PRODUCTION FLOW AND SHOP FLOOR CONTROL: STRUCTURING THE MODULAR FACTORY FOR CUSTOM HOMEBUILDING

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ABSTRACT

This paper examines production challenges faced by modular homebuilders, identifies applicable state of the art research in manufacturing systems and lean construction, and proposes future research directions to bridge the gap between current knowledge and industry needs. The greatest production challenge faced by modular manufacturers is how to maximize production capacity and increase quality, while expanding production flexibility to deliver the widening product mix and customization demanded by homebuyers. It is the thesis of this paper that the real underlying challenge is how to identify and manage floating bottlenecks caused by the great variability in process times. The paper presents a vision for modular manufacturing and identifies four interrelated research areas that can contribute to the vision: module design, process and material handling technology, factory configuration, and shop floor control. The proposed research is likely to enhance all segments of homebuilding, including HUD Code manufacturers and site builders.

KEYWORDS: modular housing, housing production, lean, flow, bottlenecks

INTRODUCTION

An increasingly popular approach to industrializing the homebuilding process is modular construction, which relocates many field operations to a more controlled factory environment. Modular homebuilders now produce about 7% of the single family and low-rise multi-family homes built in the U.S. (Traynor 2002). In 2001 their 12% growth made them the fastest growing segment of the housing market. Modular homebuilders use three-dimensional sections or modules that are typically 95% finished when they leave the factory (Carlson 1991). After transport to the construction site, modules are lifted by crane and assembled on a permanent foundation. The resulting home meets conventional code and zoning requirements and is typically indistinguishable from nearby conventional site-built housing.

While growing, the modular industry has yet to realize its potential. There are several fundamental reasons:

- Perception - Although modular homebuilders strive to differentiate themselves, many homebuyers still associate modular construction with less expensive HUD Code or "mobile homes".
- Design - While modular home design has improved dramatically with innovations such as the folding roof truss, it has not kept pace with site-built competitors in providing a sufficiently wide range of form, finish, detail, and technology options (Carlson 1991).

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- Production - Modular manufacturers still "stick build under a roof," failing to take advantage of modern manufacturing technologies that can drive vastly improved quality, cycle time and productivity.
- Construction - Modular homebuilders still finish homes on the construction site using conventional construction paradigms, failing to capitalize on the opportunity to slash delivery times with a more lean approach (Mullens and Kelley 2002).

This paper examines the ***production*** challenges faced by modular manufacturers, identifies applicable state of the art research in manufacturing systems and lean construction, and proposes future research directions to bridge the gap between current research and industry needs.

PRODUCTION CHALLENGES

Production challenges faced by modular manufacturers are driven by factors that originate far from the production floor, beginning in the marketplace and extending through the supply chain.

Product Mix: Simple ranches and capes continue to the bread and butter of the modular industry. However, increased market share has come at a price. As homebuyers become more sophisticated, modular manufacturers are routinely customizing standard models, revising floor plans and adding custom features, components and finishes. More importantly, manufacturers are increasingly building one-of-a-kind custom homes, including elaborate traditionals, contemporaries, and multi-family condominiums and apartments. Modular manufacturers may actually be producing a more customized product than some production builders, who have been narrowing design options. These trends toward higher homebuyer expectations and the need for customization are likely to accelerate. Modular manufacturing systems must accommodate them.

Market Growth and Cyclic Demand: The current boom in home building has been both a blessing and a curse to modular manufacturers. Many are experiencing massive sales growth that exceeds production capacity, resulting in one to two hours of daily overtime and the accumulation of a three to six month order backlog. While this may be acceptable for the short term, it is clearly not a long-term solution. With mandatory overtime has come increased employee dissatisfaction and turnover. Increasing lead times have threatened relationships with long-time builder-customers, who depend on shorter lead times for competitive advantage over their site-built competitors. Manufacturers are expanding production capacity to accommodate sales. However, innovation and expansion are tempered by the cyclic nature of the marketplace, which is largely driven by mortgage interest rates. Modular manufacturers are wary of making long-term financial commitments to capital facilities, equipment and systems, particularly when sales can be devastated by an unexpected rise in interest rates. Therefore, manufacturers are expanding cautiously – first by eliminating bottlenecks, second by expanding capacity in existing plants, and last by building new plants.

Engineering: Shop floor production drawings are a persistent cause of disruption in modular manufacturing. Even after prior review, incomplete or unclear drawings stop the line while engineering details are clarified. Many outright errors become obvious only after the affected work has been completed, resulting in rework. Engineering constantly juggles the conflicting priorities of preparing proposal drawings for new quotes, drafting new production orders, and providing better shop drawings to assist manufacturing.

Supply Chain: Late deliveries of low-volume specialty components (e.g., engineered structural elements, tubs, cabinets, windows) cause last minute rescheduling and delayed installation - later on the line, in the yard or even much later on the construction site. From a strategic standpoint, most materials and components are the same as those used by site builders, offering little competitive advantage for factory production. Modular manufacturers seek new materials, equipment and systems that are engineered specifically for factory production. Because of the relative size, suppliers have not focused on the modular market. When new products are developed for modular manufacturers, their introduction is not always smooth. For example, several plants were recently outfitted to handle a new supersize drywall product (8' wide and up to 24' long). The price rose substantially after product introduction and expected demand never materialized. The product was eventually pulled from the market, leaving innovative manufacturers with sizable investments that could not be recovered.

Production challenges eventually manifest themselves on the manufacturing floor. An overview of modular manufacturing is instructive. Elemental processes used by modular manufacturers are essentially manual and remarkably similar to their site-built counterparts, due largely to the use of common materials and components. Mechanized hand tools (e.g., nail guns and paint sprayers) and material handling equipment (e.g., lift trucks) are common. Manufacturers use specialized framing jig tables, some complete with integrated material handling and fastening features, to build framed sub-assemblies such as floors, walls and roofs. Labor requirements vary widely from module to module due to process randomness and product mix. For example, a module with no kitchen will require no cabinet installation, while a duplex module may have two kitchens with two sets of cabinets to install. Work measurement studies of drywall taping have documented labor usage ranging between one and twelve labor hours per module.

Instead of the fixed position layout used on the construction site, modular manufacturers use product layouts - typically progressive assembly flow lines. Line configuration varies: sidesaddle (transverse flow), shotgun (dual parallel lines with lengthwise flow), L-shaped, U-shaped and almost every conceivable combination. Early in the process, the major framed sub-assemblies (floor, wall and roof) flow into the line from jig tables located alongside the line on the floor or on mezzanines. The line cycles at an average rate that matches sales, typically once every one to four hours. Line movement is asynchronous - every module need not move simultaneously. The flow line configuration serves to pace the overall operation, simplify the flow of materials to production, and consolidate the use of special tools and equipment needed for specific activities.

Manufacturers have adopted a unique "subcontractor" approach for working on the line. The workforce is organized into 40 to 50 small groups, each responsible for a specific component/trade (e.g., interior wall framing, drywall taping, cabinet installation). A group is not restricted to a specific workstation on the line unless there is a facilities-related constraint that requires that the activity be performed there (e.g., roofs must be built on a roof jig and set at a line workstation linked to the jig via crane). All other work groups are free to migrate upstream to the next ready module and accompany it downstream as it progresses through the line.

Perhaps the greatest production challenge faced by modular manufacturers is how to maximize production capacity and increase quality, while expanding production flexibility to deliver the widening product mix and customization demanded by homebuyers. It is the thesis of this paper that the real underlying challenge is how to identify and manage floating bottlenecks caused by the great variability in process times. A bottleneck is the slowest operation in a process, the operation that limits production capacity (Goldratt 1992). A floating bottleneck is a bottleneck that shifts between operations, depending on product mix (Hopp and Spearman 2000). Bottlenecks affect the modular factory in several ways, all negative. If the bottleneck is in a facility-constrained workstation (e.g., roof assembly or roof set), upstream modules cannot cycle forward. Since there are no queues, this quickly chokes the line and its feeder workstations. New modules cannot flow into the line and upstream work groups are delayed. Downstream from a facility-constrained workstation, the line empties and work groups are delayed. When the bottleneck shifts to an activity/work group that is not facility-constrained, the line can continue to cycle forward and upstream work groups are not affected. However, downstream work groups are still delayed. As delayed modules move further down the line, they move further away from staged materials and supporting workshops. This introduces additional inefficiencies. Eventually, incomplete modules can exit the still-cycling line and end up in the yard. This introduces huge inefficiencies and probable damage and rework. To prevent this, some manufacturers will not allow incomplete modules to exit the line, thus creating another facility-constrained workstation at the end of the line. Limited work measurement studies in rough framing and drywall have indicated that delays represent at least 10-15% of work time and perhaps substantially more. This does not include working time at reduced productivity levels. To compensate for the delays and to maintain schedule, manufacturers work overtime at a 50% labor premium.

Delays are not the only impact of floating bottlenecks. Instead of working at a steady, sustainable pace, work groups routinely hurry up and wait. Frustration and exhaustion are the natural consequences and quality is a likely victim. Studies have shown that at least 7% of all labor hours are spent on rework and 44% of all drywall labor hours are rework (Mullens 1998). Rework cannot be expected to remedy all quality problems. Thus, at least some of the 2-7% of product cost currently spent on service can also be attributed to floating bottlenecks.

A conventional manufacturing response to bottlenecks is to provide dedicated queues or buffers before/after critical workstations. When queueing is required at multiple workstations, such as the case with floating bottlenecks, these queues are sometimes consolidated in a centralized storage area. Dedicated queues are rarely seen in modular manufacturing, with the exception of panelized components that can be efficiently stacked on edge. The combination of multiple bottlenecks, large queue size (driven by high process time variability) and module size (averaging about 700 square feet) makes dedicated queues prohibitively expensive. Instead, manufacturers have adopted a variety of measures to reduce the impact of floating bottlenecks.

- Asynchronous line movement - Allows downstream line movement, even when a bottleneck has blocked a facility-constrained workstation. Note that upstream line movement is still not possible.
- Overlapping workstations (Askin and Standridge 1993) – The policy to allow most work groups to migrate freely up and down the line effectively decouples work groups from cyclic line movement. This creates a project-like environment for work groups after roof set that resembles the construction site “parade of trades” (Tommelein et al 1999).
- Soft precedences - To minimize delay, a downstream workgroup will often attempt to begin

work in a module before the predecessor activity is fully complete, perhaps following close behind on a room-by-room basis.

- Shop floor planning – To prevent consecutive “problem” modules from choking the same bottleneck, manufacturing planners sequence the line by distributing the “problem” modules across the schedule. At the same time, they reassign cross-trained utility workers or expeditors to the work group at risk of becoming the bottleneck. Unfortunately, since manufacturers have little understanding of the root causes of process time variability, planning is ad hoc and haphazard at best. Furthermore, utility workers are invariably assigned to cover absenteeism and are often unavailable to assist with bottlenecks.
- Real-time shop floor control – Since manufacturers find it difficult to predict where and when floating bottlenecks will occur, shop floor control often takes the form of reactive reassignment of personnel. This often takes place after a bottleneck has started to cause delays and work groups are idled. Since workers often slow their pace to match that of the bottlenecking operation, supervision may not even recognize the bottleneck until long after it has started to affect the line. By then, the situation may already be out of control.

Clearly, existing measures have not resolved the challenge of floating bottlenecks. They continue to disrupt the production floor, reducing capacity, quality and productivity. The disruption also discourages manufacturers from becoming more aggressive in design customization. Together, these factors weaken the overall competitive position of modular homebuilding and slow the inevitable industrialization of homebuilding.

CURRENT STATE OF THE ART

Modular production is a unique hybrid of manufacturing and construction. It can be characterized as a series of housing construction projects taking place on a fast-paced (relative to construction) moving line. Relevant research areas include industrialized housing, manufacturing systems and construction management with specialty areas including lean production, theory of constraints, floating bottlenecks, production analysis/modeling, lean construction, even flow construction, line of balance, and construction labor measurement and modeling.

This author has worked with the modular industry since 1997, identifying and addressing production challenges. Research efforts have included: characterization of baseline production capabilities (Mullens 1998), studies of specific process activities ((Mullens 1998), manufacturing simulation (Mullens 1998, Mullens 2001a, Mullens 2001c, Nasereddin et al 2002), new factory design (Mullens 1998, Mullens 2000, Mullens 2001a, Mullens 2001c, Mullens 2002a, Mullens 2003), on-site set process improvement (Hickory Consortium 2000), on-site finish process improvement (Mullens 2001b, Mullens 2002b, Hickory Consortium 2003, Mullens & Kelley 2002, Mullens & Kelley 2003), quality systems (Hickory Consortium 2000, Mullens 2001b, Mullens 2002b Elshennawy et al 2002), incentive systems (Mullens Dec. 2002, Hickory Consortium 2003), and shop floor control (Mullens 2001c, Mullens 2002a, Arif et al 2002, Mullens 2003). Detailed research results were presented annually to members of the Quality Modular Building Task Force, our industry partners. Note that some reports are confidential as dictated by our industry research partners.

Related research has been conducted for the manufactured housing (HUD Code) industry (Abu Hammad 2001, Senghore 2001, Mehrotra 2002, Banerjee 2003, Jeong 2003). Abu Hammad (2003) summarizes much of this research. Finding include:

- Bottlenecks are a key problem. An activity streamlining model based on critical path methods is proposed for factory design to balance the line and resolve bottlenecks. The approach assumes an average duration for each production activity and therefore addresses the static bottleneck problem, not the dynamic floating bottleneck problem.
- Simulation can be used to assess the impact of dynamic bottlenecks. Proposed models assume that only house length affects production performance. This may be an oversimplification, even for the HUD Code units, which have considerably less design customization than modular. In addition, the measures used by manufacturers to manage floating bottlenecks make it very difficult to simulate accurately.
- Layout can affect productivity. Alternative line designs such as the spine, J-shape and central layout are claimed to offer productivity improvements by as much as four times over that of existing U-shape systems.
- Modern equipment (e.g., faster cranes) and less labor intensive line movement is needed.
- Broad adoption of information technologies such as Enterprise Resource Planning (ERP) systems (Mentzer 2002) is recommended.

A critical limitation of this research duly noted by the authors is the difficulty in obtaining activity process times for analysis and planning. Contributing factors include: 1) frequent changes in work force size, movement of workers between stations, long cycle times, and visual obstructions (e.g., walls).

Many production issues challenging modular manufacturers are not unique to industrialized homebuilding and have been addressed in the broader production literature. Much of modern production thought originated with the Toyota Production System (Ohno 1988). Lean production (Womack and Jones 1996) is the latest manifestation of this production philosophy. Lean production is based on five fundamental principles: 1) identify what the customer values, 2) identify the value stream (the steps necessary to create value for the customer) and challenge all wasted steps, 3) produce the product when the customer wants it and, once started, keep the product flowing continuously through the value stream, 4) introduce *pull* between all steps where continuous flow is impossible, and 5) manage toward perfection. In general, modular homebuilders are better positioned than site builders to conform to lean production principles.

The Theory of Constraints (TOC) (Goldratt 1992) identifies two primary contributors to bottlenecks in progressive manufacturing: process dependencies and process variability. Much of TOC thought is focused on keeping the bottleneck busy: minimizing set-up time, eliminating breaks or idle time, and assuring part availability. To assure part availability TOC advocates unbalanced line capacity – providing excess capacity for feeder operations to prevent starvation at the bottleneck. Buffers are recommended to mitigate remaining variations in flow. TOC largely dismisses the subject of floating bottlenecks. Hopp and Spearman (2000) acknowledge the likelihood of floating bottlenecks when manufacturing diverse or customized products on the same flow line. They suggest adding capacity when capacity is cheap and developing independent cells or "factories within a factory" to separate larger operations with floating bottlenecks into independent lines, each with a more easily controlled stationary bottleneck.

They also advocate a linear programming approach to address the longer term issues of optimum product mix and workforce size. They do not address the shorter term shop floor issues that disrupt modular manufacturing.

Optimization can be used to balance activities and sequence orders on flow lines. Line balance, the assignment of activities to workstations/workers along the line, is critical on most flow lines since it dictates the pace and efficiency of the line. Askin and Standridge (1993) review a number of analytical line balancing algorithms. Line balancing takes on a distinct construction-like character in modular production, due to the organization of the workforce into mobile, trade-oriented teams. This topic is addressed later in the context of construction. Sequencing custom modules on a flow line is analogous to the difficult m machine flow shop problem. Askin and Standridge (1993) propose the use of Johnsons Algorithm as a heuristic. Hopp and Spearman (1996) suggest that simulation modeling can be used to evaluate prospective schedules, but stress that this requires real time production status information and a decision support system.

Modular production bears a striking resemblance to site-built housing construction, with several important differences: 1) it takes place inside a factory on a moving line and 2) construction crews are a dedicated resource and the “parade of trades” (Tommelein 1999) happens quickly. Therefore, construction literature is relevant. Koskela (1993) uses lean production principles to derive the philosophy of lean construction (LC). A fundamental principle of LC is maintaining continuous flow. Ballard and Howell (1994) state that achieving reliable workflow is possible only when sources of variability are controlled. They identify the quality of weekly work crew assignments as a key driver of variability, with quality assignments shielding downstream production crews from work flow uncertainty. System performance is measured by the percent planned activities completed (PPC) - the percentage of the total number of work assignments planned that were successfully completed. Ballard and Howell (1998) suggest that remaining workflow variability can be mitigated through the use of plan buffers, surge piles and flexible capacity. Plan buffers refer to a backlog of reliable assignments for crews. Surge piles take the form of raw and processed materials. Flexible capacity refers to intentional underutilization of a crew or the flexible use of cross-trained workers.

Arditi et al (2001) describe the use of linear scheduling methods and line of balance techniques for planning and controlling highly repetitive construction projects. The strategy is to balance work teams to produce completed units at approximately the same rate. Activities with large work content may require more than one crew to reach a balance. It may not be possible to balance activities with low work content, thus requiring that a crew be idled or called in only when required. Arditi presents a model to optimize resource constraints (number of crews) to meet given delivery deadlines. El-Rayes et al (2002) develop an object-oriented model that can generate efficient schedules for repetitive housing construction. Bashford et al (2003) discuss the use of the “even flow” workflow-leveling strategy intended to reduce the variability in workflow for trade subcontractors. Responding to large month to month variability observed in housing starts, “even flow” attempts to provide a uniform number of starts throughout the life of a multi-house project. In general, the housing industry has found these methods unsatisfactory for production control on a large scale involving numerous independent subcontractors.

Planning and control in both the production and construction domains assume the availability of accurate activity-level labor data. Experience bolstered by previous research findings confirms the difficulty in measuring construction work. This can be an even greater challenge for modular manufacturers, who build custom homes at a rapid pace. They not only need to measure labor performance, but also predict labor needs for new/customized models. Oglesby et al (1989) describe work sampling and time study methods of data collection using direct observation, time-lapse photography and video technologies. Recent research has attempted to use time-lapse web-cam technology. Linear regression (Leung and Tam 1999) and neural nets (AbouRizk et al 2001) have been used for labor modeling.

FUTURE RESEARCH DIRECTIONS

Future research directions can be developed by starting with a vision for the modular factory. One such vision might be:

> *The factory will produce high quality custom homes for all homebuyers, from entry level through luxury. The factory will provide a productive and safe environment that will offer excellent value and timely delivery for the homebuyer, a safe and rewarding career for employees and a profitable investment for owners. Ample capacity will be provided to accommodate forecasted short-term growth. Factory design will be modular and flexible to facilitate expansion to accommodate more rapid or longer-term growth. Materials will arrive in the factory just in time to support production and be staged close to the point of use on the line. Mechanization/automation will be provided for both material handling and manufacturing processes when justified to eliminate injuries, minimize excessive physical exertion, assure capacity and boost productivity. Production documentation will be timely and accurate. Employees will know the status of any order, recognize the restrictions at any workstation or work group, and be able to react so that schedule and customer demands can be profitably met. As a result, rework will be minimal and production flow will be smooth and synchronous with demand. Employee work groups will be actively engaged in continuous improvement and will share in the resulting profits.*

Although every aspect of this vision can benefit from new knowledge, the challenge of floating bottlenecks impedes the vision of smooth production flow. Production flow is a function of line length, location of facility-constrained workstations, module sequencing, and activity process times. Process times are driven by module design, process/material handling technologies, staffing levels, and location of material staging and support workshops. These key drivers of production flow can be classified into four general areas: module design, process and material handling technology, factory configuration, and shop floor control. All are interrelated and are viable directions for future research.

While the primary focus of this paper is production systems, the potential impact of innovative module design and advanced process and material handling technology should not be underestimated. Modular manufacturers seek new designs, materials, equipment and systems that are engineered specifically for factory production and that provide strategic advantage over site builders. For example, on the framing side, producing and shipping roofs separately will enhance design flexibility by allowing higher ceilings and taller roof lines. At the same time it will smooth production flow by eliminating a critical facility-constrained workstation (roof set), effectively decoupling line flow from the highly variable roof assembly operation. On the finish side, an open building approach to interior finishing (Larson and Mullens 2002) would outsource most interior finishing to specialized first tier suppliers, who could be better able to meet specific homebuyer needs. Interior finish processes are particularly difficult and time-consuming - factory studies have shown that 55% of all factory labor is used for interior finish and 70% of all factory rework is related to defects in interior finish (Mullens 1998).

Factory configuration can play a significant role in reducing the impact of floating bottlenecks. There should be enough line workstations to provide a total flow time in which all critical path activities can be completed. Critical path activities should be examined in greater detail to see if any sub-activities can be taken off the critical path by moving off-line (e.g., wiring walls and roofs at their sub-assembly stations). The impact of facility-constrained workstations might be reduced – perhaps by providing expanded material handling access to line workstations from off-line feeder stations. Dedicated queueing should be considered to buffer the impact of bottlenecks: off-line, on the line, or centralized. Off-line feeder stations, material staging and support workshops should be located near their most likely point of use on the line. Where there is insufficient floorspace to support all activities at a workstation, consideration must be given to adding line workstations or moving non-critical path activities downstream or off-line. These strategies are non-trivial, even if variability is ignored. However, they quickly become intractable when variability caused by randomness, module design, and shared resources is considered. Research should include systematic strategies for developing and evaluating options. While analytical heuristics may be useful, simulation tools are likely to be essential.

Innovation in shop floor control is essential if floating bottlenecks are to be managed. Consider the following (Hopp and Spearman 2000):

"When luck is on your side, you can do without brains."

Giordano Bruno (burned at the stake by the inquisition in 1600)

"The more you know the luckier you get"

J.R. Ewing ("Dallas" television series)

Effective shop floor control, like factory configuration, begins with the acquisition of data - process times. Traditional approaches to collecting housing process times are cost prohibitive and unreliable – current data are simply not available. One answer may lie in real time data collection tools such as automatic identification (e.g., bar code scanning, radio frequency identification). Significant challenges lie in developing ubiquitous, unobtrusive systems that work in dirty, rough, open (even outdoor) environments. Using these tools on a perpetual basis can provide the data needed for real time shop floor control and longer-term continuous improvement. Raw data, however, provides little actual management information. Predictive labor models, using regression or neural nets, are needed for planning and control. Accurate yet pragmatic approaches must be developed, including the opportunity for real time model updates based on current data. Actual bottleneck management will require the development of decision support systems that assist in module scheduling and labor assignment. Technologies are likely to include optimization, simulation, and visualization tools for generating and evaluating alternatives.

The proposed research directions will enhance all segments of homebuilding. HUD Code manufacturers will be better able to manage existing bottlenecks and are likely to become more aggressive in expanding product offerings. Site builders will be able to use the same concepts to better manage the parade of trades, reducing lead times and costs.

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