joists, joists and galvanized blocking near the band saw (on the right side of the framing table). Stage joist hangers, nails, drywall and metal strips on the left side of the framing table.

B. Electricians consistently left their workplace to obtain electrical supplies. Most supplies were kept on a supply cart, however, this cart was seldom located at the point of use. At best, the cart was located immediately outside the current module being wired, requiring the electrician to leave the module (Figure 12). However, the 3-4 electricians wiring the walls were seldom working on the same module, requiring at least some electricians to interrupt their wiring and walk longer distances for supplies. Occasionally the cart would be left near a module where no-one was working. When an electrician walked to the cart to get supplies, they typically carried only a handful back to the point of use. A supply cart should be provided for each team of electricians that typically work together on the same module. Each team should keep their cart located close to the point of use.

Figure 12. Electrical supply cart staged outside module

C. Electricians often needed metal wall studs to mount panels (Figure 13). When studs were needed, electricians would walk to the wall framing area. Pre-cut wall studs should be located near the panel mounting location on the line.

Figure 13. Electrician installing panel

D. Exterior drywall sheets were staged two stations upstream from their point of use on the line (Figure 14). To replenish their cart, operators had to walk to this staging area. If drywall were staged closer to the point of use, carts could be eliminated, thus eliminating double handling.

Figure 14. Operators loading drywall onto cart

E. The mud mixing station is located six stations from the point of use on the main line.To replenish their buckets, operators had to walk to the mixing station.

Figure 15. Mud mix station far from point of use near end of line

When materials are unusable, they should be replaced with usable materials. For example, drywall was installed on the inside of each rim joist prior to framing. This drywall was staged near the point of use; however, it was considered unusable by the operator who routinely walked to another stack of drywall serving the main line (Figure 16).

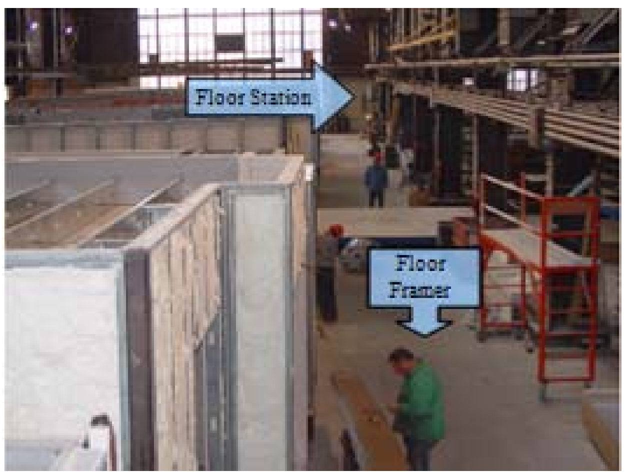

Figure 16. Dry wall staging

When operators depleted materials at their workstation, they often interrupted their assigned activities and walked excessive distances to the warehouse or stockroom to replenish. Examples include:

A. When the ceiling drywall installer ran out of screws, he walked to the warehouse to obtain more screws.

B. When the wall set crew ran out of materials, they walked to the warehouse.

C. When an electrician ran out of electrical supplies on the supply cart, he walked to the electrical stockroom located in the back of the plant. The electrician did not return for at least 20 minutes.

A kanban system should be used to replenish materials. A kanban is a visual signal indicating a need for more production or replenishment of material. For example, when the supply of screws in an area reaches a designated replenishment level (perhaps when one of two containers of screws is emptied), a kanban signal (perhaps the empty container) triggers replenishment from the warehouse. A utility/replenishment operator visually checks for kanban signals daily and performs the necessary replenishments.

3. Purchase right-sized materials

Improperly sized raw materials often lead to excessive processing, motion, and material waste. Examples include:

A. The rim joist on each long side of the ceiling frame was formed by welding four shorter components (Figure 17). One component requires cutting to size, also creating offal. Purchasing longer components, perhaps already cut to size, will minimize welding and offal.

Figure 17. Ceiling rim joist is made up of 4 components welded

B. Upper and lower steel tracks forming the top and bottom plates of the wall frame were formed by welding shorter components (Figure 18). Follow-up investigation indicated that the wrong size tracks had been purchased from the vendor. One component requires cutting to size, also creating offal. Purchasing longer components, perhaps already cut to size, will minimize welding and offal.

Figure 18. Upper and lower steel tracks for wall frame

C. Unlike other types of exterior drywall (Figure 19), yellow faced drywall used on the exterior of demising walls was not purchased in 12’ lengths. The sheets were cut and then lifted onto scaffold for installation, one piece at a time (Figure 20).

Figure 19. Installation of 12’ drywall sheets

Figure 20. Additional installation required for yellow drywall

4. Reduce welding

Welding is used extensively in the framing process. Welding is a slow, labor-intensive process that over the long-term degrades the vision of welders. Welding light gauge material is particularly difficult and risks destroying the protective galvanization on light gauge members. There are several approaches for reducing welding. First, the need for welding smaller components together to form longer linear components can be eliminated simply by purchasing longer, right-sized materials (see sections 3.A. and 3.B. above). If steel framing tracks must be combined linearly, they can be spliced by screwing into scrap stud pieces, since the connection is not structural. Some connections cannot be eliminated. For example, connection of rim joists, joist hangers, transverse joists, blocking hangars, and blocking requires considerable stitch welding in ceiling and floor framing (Figure 21). Potential solutions include replacing stitch welding with other fasteners, such as spot welding, nailing/drive pins (Figure 22), or bolting. Both Senco and Ramset have indicated that they would be willing to demonstrate their guns at the plant.

Figure 21. Floor framing- rim joist and joist hangers welded

Figure 22. Alternative fasteners (Source: http://www.ramset-redhead.com)

At a minimum, welders should use the relatively inexpensive (~$200) auto darkness/ LCD helmets, which are safer and improve productivity by eliminating the need to flip the mask up and down (Figure 23).

Figure 23. Current welding helmet

5. Use the right tool for the job

Better tool selection will minimize wasted processing time. For example:

A. The band saws used to cut components in the ceiling framing and floor framing areas were not being used to its potential (e.g., bulk cutting). At most two blocks were cut at one time (Figure 24). If bulk cutting will not be used, a chop saw with a diamond blade will be a better choice for smaller volume cuts.

Figure 24. Cutting two blocks at one time

B. Wall framing requires many screw attachments (Figure 25). Each is time consuming. Replace screws with other fasteners, such as nails/drive pins. Both Senco and Ramset have indicated that they would be willing to demonstrate their guns at the plant.

Figure 25. Wall framing using screw attachments

C. Replace the grinding wheel used to cut metal wall framing components with a chop saw with diamond blade.

D. A corded electric drill with manual feed of screws is the standard tool for assembling light gauge framing components and installing drywall (Figure 26). Replace the slow manual feed drills with auto-collating screwdrivers.

Figure 26. Manual feed drills

E. Drywall and sheathing trimming - Replace the slow manual drywall saw with a power router (Figure 27).

Figure 27**.** Manual drywall saw

6. Use jigs

Operators spend substantial amounts of time examining plans, measuring dimensions and marking locations for the same parts repeatedly (Figure 28). Yet errors still occur and rework is required. To improve productivity and reduce rework, construct or mark simple low cost jigs to guide repetitive assembly operations. Examples include:

A. Ceiling, floor and wall framing - Use scales or jigs to measure the distance between joist hangars/studs and to square components.

Figure 28. Operator measuring and marking location for joist hangers

B. Ceiling drywall installation - When two operators lifted a ceiling frame on top of the jig, they noticed that insufficient drywall had been pre-positioned on the jig. They had to relift the frame and position additional drywall (Figures 4,5). A potential solution is to measure and mark the surface of the jig indicating the perimeter of drywall required.

C. Ceiling drywall installation - Attaching drywall to the underside of the ceiling frame using screws is a long and tedious process. Each joist location behind the drywall has to be snapped with a blue line and then screws fastened (Figure 29). A potential solution is to add lights (possibly lasers) to indicate joist positions. The plant might also consider the use of a foam adhesive similar to that used in wood frame modular ceiling assembly.

Figure 29. Operator attaching drywall onto the ceiling frame

7. Spread line activity by moving work upstream

Too many activities have migrated to the end of line (Figure 30). Drywall finishing takes place at the next-to-last station, forcing all subsequent activities (sand, paint and all finish activities) to the two parallel stations at the end of the line. This is far too much activity in too little space and time to guarantee quality. At the same time, upstream modules often sit idle.

Figure 30. Many different trades work on the same module at the end of the line

To resolve this problem, work must be moved upstream: drywall finishing must be completed earlier, which means drywall installation must be completed earlier, which means electrical wiring must be completed earlier. It is believed that electrical wiring is a critical bottleneck in the process, forcing all subsequent activities downstream. The following section describes opportunities for expediting electrical processes.

8. Expedite electrical processes

Electrical processes have been identified as one of the most problematic areas in the plant. Examples include.

A. Ceiling wiring

i. Ceiling wiring activities were clearly disorganized. Wiring took place on the wiring cart at floor level (Figure 31) and on the main line after the ceiling was set (Figure 32) . It was clearly more difficult (up to 25% less efficient) and less safe on the main line, with the electrician elevated and forced to walk on the ceiling joists instead of the drywall. All ceiling wiring should be performed on the wiring cart. This is not only more efficient and safer, but also allows all subsequent activities to be started earlier.

Figure 31. Wiring ceiling on ceiling cart at floor level

Figure 32. Electricians wiring ceiling after set on module

ii. Electricians seldom wired a ceiling without interruption. Instead, they were directed (or wandered) from module to module, interspersing ceiling wiring with wall wiring (Figure 33). Electricians responsible for ceiling wiring should complete each module (on the wiring cart) before moving to another module.

Figure 33. Electrician interruptions

iii. Pulling wiring in corrugated conduit through the punch outs in the metal ceiling joists was difficult. Often requiring two operators (one to feed and one to pull), it became even more difficult as more wiring was run through the same punch out (Figure 34). Improvements might include: plastic inserts in punch outs; run wiring over joists (in 1st floor ceiling); use truss joists (e.g., JoistRite).

Figure 34. Pulling wires

iv. Electricians appeared to have difficulty locating electrical boxes for ceiling fixtures. The standard work plan (see 1. above) should clearly specify where each box is placed for each floor plan. Electricians should be trained to read the work plan and install boxes according to the plan. Ideally, with the proper line balance, boxes might be installed earlier on the ceiling framing table. If this is possible, the table might be marked to indicate box location.

B. Wall wiring

i. In most cases, electricians installed electrical boxes in walls after the ceiling had been set (Figure 35). This delayed completion of wiring installation. Electricians could install electrical boxes as soon as walls are set. Given proper line balance, boxes could be installed even earlier, during wall framing.

Figure 35. Installing electrical boxes after ceiling set

ii. In the few cases where framers installed boxes, they were often installed at the wrong location. Electricians also installed boxes in the wrong location (Figure 9). Corrective action to relocate the boxes was required by framers and electricians (Figure 36). The precise location of electrical boxes should be included on the standard work plans of both wall framing and electricians.

Figure 36. Electricians with framers discussing location of boxes

iii. Wall outlets were typically wired through the ceiling rather than through walls. This required the ceiling to be set before wiring could begin. Running outlet wiring horizontally through walls would minimize wiring in ceiling, reduce labor, reduce wiring length and allow wall wiring to begin before the ceiling is set.
iv. Instead of moving continuously from one module to the next module on the line, electricians responsible for wiring walls often appeared unsure of their next module. Once started, electricians seldom completed a module without interruption. Instead, they were directed (or wandered) from module to module, interspersing ceiling wiring with wall wiring. They seldom worked as a team on the same module. Instead they worked on as many as three modules at the same time. These factors disrupted any continuous workflow by the electricians and bottlenecked all downstream activities. The wall wiring team should move continuously, completing each module before starting the next module on the line.
v. Electricians should keep the material supply cart adjacent to module they are working on (see 2.A. above), including a stock of pre-cut wall stud components for mounting panels (see 2.B. above).

9. Create sub-assembly cells

The three progressive assembly workstations (framing, drywall installation and wiring) in the ceiling assembly area are operated independently. However, their operations are not independent. For example, drywall installation is tightly linked to wiring, since the ceiling cart must be empty before a ceiling can be moved from the drywall installation jig. The ceiling staging area between framing and drywall installation partially disconnects drywall installation from framing, but at the cost of double handling frames and carrying excess WIP inventory.

The need to synchronize flow between workstations is complicated by the need to better utilize the three operators working in the area, who are less than fully utilized at the current production rate. These operators were routinely observed to be absent from their workstation, sometimes performing other activities to fill their idle time.

A potential solution to this situation is the lean concept of cellular manufacturing, coupled with the concepts of balanced workloads, continuous flow and kanban-driven production. Treating the three workstations as part of the same manufacturing cell, total work (average labor hours) within the cell would be calculated for the production cycle. This work would then be used to determine the total manpower needed within the cell – likely two operators instead of the three currently assigned. Workload would then be balanced between the two operators. For example, one operator (the welder) might be totally assigned to welding and partially assigned to drywall installation. The other operator, an electrician, might be totally assigned to wiring and partially assigned to drywall installation. Together, their job is to move one completed ceiling out of the cell each production cycle. Within the cell, production can be kanban-driven. For example, instead of continuing to frame until we fill up the staging area (resulting in double handling and excess WIP inventory), we can eliminate the staging area and use an empty framing table as the visual signal for the welder to start framing the next ceiling.

A pure cellular manufacturing solution ignores the issue of skilled trades, pay differential and union labor rules. For example, the welder builds frames (primary task) and also helps to install drywall (secondary task). If this pure cellular solution is not possible, then one might consider the concept of skill-focused virtual cells. Here, each virtual cell is defined by function rather than the part/product produced. For example, the welding activities in both floor and ceiling framing areas might be combined in a virtual “welding cell”, where the welder(s) move between workstations and accomplishes both tasks during the same production cycle. Although this approach has the advantage of focusing and minimizing highly skilled (and high cost) labor, it may not result in the continuous flow provided when workers are assigned to a more limited area and focused product.

The cellular manufacturing concept can also be applied to the wall assembly (window/door opening framing, wall framing and drywall installation) and floor assembly (framing and plumbing) areas (Figure 37).

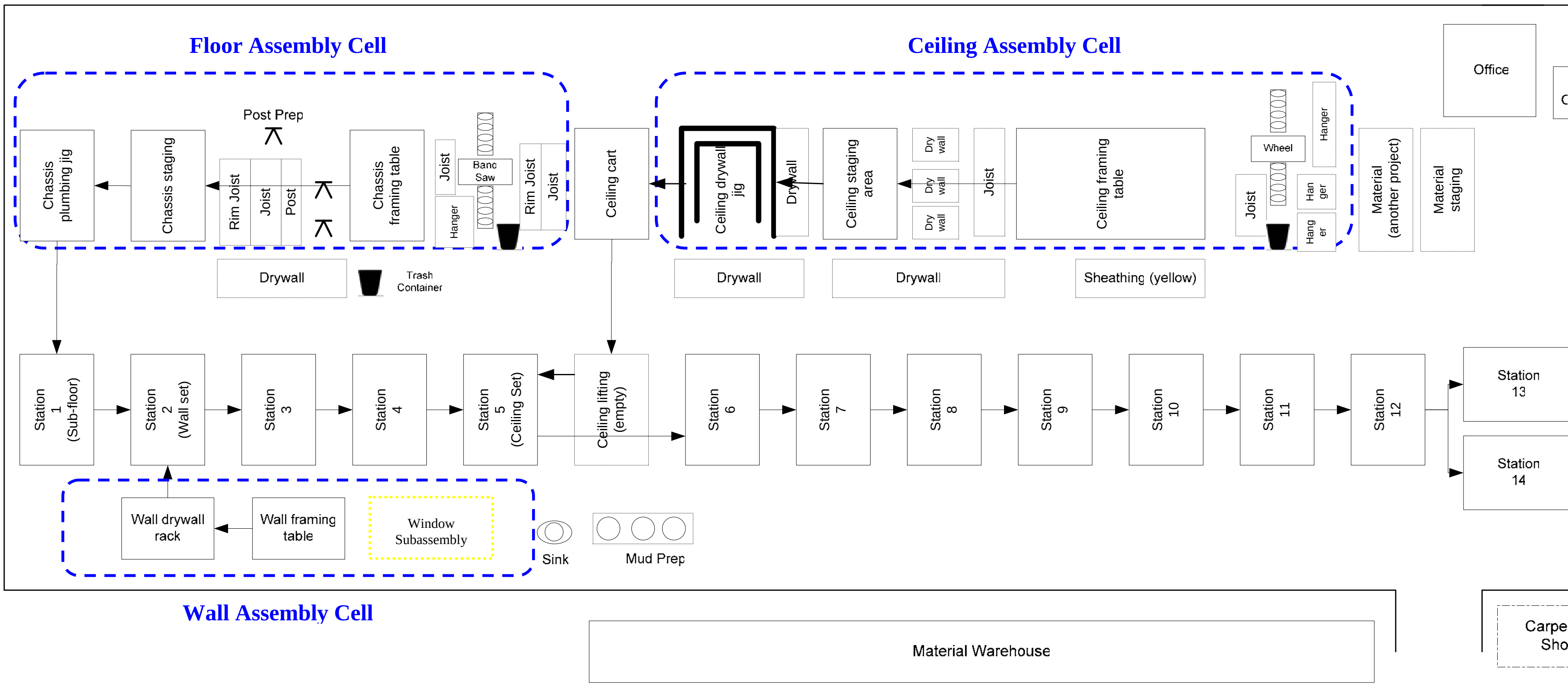

Figure 37. Layout of factory showing potential production cells

10. Re-engineer roof slope

Upper level modules have pitched roofs (8” pitch over 40’) to provide drainage. To provide this slope, wall studs are cut at progressively shorter lengths, creating many different work in process components. To increase efficiency, these studs are cut in batches and stored as excess work in process (Figure 38). This design approach results in stud to top track connections that are difficult and sometimes of poor quality. It also requires the production of truss assemblies to square the façade (Figure 39). Finally, it affects the look of the ceiling inside the module. Potential solutions include changing the approach to providing roof slope: use flat walls and pitch the joists in the ceiling frame or build flat walls and ceiling frames and create the slope using built-up roof insulation as is typical in commercial roofing.

Figure 38. Different length wall studs cut in batches

Figure 39. Wall slope and corrective trusses