



# **Concept Home Principles -** ***Improved Production Processes***

## **Research Summary**

June 2005

## Acknowledgements

Preparation of this report was coordinated by Dr. Carlos Martín of the U.S. Department of Housing and Urban Development's Office of Policy Development and Research. The text was developed by Christine Barbour, Liza Bowles, and James Lyons P.E. and reviewed by Mark Nowak of Newport Partners, LLC.

### Disclaimer

The statements and conclusions contained in this report are those of Newport Partners LLC and do not necessarily reflect the views or policies of the U.S. Department of Housing and Urban Development or the U.S. Government. The authors have made every effort to verify the accuracy and appropriateness of the report's content. However, no guarantee of the accuracy or completeness of the information or acceptability for compliance with any industry standard or mandatory requirement of any code, law, or regulation is either offered or implied. The products and systems described in the report are included only as examples of some available choices. No endorsement, recommendation, or evaluation of these products or their use is given or implied.

<i>Performance Objectives</i> .....	3
<i>Supporting Technologies &amp; Design Approaches</i> .....	4
<b>Factory Building</b> .....	<b>4</b>
Factory-Built Housing .....	4
Factory-Built Components, Panels and Kit Homes .....	7
On-Site Production Innovations .....	16
Hybrid Housing.....	16
<b>Information Technology &amp; Mechanical Innovations</b> .....	<b>17</b>
Use of Information Technology in the Production Process .....	17
Improvements in Communications Tools .....	17
Radio Frequency Identification (RFID) .....	18
Construction Robotics.....	18
<b>Manufacturing Innovations</b> .....	<b>19</b>
<i>Conclusion</i> .....	22
<i>Reference List</i> .....	23

# Concept Home Principles - *Improved Production Processes*

## Research Summary

### Background

The homebuilding production process entails the complex arrangement and scheduling of thousands of products and materials and numerous labor resources required to construct a home. Using traditional construction methods, this process may take several months and include unexpected delays that cost builders, contractors, and homebuyers money and jeopardize quality. Employing innovative production processes can streamline scheduling, minimize unexpected delays, reduce material waste, and improve the quality and efficiency of construction.

As stated in PATH's "Industrializing the Residential Construction Site" research series, there is much work yet to be done.<sup>1</sup> Although automation of factory manufacturing processes is considerably advanced in many fields at present, the design and construction of houses has seen only limited progress in automation and industrialization. The home construction industry is still very much de-pendent on manual labor and labor-intensive processes. Furthermore, when compared to other industries, home building has a reputation of low productivity, waste, and antiquated technology. The introduction of industrial methods and technologies to the housing industry promises to change the current practices of building and construction.

An industrialized housing industry is a vision that is attainable through practical innovations in current systems and technologies. We have already seen a move towards industrializing the industry, like small site factories, modular homes innovations, and prefabricated structural panels. In fact, we have seen numerous examples of this throughout modern American history.

The concept of industrialized housing in its most rudimentary form goes back to the mid-1800s, when prefabricated components were shipped from the east coast of the United States to

California and Australia during their gold rushes, as were army field barracks during the American Civil War. In the late 1800s and early 1900s, precut kit houses could be ordered directly from catalogs from companies like Sears and Roebuck. During the 1920s and 1930s, many prominent architects and engineers began to experiment in mass-produced housing. Steel, sheet metal, tubular pipe, aluminum, wire, and glass were materials considered appropriate for manufactured housing. In the 1930s Howard T. Fisher, in an effort to make home building friendly to the average homeowner, pioneered the system of prefabricated, wood-stud panels still in use today. Following Fisher into the 1940s was the development of "trailers." These trailers were constructed based on current aircraft manufacturing techniques, with Spartan Aircraft building the first trailer designed as

The construction of homes in the United States has reached record highs over the last few years. While the homebuilding industry has made incredible advances in materials and quality, it still lags behind other industries in technological innovation in production – that is, in providing new homes more quickly and more efficiently while still keeping homes affordable and at a high standard. There is much to be done, and there is much that all of the homebuilding industry would like to see done.

- *Industrializing the Residential Construction Site*, HUD, 2002

---

<sup>1</sup> O'Brien, Wakefield, and Beliveau (July 2000). Much of the following discussion comes from this groundbreaking work.

a house. In 1954 Marshfield Homes introduced the revolutionary “ten-wide,” and the prototypical “mobile home” was born (Obiso 1998).

At the same time, much progress was demonstrated on site, as demonstrated in the late 1940s through early 1950s in places like Levittown, New York. Following World War II, there was an urgent need to house 12–16 million Americans as rapidly as possible. At Levittown, site-built housing used industrialized production similar to an on-site factory. Production techniques mimicked industrial processes, with workers following a lot-to-lot, assembly-line process. The construction consisted of a limited number of standard models that were repeated throughout the subdivision, using precut lumber combined with conventional construction techniques and technology.

There is also a long history of federal government support for improved production processes in the housing industry. One notable effort is Operation Breakthrough, which was conducted in the 1960s and 1970s. Through this program, major barriers to the industrialization of housing were identified. These included the lack of unified building codes, the fragmentation of the housing market, public perceptions of the inferiority of factory-built housing, and the reluctance of financial institutions to provide permanent financing for factory built housing units (O’Brien, et al., 2000). Though inroads have been made toward a unified building code and financial institutions increasingly offer financial products to meet industry needs, all of these issues could still be considered as barriers today.

More recently, we have witnessed such changes among some of the production builders in the US industry, particularly those that have advanced very complex project management technologies through information and communication exchanges as well as advanced manufacturing supply models. Groups like Pulte Home Science who combined advanced product innovations with streamlining are at the forefront of such change. However, for the industrialization of all housing to have the same benefits that the industrial revolution offered to other products (lower cost, better quality, and faster production), there needs to be a directed change in the current housing delivery system.



Victorian house constructed with a hybrid modular and panelized approach  
Source: ToolBase Website  
([www.toolbase.org](http://www.toolbase.org))

These potential benefits establish Improved Production Processes as a key Concept Home Principle. Builders and contractors stand to realize benefits such as reduced construction time and reduced exposure to weather impacts, while homebuyers benefit from the improved quality that results from production innovations. Production process improvement is a broad topic ranging from factory production to applications of information technology. Given the breadth of the topic and the focus of the Concept Home program, this report attempts to focus the discussion to those topics with greatest potential contribution to the Concept Home while still posing a needed long-term vision.

Due to the great variety of builders, building materials, local environments, and housing styles, many production innovations have been attempted within the industry. Innovations vary in their scale and focus, from production methods in which housing is almost entirely built in a factory setting (e.g., modular and HUD-code construction) to design innovations which optimize material utilization (e.g., OVE framing), to applications of information technology to housing production.

From the consumer perspective, homebuyers may not perceive production improvements that reduce construction time in the same manner that builders view this benefit. In fact, current market research indicates that homebuyers view housing that is constructed more quickly than by traditional methods as “probably not well built.” In a related finding that highlights a gap in understanding between builders and buyers, *builders* felt that their customers would actually place a high value on a home that was built quickly.

Builders clearly value production process improvements like reduced on-site waste, and feel that factory-built components (e.g., trusses) offer benefits like reduced construction time and improved quality (Newport Partners, 2005). Major factors that can limit the effectiveness of standardized production methods cited by builders include the variability of building sites available today and the non-uniformity of local building code requirements.

## **Performance Objectives**

Improving housing production processes requires navigating through a plethora of technical, regulatory, and market issues. Technical challenges include optimizing a complex collection of factors involving production volume, design standardization, labor, materials, implementation of information technology, and site characteristics. Regulatory challenges include issues like non-uniform building code requirements, which were cited as an obstacle to increased industrialization decades ago, yet are still cited by builders today as a major barrier to standardized production methods. In terms of market challenges, builders recognize the potential benefits of process improvements like reduced construction time, reduced waste, and improved construction quality -- but don't want to give buyers the perception of a hastily constructed, low-quality home.

Constructing either components or entire housing modules within a factory setting can increase quality and reduce on-site construction time, yet the “factory-built” image may elicit negative consumer perceptions from some segments of the market. This paper explores innovative approaches to production processes that address these issues and offer potential for the Concept Home.

“Improved Production Processes” focuses on innovative construction methods and building technologies that can improve construction quality, reduce production time, and improve labor and material utilization during the homebuilding process. Improved production holds direct benefits for builders through more consolidated construction schedules and labor and materials savings, while also benefiting innovative manufacturers of systems which streamline production. Consumers benefit indirectly from a more predictable construction timeline and the opportunity for improved quality.

It should also be noted Improved Production Processes relates closely to the Concept Home Principle of Standardization, which is explored in a separate report. In many of the production processes laid out below, standardization of components or entire building modules is a key theme which helps to provide production efficiencies.

## **Supporting Technologies & Design Approaches**

The sections below offer examples of methods, technologies, and processes that support improved production of single-family houses. The methods reviewed in this report represent a cross-section of approaches for improving housing quality and design, reducing production time, and optimizing labor and material utilization. These reviews are not all inclusive, but instead illustrate that there is a wide range of methods to improve production efficiency. While general information on the applicability of these methods is included, their effectiveness for an actual project would depend on relevant factors such as housing density and style, site considerations, labor availability, climate, transportation infrastructure, and land availability.

### ***Factory Building***

Factory building encompasses several forms of housing production which involve industrialized production techniques. Factory-based production approaches include factory-built housing, factory-built components and kit homes, on-site production (using industrialized methods), and hybrid production. Each of these categories relies upon a more industrialized approach than traditional stick-building of houses on site to realize production improvements. The general characteristics of these approaches as well as some advantages and limitations are discussed below.

### **Factory-Built Housing**

Manufactured housing (HUD Code) and modular housing are both well established categories of factory-built housing substantially constructed within a factory environment. They are treated together for the purposes of this discussion as the similarities for production processes outweigh the differences. Both types of housing hold several potential benefits, including:

- improved utilization of labor and materials;
- reduced waste;
- increased quality control;
- minimized production impacts from weather conditions;
- enhanced protection of building materials during construction; and
- increased safety.

Each of these benefits can result in a steady, predictable production flow and reduced production costs. Some of the cost advantages which can be realized in production, however, may be offset by transportation expenses and restrictions, or the work associated with integrating factory components with site-built features.

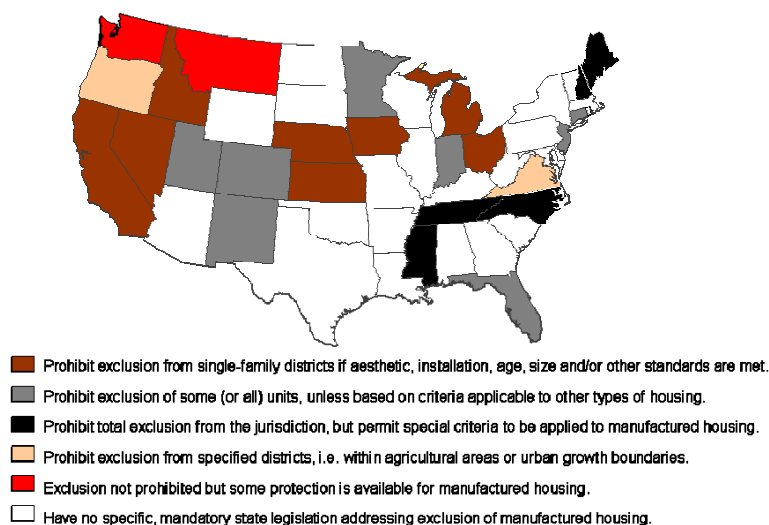
## Barriers

There are also barriers based on:

- 1) limitations of the production method;
- 2) zoning and regulatory restrictions; and
- 3) market-based perceptions of the product.

Production-based limitations for modular and HUD-Code homes revolve around the fact that the factory-built approach creates units or modules of a standardized size and shape. More complex house designs that call for numerous corners, complex roof structures, or numerous architectural features will likely not be appropriate for this method of production. Factory-built homebuilders in other countries have approached this barrier by providing a great deal of buyer customization options for interior and exterior features, but all within the standardized framework of the basic unit dimensions and shape. For example, in countries like Japan buyers of factory-built homes are typically not given the option of bumping out a wall to enlarge a room, but they are given extensive options to select their finishes and interior products (Levy, 2005).

Zoning and regulatory barriers may strongly impact both modular and HUD-Code although barriers to HUD-Code homes are more prevalent. Regulatory barriers at the local level may include minimum roof pitch requirements, minimum building footprint requirements, or even outright restrictions of the placement of HUD-Code houses in a jurisdiction. Restrictions of this nature are often driven by a fear of negative property value impacts and concerns about the burden that manufactured home developments will impose on municipal services. In response to these issues, a number of states have enacted legislation designed to provide a “level playing field” for manufactured housing. (See map below). This state legislation is typically aimed at preventing communities within the state from specifically excluding manufactured housing or creating design requirements that only apply to manufactured housing.



Map of State Laws Regulating Local Zoning of Manufactured Housing  
Reproduced from *Home Builders' Guide to Manufactured Housing*. HUD 2000.



Market-based barriers may include perceptions of factory-built housing as “cookie-cutter” homes; negative perceptions of “mobile” homes and trailer parks communities (Beamish, 2001); and the impact of reduced cycle time on perceptions of quality (Concept Home Survey 2005).



*PATH Concept Home Consumer Focus Groups*

The results of PATH Concept Home focus groups conducted in 2004 suggest that consumers are skeptical of the quality of materials used in factory-produced homes. The underlying basis for their skepticism is their perception of old-style trailer parks and their associated demographic (Beamish, et al., 2001). The PATH program is currently conducting a broad consumer survey investigating perceptions of all types of factory-built housing that is expected to be completed in late 2005.

### Production Advancements

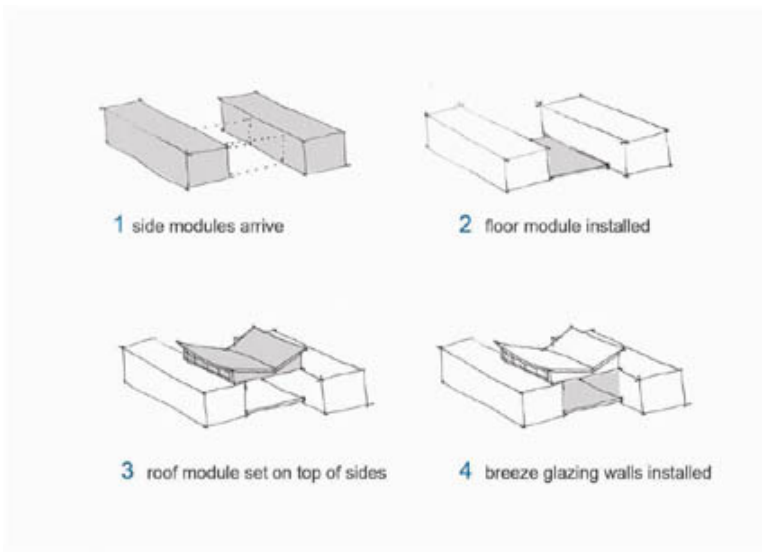
Neither manufactured nor modular production approaches are new, but segments of this production area have undergone continuous improvement in design and construction techniques that have made them more competitive and increased their potential markets. For example, one distinguishing characteristic of manufactured and modular housing has traditionally been a lower slope roof pitch. The roof pitch was driven by transportation requirements for the housing modules, with the lower pitch allowing shipments to pass beneath highway overpasses. Recent advancements have brought about systems that allow a high-pitched roof to fold flat during transport. These systems involve the use of hinged connections that allow the roof to fold down into sections, gable-end planes that are erected on site, and a ridge section that is also installed on site. For modular homes, a higher pitched roof can accommodate the use of a second-floor area for additional living space. One manufacturer estimates that adding unfinished second floor space, including stairs and floor decking, adds costs of roughly \$3500. The higher pitch roof can achieve designs more suitable for infill housing applications.



Drawing of Finished Home Using Tilt-Up Roofing  
Image Source: ToolBase Website ([www.toolbase.org](http://www.toolbase.org))

Other design and construction advancements include two-story designs for both manufactured and modular units, integration of the chassis into the floor system of HUD-code homes, and even the development of wood chassis systems.

One example of an innovative approach to modular construction is the Breeze House. The uniformity and standardization of modular construction drives the efficiencies of the process, but can also detract from the ability to customize a home or a development. MK Architecture works to incorporate an innovative approach to customization on the community scale using modular housing. In the Breeze House the design approach focuses on customization while still maintaining the efficiencies of standardized, factory-built unit. Buyers may make changes to the to the center, or “breeze”, module, while the other two or three modules that make up the home are not changed. Further, the modules can be combined in different orientations, creating a community which appears to be made up of different, more customized home designs.



Breeze House Image and Site Construction Process

Images Source:  
[www.michellekaufmannndesigns.com](http://www.michellekaufmannndesigns.com)  
 Copyright 2004 Michelle Kaufmann Designs.  
 All rights reserved. All designs, renderings and ideas are under copyright and owned by Michelle Kaufmann Designs.

### Factory-Built Components, Panels and Kit Homes

Another building method that takes advantage of factory production efficiencies involves the use of factory-built components and panels. “Components and panels” is a broad term that encompasses individual elements like floor or attic trusses as well as system assemblies like wall panels, floor decks, and pre-cast foundations. Given the breadth of this production approach, the use of factory-built housing components is increasingly common. In fact, the demand for factory-built components including roof trusses, floor trusses, I-joists, and wall panels more than doubled from 1992 to 2001, according to Structural Building Components magazine (based on data from the report “Factory Built Housing Components”). Further, the magazine learned from discussions with forest product marketing executives that key drivers for the increase in “componentization” in

homebuilding include labor shortages, jobsite waste concerns, and consolidation within the building industry.

The potential production benefits of using factory-built components or panels include:

- improved quality;
- reduced on-site construction time and a shorter project cycle;
- reduced reliance on skilled labor;
- a shorter amount of time to get a building dry and under cover; and
- reduced material waste and a cleaner site.

In some of the examples discussed below, these benefits are further enhanced through the use of automation, vertical integration, and information technology tools that integrate design, engineering, and production.

However, there are also challenges and limits to the successful application of factory-built components. These include:

- Scheduling: using factory-built components may require different product ordering and scheduling processes;
- Impacts of changes: factory-built components may be less adaptable to late design changes or inaccurate as-built dimensions;
- Building codes: the use of a standardized production approach relying on factory-built components may face challenges from building code requirements that vary from one jurisdiction to the next;
- Incentive to change: depending on their volume and market, some builders may not have adequate incentive to adopt the use of certain factory-built components; and
- Geographic location: some builders may not be close to factories that produce certain components (e.g. wall panels), which can increase costs.

As an example, factory-built wall panels are often considered as a potential means to improve the production process. Factory-built wall panels are typically designed from software which generates wall panel specifications based on a building plan. Walls are then constructed within a factory setting with greater control over labor, materials, and the working environment. Wall panels can typically be ordered with or without sheathing and siding, and even with insulation and windows installed. The panels may be load-bearing or non load-bearing, and include exterior walls as well as interior partitions.

In more automated facilities, panels can be fabricated with minimal labor and material handling from wood members or alternative materials like Structural Insulated Panels (SIPs). SIP panels consist of two pieces of oriented strand board (OSB) laminated to both sides of a rigid foam core, forming a sandwich which is adequate for load-bearing applications. SIP wall panels will have channels cored in the foam section for the electrical runs, and may even have electric lines pre-

installed in the factory. If electric lines are pre-installed, modular connectors can be used to easily connect the lines in wall panels once they are erected on site.

Another alternative material used for panels is light-gauge steel framing, which is often used for interior partitions but can also be used for load-bearing panels as well. An example of a prefabricated steel panel operation is found later in this report. Following fabrication in the factory, wall panels are shipped to a building site. Panels can be reverse-loaded on trucks, so they are erected on site in the order that they are unloaded.

The potential benefits of this approach include smaller on-site framing crews, a shorter timeframe for framing a house (even with a smaller crew), reduced impacts from weather, improved price stability because of factory material volumes, and reduced onsite waste. And, if factory-built walls are used for a number of homes with a similar design, the builder can continue to make improvements in the panel design and layout on each successive house to further improve quality and production efficiency.

Some potential challenges (Ruiz, 2005) of this same approach include:

- *Timing the Order and Delivery of the Wall.* Factories require lead time to design and construct wall panels. Pouring the foundation and getting exact foundation measurements, and *then* ordering the wall panels is the safest approach, but can also create on-site delays while the walls are constructed. A quicker alternative is to order the panels based on the building plan and taking measures to ensure the foundation is formed exactly per plan. This is the greatest “learning curve” issue with using factory framed walls.
- *Impacts of Plan Revisions.* Making major floor plan changes like reversing the orientation of the house once the wall panels are built in the factory can create major problems and undermine the production efficiency of using factory-built panels.

Other factory-built components with the potential to improve cycle time and quality include the following.


- **Open web floor trusses** represent the predominate type of floor truss used in homes today. They typically consist of a wood top and bottom flange, usually Laminated Veneer Lumber (LVL) or 2x4 materials, and wood web materials connected at joints with metal plates. Some manufacturers are also using steel framing for the web. These members offer potential benefits of enhanced span capabilities (often used in 20' to 24' spans) and room to accommodate mechanical system runs within the web area.
- **Trim-able floor trusses** are open web floor trusses with a length at the end that can be cut to exact dimensions in the field. This reduces the need to have exact dimensions when ordering the members and makes it easier to adjust to as-built conditions. One trim-able product is a hybrid of truss and I-joist technology. The main part of the truss has steel webs with the top and bottom



Open Web Trim-able Floor Truss

flanges made from LVL or 2x lumber. The web material for a short distance on each end is made from OSB, effectively forming an I-joist on each end that can be trimmed as needed.

A second type of trim-able open-web floor truss is an all wood truss. This product has a section of dimension lumber on the ends as opposed to an I-joist. It does not rely on truss plates for connections like most open-web wood trusses. Rather, the flanges and webs are connected using finger-jointing technology.

- **Pre-cast concrete foundation panels** are manufactured off-site, trucked in, and lifted into place with a crane. This production approach reduces construction time and improves quality by avoiding weather delays that can hamper foundation pouring on site. Within a factory setting, raw materials like sand and aggregate are kept under controlled conditions prior to batching, and once foundation panels are poured the walls are allowed to cure in a controlled environment. Superior Walls ([www.superiorwalls.com](http://www.superiorwalls.com)), a manufacturer of pre-cast concrete foundations, also produces a foundation panel which provides for an insulation cavity and interior framing (like an above-grade wall), in addition to the foundation itself.
- 
- **Prefabricated floor systems** can be constructed in factory settings and then lifted into place on site. These assemblies often incorporate the truss products mentioned above. Constructing floor assemblies in a factory setting can allow the use of material handling equipment and automated cutting and fastening tools. This production environment allows for the use “jumbo” OSB sheets (8' x 24') in floor assemblies, which reduces the number of components to assemble and also the number of seams in a floor system.
  - **Pre-fabricated roof systems** can also be constructed in a factory setting and are can then craned into place on site. Several potential systems are available:
    - SIP roof panels typically consist of two 5/8" sheets of OSB bonded in a sandwich fashion to solid foam insulation in thicknesses from 5 1/2" to 9 1/4". These panels are unvented. There are also metal SIP roof panels available in which the OSB is replaced with steel or aluminum facing. These are used more often for commercial or industrial purposes.
    - Another pre-fabricated roof product is a vented panel system that is available in 4' wide by 8' – 20' long sections. It uses a rigid insulation board with a vented space above the insulation to cool the roof covering and to help prevent ice dams. The top surface of this panel is plywood, while the finished (down-facing) surface is determined by homeowner (drywall, wood, etc).
    - A more leading edge system consists of pressure-laminated composite panels that use either fiberglass reinforced plastic, polyethylene, or aluminum skins over a variety of materials to accommodate a wide range of applications. The panel sizes range from 4' x 8' up to 5' by 12' and are used for roofs, as well as walls, floors, and doors.

- **Prefabricated cores** for bathrooms, utility areas, or even kitchens have been researched as a means to improve production efficiency, especially in multi-family housing. The core essentially contains much of the equipment that would otherwise be field-installed in a house, such as plumbing lines, HVAC ducts, and fixtures. By prefabricating these components into a factory-built product of standardized dimensions, significant time and labor savings during field installation may be realized. One major hurdle to the successful use of prefabricated cores is the need to use cores of standardized size and configuration. Utility core systems are discussed further in the Separation of Home Systems report.

#### Factory-Built Component and Panel Projects

While the use of factory-built components and panels has become fairly common, there are also innovative applications which seek to further improve on the production, construction quality, and material utilization benefits of this approach to building. Several notable efforts are summarized below.

**Integer Millennium House** This demonstration house in the United Kingdom features themes of sustainability, prefabrication, and production efficiency ([www.integerproject.co.uk/watford.html](http://www.integerproject.co.uk/watford.html)). Production innovations included:

- Prefabricated concrete floor slabs to minimize on-site concrete work;
- An integrated design and procurement system in which CAD files were shared directly between designers and the manufacturers of prefabricated components to expedite production;
- The use of a central utility core to vertically route mechanical systems like pipes and wiring within the home; and
- Incorporation of prefabricated bathroom modules which were designed for offshore oil platforms. (Modules were lifted into place as fully completed rooms, which minimized on-site plumbing work).



Integer Millennium House  
Source: [www.integerproject.co.uk/watford.html#team](http://www.integerproject.co.uk/watford.html#team)

Each of these innovations was designed to reduce on-site labor and construction requirements through factory-built components or production processes. The use of utility cores is discussed further in the Separation of Home Systems report.

Another feature of the Integer Millennium house - pre-built bathroom modules – could reduce costs and on-site labor requirements by shifting the construction of bathroom components to a standardized component made in a factory. The effective application of prefabricated modules for bathrooms or kitchens, however, requires standardized room dimensions and configurations such that a large volume of these modules can be cost-effectively made in a factory setting.

**Pulte Home Sciences**, the research and development arm of Pulte Homes, recently opened a 119,000 square foot panel factory in Manassas, VA. The Pulte Home Sciences (PHS) facility is a unique operation which incorporates many of the production process innovations discussed in this report. Innovations include prefabricating most of the building shell including pre-cast foundation panels, SIP exterior wall panels, steel-framed interior wall panels, and floor assemblies supported by open-web trusses with steel webs. Further, the PHS factory utilizes integrated software and automated production processes to a large extent. This enables a paperless system that integrates design, development of product specifications, and fabrication that customizes the design and production of each individual house. Process automation also facilitates software-driven processes like automated fastening of large OSB sheets to floor trusses. This automation allows for the creation of larger, more economical assemblies within tight tolerances, while also reducing labor requirements.



Prefabricated wall panel being set on a site  
Source: Washington Post, Photo by James A. Parcell

The PHS approach is designed to offset challenges that Pulte, and many other homebuilders, face. These include a lack of skilled labor, inconsistent material quality, and susceptibility to weather-related delays and construction impacts. Using the PHS factory-built panel approach, a typical building shell is erected on site within 3-5 days, as compared to 20 or more days using traditional methods. In addition to this construction cycle, Pulte feels that this approach enhances their construction quality and helps them to control factors which impact their scheduling and costs. Despite these benefits, PHS cites varying building codes from one jurisdiction to the next and transportation regulations as persistent challenges to its operation (Pulte 2005). It should also be noted that a market of roughly 1000 homes per year is the estimate of the minimum market required to justify an investment of this level. Many more of the unique features of the PHS facility are detailed in the case study below. The PHS case study also includes process improvements that relay on IT innovations discussed in the next section entitled, *Information Technology Innovations*.

---

---

### **Case Study of Improved Production Processes - Pulte Home Sciences**

In developing its Virginia production facility in the late 1990's, Pulte Home Sciences (PHS) sought to improve the quality of its construction while also reducing the company's exposure to material quality issues, labor and material shortages, and weather-related problems - all of which strongly impact costs. Critical goals for homes produced through the PHS facility include:

- Enhancing the speed, quality, and durability of construction;
- Simplifying field processes;
- Improving thermal and moisture management performance;
- Enabling customized production within the factory setting.

One strategy to achieve these goals is to reduce the number of parts and connections in building systems. Construction is simplified by using larger, more precise parts with fewer connectors required in field processes. For example, floor assemblies constructed in the PHS facility use "jumbo" OSB in 8' x 24' sheets. These large assemblies contain fewer seams, and are cut and fastened by software-driven machinery within a tolerance of 1/16". To further simplify and minimize field processes, the CNC-controlled saws also cut floor deck penetrations for HVAC and plumbing components at predetermined locations, and lines for the locations of interior walls are also marked on the deck. The end result is a large floor assembly constructed within a protected environment with minimized material waste, which is designed to ease subsequent field operations such as mechanical rough-ins.

PHS applies the advantages of a highly automated factory to produce large assemblies that simplify and expedite field work to all of the building systems in the house. This stands in contrast to simply combining prefabricated wall panels with traditional foundation, insulation, and floor framing technologies. Previous studies show that the interface between the innovation (wall panels) and the unchanged systems (foundations, utilities) is frequently the cause of conflicts that ultimately degrade the performance of the innovation and in some cases, the original system itself. (O'Brien, et. al. 2002).

By considering all facets of the production process, including IT tools, material procurement, labor, and automated machinery, the interfaces between subsystems are purpose-built to meet with a degree of precision that enhances both speed and accuracy in component plant and field operations. The major elements of PHS' systems process include:

- Cross-domain integration of information from design to engineering to production
- Parametric CAD modeling
- Web based process scheduling
- Conversion of raw materials (steel, OSB, foam) into component products
- Numerically controlled fabrication tools
- Just-in-Time (JIT):[[[[[ component delivery
- Cross-trained field labor



The major components of the redesigned house system are:

- Crushed rock footing bed;
- Pre-cast concrete foundation walls with field-applied exterior insulation;
- Prefabricated floor panels with steel webbed trusses;
- Prefabricated wall panels with pre-installed windows;
- Prefabricated light gauge steel interior partition framing;
- Prefabricated roof trusses
- "Pultrim" fiberglass trim products

By producing these components in its plant (except for roof trusses), PHS enhances its ability for mass customization - to build unique, individualized houses while still maintaining the economies of factory production.

Production of the pre-cast foundation walls, prefabricated trussed floor panels, and prefabricated wall panels with preinstalled windows has required extensive process engineering and tooling design, extending all the way to the design of the racks and trailers used to ship the components to the jobsite.

On the plant floor, laser layout tables are driven by the CAD information to guide the location of bulkheads, inserts, and holdouts in the foundation formwork. Numerically controlled inventory processes maintain a JIT relationship with suppliers of raw materials for the foundations, floor panels, wall panels and partition framing. The central process controller schedules delivery of large-scale oriented strand board (OSB) panels and steel truss components that will be used to assemble floor trusses. The CAD

information guides the numerically controlled tooling to assemble the floor panel, and precut the holes for pipes, HVAC ducts, and registers in the floor.

The SIPs wall panels are similarly developed. Large-scale structural wood panels are pulled from inventory, squared, and delivered just in time for the numerically controlled machine to pick them up and place them on a moving assembly table. Adhesive is laid down, insulation panels with integrated electrical raceways are dropped onto the adhesive, another layer of adhesive is sprayed over the insulation, and a face of the same "jumbo" OSB paneling is installed. The assembly is pressed together, and then a numerically controlled router cuts out rough openings for doors and windows. The panel moves to a vertical rack where flashing and the window unit is installed, and the panel is labeled and prepared for shipping.

The light-gauge steel partition framing is fabricated at a workstation fed by a large coil of galvanized steel roll formed into steel studs, precut to length from CAD information, and then assembled into interior partition panels. Throughout the plant, components are labeled with the project, location, and component identification to increase field erection accuracy and speed.

The roof trusses are procured through an independent fabricator as the degree of customization, accuracy and just in time delivery needs for this component are widely available. PHS judges that in-plant production of these components would not yield tangible benefits.

Overall the system developed by Pulte Home Science is one of the most

significant developments in the systems approach to housing. Pulte's recognition and integration of production system

design and planning as an enabler of high performance, high value housing is unparalleled in North America today.

---

---

### Housing Kits

"Kit homes" are another variation in which a set of factory-built components is produced and pre-cut to length and then packaged according to a particular design. Kit houses are generally marketed directly to consumers with the expectation that the buyer will acquire land, arrange for site and foundation preparation, and have some involvement with setting the structure on site and interior finishing.

There has been a recent resurgence in kit homes, but unlike their predecessors from Sears and Roebuck catalogs, these are not necessarily designed to be affordable do-it-yourself projects. Kit homes are now available in widely varying architectural styles, from rustic log cabins to modern designs, with price points from \$48 per square foot to over \$1 million for a complete package not including site considerations (land, site and foundation preparation, field work, etc.). Kits range in size from 436 square feet to over 3,000 square feet. Some are designed to be primary residences, while others are vacation homes in remote areas. Kit homes can utilize various construction methods, but they are most often factory-built components that make up a complete building shell package. They are shipped to a location and erected on site. They have the potential to reduce costs and speed construction time, however, depending on the location and specific site there can be significant shipping costs and design limitations.

One example operation is Rocio Romero's Camp Series SIP structures. These homes are designed as second homes and are made more affordable by relying on homeowners to do much of the site work. The Camp Series SIP panels come complete with interior and exterior finishes, and can be easily lifted by two people. These kits include with assembly instructions and pre-drilled holes. The only tool needed is a power-driven screwdriver that is included. All of the components can fit on one truck bed and they are bundled to unload in one hour. Shipping costs range from \$1.95 to \$2.50 per mile. (Romero, 2005).

The NowHouse by Clever Homes ([www.nowhouse.org](http://www.nowhouse.org)) is a demonstration home that opened in October 2004 in the parking lot of San Francisco's SBC Park. The house was designed with themes of sustainability, prefabricated production, and expandability. The NowHouse was built from prefabricated SIP panels that were shipped to the site and erected. The core design of the NowHouse is intended to grow with its residents by easily accommodating additional rooms or levels. The NowHouse is the first house that Clever Homes has built, but they currently have 66 homes in different stages of planning and construction. Clever Homes works with different manufacturers to make SIPs to their specifications.



NowHouse  
Source: [www.nowhouse.org](http://www.nowhouse.org)

As a final example, the outdoor catalogue retailer Orvis recently announced that they would begin selling six home plans for luxurious log homes. The homes are shipped by truck to the site. The entire package includes walls, floors, roofing material, interior and exterior beams, windows, doors, and hardware. Prices for the kits range in price from \$554,000 to \$1.2 million (Groer, 2005).

## On-Site Production Innovations

For large scale communities, on-site fabrication facilities may provide increased efficiencies since the builder and consumer retain all of the benefits of a factory environment while reducing transportation costs. One model for this type of production is being pursued by Cohen Brothers Homes, LLC (<http://www.cohenbrothershomes.com>) Whole House Building System. Cohen Brothers has patented a manufacturing unit that is erected on the building site for the duration of the construction project. In this case, a 50,000 square foot structure with parallel production lines produces structural sub-assemblies. These are delivered to an assembly site where the sub-assemblies are erected into a home. The home is then rolled onto a permanent foundation. This innovation, although promising, has yet to be implemented.

A smaller-scale variation of on-site fabrication involves standardizing and adding a degree of automation to steel wall panel fabrication. The system used by Dietrich Residential Construction at their construction sites in Hawaii involves the use of formed, pre-cut steel members that are delivered to the on-site “plants” by company trucks. The steel members arrive pre-marked with a color-code system for easy size identification (e.g., red = 3’ door header). The on-site fabrication system uses a hydraulic table to assist in the connection of the track and full-length studs to form wall panels. The studs are set in position by the worker and the table holds pressure on the top and bottom track members to keep the studs in position. Fastening units with dual screw guns (one on top and one on bottom) are on each side of the table to secure the tracks to the studs. The worker lines the unit up with the track-stud connection, and then presses a trigger to activate the screw guns. Once all the connections are completed, the table releases the panel and it is passed along to the next step.

This system speeds up the track-stud connection because each worker is essentially operating two screw guns simultaneously. It also helps to keep the studs stable during fastening, which reduces the number of wasted screws and keeps the worker from bending over as often. Dietrich uses this system at all four of its steel panel production plants on a regular basis. They feel it works well and improves the production output for smaller, labor-intensive operations.

## Hybrid Housing

In “*Whole House Production: Integration of Factory-built and Site-built Construction*,” Syal and Hastak review current research on manufactured housing production and whole-house related research. The report proposes a number of research areas to integrate the best aspects of factory-built housing with site-built construction which could yield improvements in quality and lower cost homes.

Many of the examples in this report could be considered in the context of “hybrid housing”, since they can be applied with a combination of site-built construction and factory production. The Susquehanna Prototype House (Lee, circa 2000) provides a number of key lessons and considerations for the development of the PATH Concept Home. This prototype utilized open building elements such as flexible and adaptable technologies, disentangled utilities, and a “rationalized construction process” with the goal of optimizing the efficiencies of off-site and on-site labor. The report by Lee notes that the disentangled shell allowed for interdependencies between trades to be dramatically reduced, enabling each trade to finish their work without the lost time of waiting for another trade to complete their work. Though they achieved many of their goals, the project took 128 days to complete as a result of communication, ordering and delivery problems, in addition to dimensional mistakes and lack of familiarity with new technologies and production processes.

## ***Information Technology & Mechanical Innovations***

Innovations in information technology probably represent the most critical change in homebuilding production over the last decade. The flow and exchange of information throughout the construction process can influence production efficiency tremendously and has been shown to contain several potential gaps where communications systems break down and create inefficiencies (HUD, 2000).

### **Use of Information Technology in the Production Process**

Information technology has a clear role in both factory-built housing and components as well as in the more traditional site built units. In factory-built housing the extent of automation in production involves the consideration of several factors including:

- capital costs – what is the cost of equipment like automated material handling machines;
- degree of standardization – how uniform are the components to be manufactured;
- production volume – what volume of components will be made;
- labor issues – what labor savings are associated with increased automation; and
- production efficiency gains – what are the expected benefits in production speed and component quality.

A comprehensive discussion of IT manufacturing systems that have a potential to impact housing production, is presented in *Industrialization the Residential Construction Site, Phase III Production Systems*, HUD 2002. The authors note that disconnects that cause bottlenecks in the production process can be resolved through information technology that links: sales to design to production; production to design/engineering; and customer service to design to production. Improvements the research team has found in the field include web-based scheduling, site factories (treating the development like an assembly line similar to Levittown communities), on-site management/production integration in a modular manufacturing facility, database software to improve communications and analysis, and computer modeling. Computer modeling has promise in terms of front office sales and the integration of sales and change orders with production drawings, as well as with purchasing, inventory, and scheduling.

There are many examples in manufacturing of the application of information technology to the production process, and almost all are relevant to factory housing and factory components with others equally applicable to site-built housing. These are discussed in the Management Innovations section below.

### **Improvements in Communications Tools**

The use of IT systems to enable communications and information exchange by all types of builders has risen dramatically in recent years, especially in back-office tasks like estimating and accounting. However, many job site and production processes continue to rely on traditional methods for construction and project management. Simple technology is now available that can help increase efficiency and profitability for residential homebuilders. Most systems are used to keep projects on schedule and increase the efficiency of communications between all parties involved in the building process. Others are used to document certain phases and standardize best practices.

For example, a commonly used software tool used by many builders is Microsoft Project. The package contains multiple management tools including project planning/scheduling and detailed drawings, and project files can also be accessed remotely via a web interface. This allows all those involved in a project (subcontractors, superintendents, architects, etc) to easily view the schedule and track the status of the project, while reminder emails can be automatically sent to individual subcontractors when a particular jobsite tasks requires their services. Other technologies being explored and applied by builders include:

- On-site wireless networking to promote communications and easy access to information;
- Live webcam site monitoring to monitor status and discourage theft;
- Digital photo documentation to efficiently document and exchange information;
- Web-scheduling to streamline scheduling and communications;
- Online daily logs to track status and jobsite progress; and
- Online fax service (efax, etc) to promote mobile communications that allow site personnel to receive faxes as emails instead.

### **Radio Frequency Identification (RFID)**

Radio Frequency Identification (RFID), a technology that has been available for several decades, has attracted renewed attention as system costs have dropped, functionality has improved, and new applications have been pioneered. RFID systems are not yet used in the home building process, but they are used for applications such as automobile ignition security and immobilization systems; identification of animals including livestock and pets; automated vehicle toll collection systems; and patron wristbands with "electronic wallets" at theme parks. In Hong Kong, millions of consumers have used an RFID-based electronic cash system since the 1990's to pay mass transit fares and for other retail transactions.

Growing interest among retailers has raised the prospect that RFID tags will ultimately replace item-level barcodes for tracking inventory as well as for customer checkout. The power and flexibility of this technology suggest that it will find valuable uses in building product distribution and inventory management, as well as in the home construction process.



**RFID Tags**

Courtesy: Dynasys Technologies, Inc.

### **Construction Robotics**

Information Technology is also finding applications in construction robotics. The use of robots in construction provides a more forward-looking opportunity for production enhancements which involves the use of automated machines that operate under computer control and incorporate some element of feedback or adaptive response. Construction robots also have some degree of mobility which might involve the movement of a robotic arm or an entire device. The ability to adapt, which represents a primitive form of intelligence, and device mobility can both help to distinguish robots from automated machines.

When considering potential applications in homebuilding industry, robotics are generally more appropriate for factory building than site-built housing (HUD, 2004), although several examples of potential on-site applications were mentioned. These applications, many of which have been developed in Japan, include the use of robotics for:

- concrete distribution, leveling, surface treatment, and finishing;
- painting tasks;
- fireproofing tasks;
- welding steel building frames;
- remote-controlled demolition equipment;
- remote-controlled earth moving equipment;
- excavation and trenching operations;
- bricklaying; and
- hanging drywall.

These experimental applications illustrate many of the benefits that can be realized through robotics, including:

- Labor savings;
- Cost savings;
- Improved worker safety; and
- Enhanced process accuracy and quality.

Within a factory environment, robotics has the potential to take automated machinery a step further to produce further labor savings and production benefits. However, the efficiencies provided by automated equipment operated by low skill labor in operations like the Pulte Home Science facility may be challenging to compete with. Despite its challenges, the potential benefits of robotics in construction and other industries is evidenced by the level of interest in these technologies. There are national and international trade associations devoted to robotics such as the International Association for Automation and Robotics in Construction ([www.iaarc.org](http://www.iaarc.org)), which publishes the *Catalog of Robots and Automated Machines in Construction*, the International Robotics Council ([www.irc.org](http://www.irc.org)), and the U.S. Robotics Industries Association ([www.roboticonline.com](http://www.roboticonline.com)). International groups like Intelligent Manufacturing Systems ([www.ims.org](http://www.ims.org)) are dedicated to advancing intelligent manufacturing systems through consortia-sponsored R&D activities. One program organized through IMS is "FutureHome", a multi-year European effort to reduce housing cost and improve quality through the use of advanced manufacturing technology.

## ***Manufacturing Innovations***

Discussed below are a few of the most relevant manufacturing innovations that rely on one or a combination of the information and communications innovations described above, and that could readily be used to apply in the factory building concepts described earlier. These include Lean Construction, Computer Numerical Control, Design for Manufacture and Assembly, and Enterprise Resource Planning.

## Lean Construction

Lean construction applies to the maximization of work flow through the minimization of performance variation and the elimination of waste. Lean construction applies to factory built housing and components as well as site built. It applies in theory to all parts of the construction process including financial management, supply chain management, and land development - as well as actual housing production. The Lean Construction Institute ([www.leanconstruction.org](http://www.leanconstruction.org)), founded in 1997, identifies lean construction and management as a process with substantial potential to reduce costs in residential construction. The Institute's goal is to reduce lead time for engineered-to-order components by linking design, supply, fabrication, and installation into a production system that maximizes consumer value and minimizes waste. Mullens, et al (2004, p.23) found that the "lean scheduling concepts such as continuous flow and single piece production can...reduce on-site construction cycle time for modular homebuilders by as much as 50 percent." Although perhaps not as drastic, one could expect substantial savings for other factory production processes that employ lead scheduling as well.

## Computer Numerical Control

In countries like Japan, factory-built housing is a highly automated process in which building components like a wall can be fabricated almost entirely by automated equipment. In North America, Precision Designed Homes is creating a modular factory (planned opening in 2006) which relies upon patented software to optimize the manufacturing process. The software converts CAD drawings into computer code for robotic Computer Numerical Control (CNC) machining. The factory, using European tooling, will be roughly 84 percent robotic. The precision tolerance is being designed as low as 1/32 of an inch to accommodate interior finishes. The CNC automation offers the potential of highly automated production of custom designed homes, while still realizing the benefits of factory-built, mass production. In the long term, computer controlled factory systems may offer great potential for production improvements.

## Design for Manufacture and Assembly

Design for manufacture and assembly (DFMA) is a production method utilizing information technology that originated in the 1980s for the manufacturing of mechanical products to reduce the number of parts and ease assembly. DFMA has the following advantages:

- Less overhead resources associated with ordering and scheduling parts;
- Less time and therefore cost of assembly labor;
- Lower assembly rates due to reduced part counts; and,
- Improved reliability by reduced parts and pieces.

Much of the success of DFMA can be attributed to its success in reducing the amount of labor requirements.

A modified version of DFMA being used in the construction industry for factory-built components is NUCONSTEEL™'s prefabrication process, which has been specifically designed to reduce the number of manufactured parts and assembly requirements. NUCON's

Concept Home Principles –  
Improved Production Processes



NUCON's Series 700 Roll Former &  
Decoiler

approach utilizes prefabricated light gauge steel wall panels, floor systems, and truss systems for residential and light commercial projects. Through the use of its proprietary software, NUCON integrates building plans, development of product specifications, and component fabrication. Utilizing this approach, NUCON states that its wall, floor, and truss components for a house can be designed, fabricated and delivered in less than a day. This approach is also designed to account for local code requirements, which is a frequently cited obstacle to prefabricated building methods.

The "NUWALL<sup>®</sup>" wall panel is load bearing and manufactured with just-in-time roll forming. The "NUTRUSS<sup>®</sup>" systems allows for design flexibility and wider spans.

### Enterprise Resource Planning

For the factory built sector and large home builders, there is potential to make operations more efficient with an extensive business management system called enterprise resource planning (ERP). This system is in the early stages of adoption in the housing industry, but has shown promise in the manufacturing sector over the last decade.

In basic terms, ERP systems involve answering some simple questions, such as:

- How can the process be done better or more efficiently?
- What is not being done in the correct order?
- What is not being done well?

ERP can provide a whole new level of knowledge and value creation for home builders. The potential is considerable for those that can justify the expense of management systems and customized computer software systems. Because the value of ERP programs is based in economies of scale, these systems may be impractical for companies that build fewer than 50 homes in a given year.

Several companies currently produce and market ERP systems. The largest producers include SAP, Oracle, J.D. Edwards, Baan, and PeopleSoft.

#### Enterprise Resource Management at K. Hovnanian

Mark Hodges of New Jersey-based Hovnanian Enterprises said that the SAP brand system his company is using "is the most profound business change [they] have ever done." Hovnanian has divisions all over the country and, like many of the giant U.S. home building companies, Hodges believes that ERP systems "will absolutely change the home building process."

A primary function of the system used by Hovnanian is one-time entry of all data. This eliminates the extremely arduous task of entering the same data at many different points in the company documents. Another key function is universal access by the company's personnel and trade partners. Currently being tested at Hovnanian's Four Seasons at Smithville (N.J.) community, the SAP system allows trade partners to look ahead two weeks in the production process. The trade partners are also paid electronically as soon as the construction superintendent for Hovnanian certifies via Palm Pilot that the work has been done. When asked how much costs were reduced with this system, Hodges said, "We are not going to tell. We will let the industry imagine what that might be."

The construction of homes in the United States has reached record highs over the last few years. While the homebuilding industry has made incredible advances in materials and quality, it still lags behind other industries in technological innovation in production – that is, in providing new homes more quickly and more efficiently while still keeping homes affordable. There is much to be done, and there is much that all of the homebuilding industry would like to see done.

- Excerpted from: *ToolBase, Quality Management, July 2000.*



## Conclusion

For the purposes of producing plans and specifications for the PATH Concept Home, production process improvements will inform the design process and selection of technologies. While many of the improvements discussed above are as much about the design and building *process* as they are about the actual house, it is important to understand and consider the limitations inherent in different production methods.

Though there are likely to be different proposed methods for realizing production process improvements for the attached infill and the single-family Concept Homes within the context of a community design, both are likely to utilize a hybrid or component based approach. Thus, perhaps the most important consideration for production process improvements is the integration of lean construction management principles and advancements in information and communication technology that can be used with all production assembly methods.

## Reference List

Arieff, Allison and Bryan Burkhart. "PREFAB," Gibbs Smith: 2002.

Beamish, Julia O., Rosemary C. Goss, Jorge H. Atilas, Yougjo Kim. "Not a Trailer Anymore: Perceptions of Manufactured Housing," *Housing Policy Debate*, V.12 (2); Fannie Mae: 2001.

Bensonwood Homes. "What is Open Building?" Available on Bensonwood Homes website at: <http://www.bensonwood.com/company/whitepaper2003.pdf>. 2003.

*Better Homes and Gardens*, February 2005, pp. 88-92

Brand, Stewart. *How Buildings Learn: What happens after they're built*, Viking Penguin, New York, 1994.

Concept Home Focus Groups, 2004.

Dean, Daniela. "Home From the Factory; Pulte Says Its New Way of Manufactured Building Is Faster, Better," *The Washington Post*. Washington, D.C.: Dec 11, 2004. p. F1.

"Factory Built Housing Components." The Freedonia Group. Cleveland, OH. As referenced in Structural Building Components Magazine, April 2003. [www.sbcmag.info/past/2003/03apr/economicenv.htm](http://www.sbcmag.info/past/2003/03apr/economicenv.htm)

Groer, Annie. "Orvis Angling to Sell Luxurious Log Homes," *The Washington Post*, Washington, DC: Tuesday, March 3, 2005, p. H1.

Lee, Stephen. "Demonstrating Design for Flexibility in the Susquehanna Prototype House," Carnegie Mellon University, Pittsburgh, PA, circa 2000.

Levy, Emanuel. "What are Toyota and IKEA Doing in the Homebuilding Business?" Presentation at National Building Museum, Washington DC. March 22, 2005.

Lytle, Bethany. "Havens: Living Here; Modern Kit Houses: Thinking Inside the Box," *The New York Times*, October 15, 2004.

Mullens, Michael A., Makarand Hastak, et al. "Defining a National Housing Research Agenda: Construction management and Production," PATH, 2004.

Newport Partners. Market Research on PATH Concept Home Principles, 2005. Not yet published.

Newport Partners. Information Technology to Accelerate and Streamline Home Building. 2003.  
O'Brien, Michael, Ron Wakefield, and Yvan Beliveau. *Industrializing the Residential Construction Site*, US Department of Housing and Urban Development, Office of Policy Development and Research, July 2000.

O'Brien, Michael, Ron Wakefield, and Yvan Beliveau. *Industrializing the Residential Construction Site Phase II: Information Mapping*, US Department of Housing and Urban Development, Office of Policy Development and Research, June 2001.

O'Brien, Michael, Ron Wakefield, and Yvan Beliveau. *Industrializing the Residential Construction Site Phase III: Production Systems*, US Department of Housing and Urban Development, Office of Policy Development and Research, June 2002.

Prefab Proactive Conference. Sponsored by *Dwell* magazine. February 2005, Oakland, CA.

Pulte Home Sciences. "Building for the 21st Century: Factory Built Components and the Modern American Home", Presentation at National Building Museum. May 25, 2005.

Romero, Rocio. Presentation at Prefab Proactive Conference. February 25, 2005. Oakland, CA.

Ruiz, Fernando Pages. "Better Framing with Factory Built Walls," *Fine Homebuilding*, March 2005: No. 169.

Syal, Matt and Makarand Hastak, *Whole House Production: Integration of Factory-built and Site-Built Construction*, 2003.

Task 16 Report to HUD, Cost-effective Home Building.

Turrentine, Jeff. "The Prefab Future, Practically Here: The Dream of Factory-Built Modernism Takes Shape at Last," *The Washington Post*, Thursday, March 31, 2005; Page H01.

U.S. Department of Housing and Urban Development. Partnership for Advancing Technology in Housing, "Technology Roadmap: Whole House and Building Process Redesign – 2003 Progress Report", 2004. Available on [www.huduser.org](http://www.huduser.org).

U.S. Department of Housing and Urban Development. "Industrializing the Residential Construction Site", 2002. Available on [www.huduser.org](http://www.huduser.org).