Flexibility in Prefabrication Approaches: Lessons from two US Homebuilders

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Introduction

The growing attention to producing consumer friendly, sustainable and affordable housing has triggered innovative prefab housing approaches. To satisfy diverse and individualized customer demands, leading architects have pioneered the concept of prefabricated modernism, collaborating intimately with contractors to take more control of the production and assembly process. This shift is partially attributed to the advancements of digital design and manufacturing technologies that connect Building Information Modeling (BIM) and parametric modeling tools to prefabrication.[1] Literature suggests the return of "master builders" based on enhanced communication and control capabilities of the architect.[2] However, the widespread delivery of architect-designed homes remains largely unrealized.[3] The authors believe that lack of understanding of the prefab production processes is a significant barrier to this adoption.

This paper outlines the various prefabrication approaches in the US residential market and elaborates on the prefabrication approaches of two US production builders. The paper draws on previous research that has been conducted through literature reviews, structured interviews to collect data for the case study, and observations of the writers. We focus on the specifics of panelized building systems of (1) Pulte Home Sciences, and (2) Empyrean International, and describe the information bottlenecks in current production processes. It is shown that production logistics pose challenges to automated industrialization and that various approaches may lead to different levels of customization.

The paper aims to first, provide an understanding of digital design and manufacturing strategies in production homebuilding, and second, to suggest research needs for a framework to increase flexibility in fabrication processes to effectively accommodate diverse design aesthetics (e.g., modernist style, traditional style housing, etc.), cost effective delivery approaches, product distribution and managing customer satisfaction. The ultimate goal is to economically address diverse customer demands and contribute to the built environment by successfully integrating with natural ecosystems.

Flexibility in Prefabrication

Flexible automation technologies and techniques have drawn much attention towards "mass customization" in housing which paradoxically allows achieving higher levels of customization in housing design via higher levels of standardization.[4] A main driver behind this idea is the production capacity of computer-aided design and manufacturing technologies which enable economies of scope through flexible production automation (FPA). Hereby, a variety of products with low volume runs are produced with the same manufacturing equipment and processes without having to change production lines. These developments have brought a paradigm shift to industrialization which has been historically associated with economies of scale.

While mass customization techniques have been well established in industrial consumer products, the applicability to housing and architectural products is less understood. Various research efforts have attempted to develop definitions of and techniques for customized industrialization in housing. Barlow et al. discussed generic supply chain models of Japanese housing suppliers and explained the different degrees of usage of standardized components and modular systems.[5] Thillart developed a comprehensive framework and model for customized industrialization, incorporating concepts of open building principles, product flexibility for new construction to remodeling.[6]

To examine the integration of FPA into production processes, our paper builds on work that characterizes a building by its degree of openness and industrialization.[7] At the extreme ends of the spectrum lie "open" and "closed" systems. "Open systems can be achieved through standardized sizes, threshold values, flexible connection technologies, standard interfaces and tolerances." The classic client-architect relationship is an example of an open system where the client can choose various building systems on the basis of price and quality to generate a unique solution to his requirements. In comparison, an example of a "closed system" is a catalogue home offered by a production builder which follows a standard model design that is predetermined without the involvement of an external architect's service or the individual customer's input.

According to Thillart, in between the open and closed systems is the semi-closed building system which can be classified into "design plan" and "customer plan." This system corresponds and applies best to mass customization approaches.[8] "A design plan offers customers unique combinations of building systems to be assembled on the building site according to the customer's design while the customer plan offers a predefined flexible design concept with predefined options from which the customer can select from." The customer plan can be economically advantageous over the design plan if the design concept can be reused in various locations. Mishra et al. define the degrees of customization into three levels of configurations (floor plan), permutations (elevations), and variations (interior fit-ups) which can be offered altogether or partially.[9]

In addition, to facilitate customization through prefabrication, the notion of a "virtual kit" is introduced to provide a large collection of candidate building systems that can be ordered and selected and connected for the implementation of a building to allow various options and accomplishment of customizations.[10]

The following discussion will examine how two US homebuilders have explored flexibility in their production processes.

Case Studies Background

According to various research efforts of the U.S. Department of Housing and Urban Development (HUD), US production homebuilders can be characterized by their factory based production processes and technologies. Martin classifies prefabrication technologies into factory-built homes (modular homes and manufactured homes), factory-built components, panels, and Kit Homes.[11] From a total process perspective, production homebuilders can be categorized into site-builders who are typically land developers that deliver the home as part of the overall package to the customer, and factory builders whose product is the home.[12] Production builders can also be categorized by their production volume into large, medium, and small size builders. Depending on their business strategies, production builders operate under different market dynamics, regulatory constraints, and business cultures. Our analysis focuses on two distinct types of production builders: (1) Pulte Homes which is one of the nation's five largest home builders whose core business is land development and homebuilding, and (2) Empyrean International which is a medium size homebuilder that concentrates on the design, manufacturing, and delivery of single family homes. The following analysis will highlight the different approaches of these two builders in regard to production systems and levels of customer choice of their building systems, and examine the information management and processes.

Pulte Home Sciences (PHS): Factory-Based Panelization

Company and Facility Background[13]

Pulte Home Sciences is the research and development arm of Pulte Homes which comprises three major brands, Del Webb, DiVosta Homes and PHS, building almost 40,000 homes a year.[14] One of PHS's innovative research and development efforts included the operation of an 119,000 square feet plant in Manassas, VA, from 2005 to 2006. The PHS facility was a major move into construction automation by incorporating CAD/CAM processes into prefabricating most of the building shell, including precast foundation panels, structural insulated panel (SIP), steel-framed interior wall panels, and floor panels supported by open-web trusses with steel webs.

Pulte Homes' business model focuses on land development and home building through high quality products. The expansion into manufacturing through the PHS facility involved substantial investment and innovative thinking in relation to its conventional core business model. The estimated minimum market for this facility was about 1000 homes per year, optimally projected at 2000 homes per year at an average area of 2000 square feet homes ranging up to 8500 square feet.

Constructive Systems

The panelized components within the PHS factory included foundation wall, exterior wall and floor (roof trusses were outsourced). "These components were carefully engineered into subsystems and independently deployed first, and gradually integrated into a full shell system to achieve higher structural, thermal, moisture management, and improved assembly performance."[15] Critical goals for this system included:[16]

- Enhanced speed, quality, and durability of construction
- Simplified field processes
- Improved thermal and moisture management performance
- Customized production within the factory setting

The key components and sub-assemblies of the system are described below: [17]

> "A moisture resistant precast foundation system composed of 5000+ psi concrete to provide more water resilience was installed on site with urethane coating applied to the wall seams. On top of it 1" rigid foam insulation was then covered with shotcrete for finish.
>
> A strong floor panel system composed of a 7/8" thicker decking with increased floor truss spacing of 24" was prefabricated into floor panels offering a very low deflection of L/720.
>
> SIP walls consisting of 7/16" oriented strand board (OSB) that sandwich a one-pound density extended polystyrene core with moisture-cured urethane adhesive. Delivered in 9'1" x 24' long units this system offered higher energy performance over typical stud wall systems.
>
> The factory also produced interior steel walls due to their light weight transportation advantage and to achieve improved finishes and elimination of nail pops. Two types of walls (i.e., bearing walls and non-bearing walls) were produced for the 9'1" first floor and 8'1" second floor wall system.
>
> By increasing the size of preassembled units such as the 36 feet long SIP walls and 45 feet long floor panels, constructability improvements were achieved through the reduction of connections and alignment issues on the site. Additionally, the stronger floor system provided lateral pressure support during backfill of the foundation, thus compressing schedule. The average timeframe from stake-out to dry in and hand over to the mechanical contractor was established as 23 days."

Levels of Customization: Catalogue Homes

Pulte Homes primarily identifies customers through marketing and offers catalogue homes with little customization options that are based on marketing.[18] Following Mishra et al.'s definition of the three levels of customer choices, customization is very limited and geared towards the finish level such as wall colors, flooring color, and tile colors. Kitchen cabinetry grades are preselected based on marketing, and sometimes there are options for finished basements, or predetermined structural options such as adding an additional bedroom or an additional floor to a room. Exceptionally, internal designers get involved when there is need for customized ADA requirements such as wheelchair ramps to the garage.

The elevation of a house is usually predetermined by an internal monotony code which does not allow a same color home within three doors on either side. This may apply to different finishes such as cedar shakes siding, lap siding, or vertical siding.

The imperative for standardization is to achieve significant economies of scale. From a floor plan configuration standpoint Pulte continues to expand its national library of standard designs (about 400),[19] comprised of the sublibrary of regional plans. They typically select only a limited number of design types within a series for specific developments, and further narrow down the selections that are offered to customers in a given development.

Digitally Enabled Design for Prefabrication[20]

PHS computer-aided manufacturing processes provided flexible production automation based on a few standard parameters such as web depth and framing centers. To convert architectural designs into engineering construction data to drive the automated production equipment, PHS developed proprietary software with the help of Keymark. This software is based on a 3D model that analyzes the construction and assembly composition of the building and designs the member sizes, which then produces manufacturing instructions for fabrication. The 3D model generates bill-of-material, take-offs, and construction details.

From an organizational standpoint, Pulte is a vertically integrated design-build firm that incorporates design and engineering expertise within its organization. On the other hand, land development design and engineering is outsourced, and the authors observed that CAD information was manually shared between the architect and the land development consultant based on paper drawings.[21]

Production Process[22]

The precast foundation panels integrated the location of bulkheads, inserts, and holdouts in the formwork, with the guidance of a CAD driven laser layout table. Numerically controlled inventory control processes were linked with raw materials suppliers for the foundations, floor panels, wall panels, and partition framing, thus driving delivery of large scale OSB panels and steel truss components. CAD data drove numerically controlled tooling to assemble the floor panel to precut holes for pipes and HVAC ducts in the floor. SIP panels were similarly produced picking up just-in-time delivered OSB sheets on a moving assembly table applying adhesive to attach insulation panels with integrated electrical raceways. Then another layer of adhesive was sprayed to apply the other face of OSB. A CNC router cuts out rough openings for windows and doors, which were moved to a vertical rack to apply flashing and the window unit. The panel was then labeled and prepared for shipping. The light-gauge steel partition framing was fabricated at a work station fed by a large coil of galvanized steel roll formed into steel studs and precut to the length of CAD data.

Lessons Learned

Despite the flexible production automation capacities of the PHS facility, the number of detailed variations of standardized plans posed logistical challenges during the implementation. Every variation propagates through process from design, fabrication, inventory control, and installation which increases the overhead for managing this complexity and increases the chances of errors in the process.

The economical range of transportation of this system was limited to a 125 miles range.[23] In addition to the aspects of dealing with logistical variations, the investment of this type of production facility still requires a minimum level of production demand to satisfy return on investment. The cyclical downturn of the housing economy negatively impacted the economic viability of PHS capital investment. Also, because PHS's business model is not in manufacturing, delivering products only within Pulte Homes resulted in short demand.

Regulatory review processes also pose challenges to new building systems and thus required education of code officials to streamline permit approval processes.

Case Study: Empyrean International's Hybrid Panelized Systems

Company Background and Business Model

Empyrean International, previously known as Deck House and Acorn Structures, holds a 60 year long history of design and manufacturing of pre-engineered and pre-fabricated houses in their integrated design and manufacturing 200,000 square foot facilities in Acton, MA. Wentworth Holdings acquired Deck House Inc. in 2003, and became Empyrean International, LLC in 2005. After the acquisition, a successful partnership with Dwell Magazine developed into a third brand that complements the family of products and services provided by Acorn Homes and Deck House: Dwell Homes by Empyrean. The goal of this partnership was "to create a collection of custom-designed, modern pre-manufactured homes." Empyrean has a total number of 120 employees, offices across the US and the UK, and has manufactured and delivered homes globally in several countries including: Japan, Israel, United Kingdom, Albania, Argentina, Bahamas & the Caribbean, Mexico, and the United States. Along its history, Empyrean has produced more than 20,000 houses and residential building types, and today it produces around 180 units a year of an average area of 2000 square feet.

Empyrean International's core business is focused on the high quality manufacturing and shipping of custom designed prefabricated wood structures, using sustainable home building systems. For prospective homeowners, Empyrean encapsulates the complete process in a one-stop shop for both design and manufacturing. Recently it has focused also on practicing architects, to whom they offer a design partnership program, allowing an efficient outsourcing of the design development process, production of construction drawings, details and manufacturing. Both approaches provide the flexibility to work on projects based on in-house designs, or in collaboration with external design professionals. In both cases, Empyrean maintains control over the quality of the final product through the production of systematic and optimized information that suits their manufacturing processes, while providing a range of flexibility and customization within the constraints of their constructive systems. The core of their business model relies on efficient and high quality fabrication, shipping and assembly processes of their "panelized" and "post and beam" structures.

Constructive Systems

All of Empyrean's homes are based on two different building systems that work as two different kits-of-parts using similar wood frame structures. They are both hybrid systems that share common structural and shell elements. The Acorn system (Fig. 1-Top) is mainly based on pre-assembled wood panels that have structural capabilities, also known as a "Panelized System." It can also incorporate post and beam members to allow wider spans, something that is common in many projects. The Deck house system (Fig. 1-Bottom) is essentially based on post and beam construction, where the exterior and interior partitions can be prefabricated as panels but usually play no structural role. There are specific sets of parameters for each system that determine the level of flexibility and amount of feasible customization of main structural and non-structural components.

Pre-fabricated Panels: Acorn Structures

The Acorn system (Fig. 2) is based on 4′ wide 2x4 (or 2x6) exterior prefabricated structural wall panels with plywood and integrated windows, usually taking loads directly from the roof and the upper floors. 2x4 wall panels are typically 4′ wide (8′ maximum width for domestic construction (US), and 7′6″ for international projects. Wall panel heights range from 3″ to 18′. The system's roof is based on 2x12 rafter framing components every 24″ on center, and allows 4 standard roof pitches. Spans are generally limited to 16′ at the roof (constraints for 2x12s used in roof structure). Overall plan geometry is usually based on a 4′ grid that also corresponds to the roof gable cross sections' increments, while the length of the ridge can be developed in 2′ increments. Standard floor to floor heights are 8′-10-1/2″, with increases in 7-5/8″ increments, which generates the basic rules for fabrication of standard stairs. Spans are typically limited to 18′ - 20′ for the floors (11-1/4″ truss).

Hybrid Systems based on Post & Beam Structures: Deck House System and the Dwell Homes

The Deck House system (Fig. 3) is based on laminated Douglas fir timber members for all columns (posts) and beams, which are usually left exposed for the interior spaces. It is a hybrid system because it incorporates non-structural interior and exterior wall panels. The system uses a standard framing of 2x4 or 2x6 studs at 16″ on center with 1/2″ plywood sheathing for the exterior wall panels. Typical structural bays for this post and beam system are 8′-0″. The roof system is based on Douglas fir laminated architectural grade beams and rafters which support 3x6 T&G pine or cedar laminated decking (Fig. 4). This is where the system adopts its name from: the base of the roof structure consists of three laminations glued together tongue and groove over which asphalt shingles, roofing felt, ice and water shield, metal drip edge, OSB sheathing and rigid foam insulation are all layered. It allows 4 standard roof pitches. Typical floor heights include: 8′-11 1/4″ standard basement slab to finish entry floor elevation, and 9′-2 1/4″ standard entry level to upper level finish floor elevation, which determine the parameters for all interior standard stairs.

Levels of Customization: Catalogue Homes vs. One-off designs

Over more than five decades, a significant number of finished projects have consolidated into a solid catalogue of housing types for both systems, Acorn and Deck House. In many cases clients buy one of these options, or use them as a starting point to adjust to their personal requirements. This has naturally transitioned into a third offering based on a series of standardized details put together as a kit-of-parts: the Dwell Homes by Empyrean, focusing on distinctly modern designs. This has allowed Empyrean to expand its business model into a partnership program with independent contemporary architectural offices, which benefit from the systematized manufacturing processes while allowing the possibility of completely customized designs.

The efficiencies of the system come from the subordination of the design to the logic of production of components. At each phase of the design process and at each scale there are different levels of flexibility and customization. But to fully achieve the benefits, designers should follow a series of design guidelines that are tailored to expedite the manufacturing and assembly processes, reduce costs, errors and increase efficiency.

Digitally Enabled Design for Prefabrication

The design process typically begins with the gradual translation of the design schematics into complete sets of 2D CAD drawings (Fig. 4-left), including details and construction drawings for all structural members, panels and other components. These are reproduced in print form and traced to generate a 3D model using customized component-based software specialized for wood construction (Vertex BD). Using this system the design is easily split into each panel, where components are assembled from a customized database of preset elements based on geometry and fabrication rules. For example, wall object types that contain framing, siding and drywall are imported into the model as one single element (Fig. 4-right). It also automates all the trims on all the pieces using standard rules (e.g. roof angle pitches, stair elements, window openings).

3D models are used for tolerance control and construction process simulation, improving precision and material efficiency. Tolerances, interferences and clashes are checked visually. Individual print-outs and shop drawings for each panel are made from the 3D model, as well as automatic production of complete lists of materials for each panel and component. These drawings are double checked against the 2D CAD and all components, including hardware and smaller pieces not modeled, are counted and listed. Structural elements for the roof and floor are modeled using specialized software for open web joist systems (Mitek).

Bills of Materials are generated in spreadsheet format and integrated into a database (Fig. 5). The manufacturing process, as well as supplies and shipping, are controlled through an Integrated Inventory Manufacturing Software (Macola) that controls the workflow.

Despite the redundancy of information from the different digital modeling environments to the process management software, the process still benefits from efficiencies in the manufacturing process and prefabrication. Currently they are transitioning to Building Information Modeling (BIM) to integrate more effectively all the digital data, and the control of schedules and costs.

Options for customization during the design process reduce as the design is finalized. Once the final schematics are produced into 2D and 3D drawings, and all the details are drawn, the client signs on the design and options for variation are reduced. Changes incorporated later in the process, including the construction and assembly phase, come at a high cost and cause expensive delays in the process that defeat the logic of the system.

Production Process and Customization

Home production is based on a series of effective pre-assembly processes, in which the specific means of production and division of labor for the fabrication of discrete components translates into different levels of flexibility and customization. In essence, standardization is focused on the details of components, which means there is a level of flexibility at the sub-assembly level that allows for different degrees of variation based on the same standard stock material and the use of specific machinery (*economies of scope*). Be it rail designs, stairs, doors or windows, there are pre-set designs for each that are based on standard details. These components can be adjusted to specific dimensions or shapes within the limits of the specific materials, tools and assembly processes. This allows large benefits in terms of predictability, efficiency and organization of production and supply chain.

With the exception of a large rigging platform for open frame wood trusses and wood saws, there is little automation. Manufacturing is mainly conducted at the factory floor using traditional methods and tools for wood construction. This opens the question of whether increased flexibility for customization and efficiency of production could be achieved by increasing automation in the workflow through the incorporation of CAD/CAM technologies and CNC machines.

Opportunities and Limitations for Digitally Enabled Customization

We have attempted to highlight flexible production approaches within the context of two production builders who mainly focus(ed) on in-house shell production, to discuss the opportunities and challenges in a digitally-mediated design and production process. A key finding is that panelization strategies require the integration of production processes, logistics, management of options, information platforms, customer interfaces, and organization structures to capitalize flexible production approaches.

Information in the Design Process

Observations of both case studies revealed information and communication inefficiencies such as data reentry between design systems, material and inventory systems, and fabrication systems. Regardless of the openness or closedness of particular building systems, production builders are inevitably dealing with design options. In the catalogue home approach as in the PHS system, we observed management challenges of variations. BIM could reconcile such variations. Panushev et al. have observed in a case study of K. Hovnanian, innovative BIM implementations to manage design options.[24] The standardized kits-of-parts approach of Empyrean International takes on a different strategy that is favorable towards customization. The case illustrates that there is room for streamlining the data transition between the individual process stages.

Production Process

The management of connections between internal and external systems and components requires careful attention. Despite the potential of flexible production automation strategies, we observed logistical complexities of managing product variations that posed challenges to automation processes such as system integration of electrical wiring spaces or duct and piping penetrations. Further research could address the implications of specific detailing strategies and component modularization approaches to streamline automation processes in design and fabrication.

Notes

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