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The impact of product choice on lean homebuilding

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Abstract

Purpose – The purpose of this paper is to better define the relationships between product variety and lean production in enabling mass customization in industrialized homebuilding.

Design/methodology/approach – This study includes a case study analysis of two housing plants that instituted lean production systems. For each company, the case study documented the company's background, the product choice offered, the lean implementation approach used, the results obtained, and the effect of product choice on the lean implementation. Using these case study findings, common trends were identified and used to develop guidelines for an effective mass customization strategy for industrialized homebuilders. This paper summarizes the extensive findings for one of the two plants and provides the recommended guidelines developed from common trends identified at both plants.

Findings – Case study findings indicated that product choice does not necessarily make the implementation of lean concepts more difficult. In fact, good lean concepts (e.g. continuous flow, pull system, workload leveling, defect-free processes, standard tasks, good visual control, and reliable technology) were also good concepts for (or easily accommodated) handling a range of product choice.

Research limitations/implications – Research findings are limited by the small number of plants involved in the study.

Originality/value – The paper makes an important contribution to the understanding of both lean production and mass customization, identifying the lean principles that facilitate mass customization for industrialized homebuilders. Findings also provide useful guidelines for builders interested in better addressing specific customer needs, while managing the operational complexities resulting from product variety.

Keywords Construction industry, Lean production, Mass customization, Product design, Housing

Paper type Case study

Introduction

Current housing trends point to an increasing interest from homebuyers to demand houses that reflect their personal and unique styles, and which are individually configured according to these needs (NAHB, 2004). This creates pressure on builders who are often reluctant to sacrifice production efficiencies by deviating from standard models. Customization can disrupt the entire estimating, production, delivery and management process, making it even more difficult to manage homebuilding efficiently and effectively. The question faced by homebuilders in these conditions is how to manage this trade-off and deliver exactly what homebuyers want, at reasonable prices and lead times with minimal disruptions in efficiencies.

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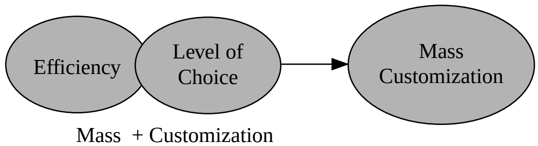
Mass customization and lean production

Mass customization is the ability to design and manufacture customized products at mass production efficiency and speed (Pine, 1993) (Figure 1). Duray *et al.* (2000) investigated mass customization from a generic manufacturing perspective. Their classification of mass customization strategies is based on the timing of customer involvement and the type of product modularity, evaluated along the production cycle: design, fabrication, assembly and use. Barlow *et al.* (2003) classified mass customization strategies used by five of Japan's leading industrialized homebuilders, using Lampel and Mintzberg's (1996) continuum of five degrees of customization. The three mass customization principles shown in Table I are summarized from Duray and Barlow and extended to the industrialized housing industry. These mass customization principles were used to develop the pre-determined interview questions for data collection.

Womack (2005) defines lean as getting the right things, to the right place, at the right time, in the right quantity while minimizing waste and being flexible and open to change. Liker (2004) identified 14 principles that drive the techniques and tools of the Toyota Production System, also known as the lean production. Principles 2 through 8, "the right process will produce the right results", are renumbered and summarized in Table II. These seven lean principles were used to structure the analysis of lean improvement in the case study.

Womack emphasizes that lean concepts can be implemented in any industry, but keeping in mind the industry's own characteristics. Koskela (1993) addresses the application of lean in the construction industry, emphasizing the importance of process flow and the conversion of inputs into finished products. Mullens (2004) notes the unique characteristics of industrialized housing production:

- complex product with large components;
- few small and fixed stations located along side of the main production line (i.e. plumbing);
- few large and fixed stations located along side of the main production line (i.e. wall build);
- labor and material flow to the product while product flows continuously on the main production line;
- some activities could stop the main line roll because they need to happen at certain locations (i.e. large components need crane);
- multi-operator teams perform specialty work (i.e. trades), making it difficult to measure work content and cycle time for each unit; and
- little inventory due to lack of space.



Source: Nahmens (2007)

Figure 1.
Mass customization definition

Principles	Description
Postpone where customization impacts the production process	Delaying customization is a function of product architecture and process design. If the architecture permits a delay in customization, then it must be built into the production process This principle may be used in several ways: (1) component build-to-stock and then final product customize-to-order (provides benefits of process standardization and cycle time reduction), or (2) complete build-to-order (providing benefit of process standardization and flexibility for customer to continue customization during early production – note that this flexibility can rarely be exercised due to the short time window)
Use modular architecture and product platform designs with common components to achieve product customization	*Modularity/commonality* – refers to the tightness of coupling between components and the degree to which the rules of the system architecture enable or prohibit the mix-and-match of components MC encourages the use of a small set of standardized, plug compatible components to create this choice Changes in the core architecture of the product for each customized configuration might limit the use of this principle
Design the production process so that it can facilitate the production of a variety of products, while accommodating different product mix and volume	Refers to the configuration of the production process and how it could support a given mass customization strategy. Process flexibility also defines the limitations of the factory *Labor flexibility* – refers to the number and variety of activities that employees can perform without incurring higher cycle time or large changes in performance outcomes (i.e. cross-trained workforce) *Layout* – refers to the arrangement of the area layout to facilitate the production of a variety of products (i.e. cellular production, queuing subassemblies, ability to perform activity upstream/downstream of preferred workstation – may be facilitated by equipment flexibility) *Equipment/tools* – refers to the flexibility of equipment and tools to facilitate the production of a variety of products (i.e. a fixture that can accommodate a variety of sizes of window frame)

Table I.
Mass customization principles extended for the industrialized housing industry (Nahmens, 2007 expanded from Duray *et al.*, 2000; Barlow *et al.*, 2003; Mullens, 2004)

Mullens (2004) also suggested that these characteristics dictated how lean principles are implemented, e.g. queuing availability and the flexibility for work to migrate upstream/downstream can mitigate some of the inefficiencies resulting from home variation.

Although mass customization and lean production are both being considered by innovative industrialized homebuilders, there is some debate about the concurrent use

	Principles	Description
1.	Create continuous process flow to bring problems to the surface	One-piece flow Once started, add value without interruption – create continuous flow Standardize work to stabilize flow Synchronize flows – synchronize production activities so that one does not start until the previous activity has finished Use flow oriented layout Use inventory buffers in the right places Reduce cycle time
2.	Use "pull" systems to avoid overproduction	Pull from the customer end – including both internal and external customers Pull services, components and materials just when necessary Use "supermarkets" – controlled inventory Use visual control – kanban systems
3.	Level out the workload (Heijunka)	Eliminate overburden to people and equipment (Muri) Eliminate unevenness in the production schedule (Mura) Level out the workload of all manufacturing and service process – a true balanced lean flow of work
4.	Build a culture of stopping to fix problems, to get quality right the first time	Continuously improve – reveal and solve problems at the source, as they occur Deliver perfect first time quality – "build in quality" (i.e. poka yoke, jidoka-Japanese word for automation with a human touch) Keep quality control simple and involve team members Create culture – involve and empower employees to continuously improve
5.	Standardized tasks are the foundation for continuous improvement and employee empowerment	Standardized work – takt time, sequence of processes and standardized stock on hand – employees should participate in the writing of standard procedures Rules and procedures are used as enabling tools – performance standards are used in parallel with information on best practices for achieving them Supports organizational learning – "pilot teams" Empowered employees Standardized work should allow customization to different levels of skill/experience and should guide flexible improvisation

(*continued*)

Table II.
Lean principles associated with "the right process will produce the right results" (Liker, 2004)

	Principles	Description
6.	Use visual control so no problems are hidden	Clean it up, Make it visual – use simple visual control systems (e.g. 5S) Integrate the visual control systems to the value-added work – use visual control to improve flow Reduce reports to one piece of paper whenever possible
7.	Use only reliable, thoroughly tested technology that serves your people and processes	Use technology to support people, process and values Technology must be flexible to accommodate process improvement as business changes Supplement the system information with "genchi genbutsu" (go look, go see) Use tested technology that can improve flow – pilot tests

Table II.

of both techniques. Although the goal of both mass customization and lean production is to reach mass production efficiencies, lean principles are not necessarily concerned with increasing product variety. Qiao *et al.* (2004) indicate that the efficiency of lean is diminished in an environment where product mix changes irregularly and drastically and where downstream processes require randomly customized parts on flexible schedules to be supplied from their predecessor processes on short notice. Under these conditions, they argue that extra inventory, equipment, and labor are needed to compensate for product and order variations. Tu *et al.* (2001) and Da Silveira *et al.* (2001) argue that lean production is an important factor that supports mass customization. This view is supported by Chandra and Grabis (2004), who argue that lean production can be an effective strategy for customized products with stable demand. The purpose of this paper is to better define the relationships between lean production and product variety in enabling mass customization in industrialized homebuilding.

Methodology

The research used a case study approach to identify and analyze the effects of mass customization on lean implementation and vice versa. Two of nine industrialized housing plants actively involved in an industry-wide Lean Initiative (Manufactured Housing Research Alliance, 2007) were selected for the study. Since the lean implementation was in its early stages, a specific department was selected. Plant data (e.g. company's background, product choice and lean implementation) were collected using two approaches, interviews and on-site observation:

- *Interviews* – The main purpose of the interviews was to capture the level of choice offered and the mechanisms to accomplish it. A two tier interview (e.g. plant and department) with each plant was conducted. The pre-determined interview questions (Nahmens, 2007) were aligned with the mass customization principles identified in the literature. A wide range of employees, from CEOs to trade workers, were interviewed.

- *Observations* – The authors observed lean rapid process improvement (RPI) events in the selected departments. An RPI event is a rapid form of Kaizen or "continuous improvement" focused on a specific area. The RPI objective, initial process, improved process, and accomplishments were documented.

After gathering the case study data, a detailed analysis of the RPI results were performed. The impact of each dimension of choice on each lean production principle was assessed. Did the implementation of lean principles make it more difficult to offer product variety? Did offering product choice make it more difficult to implement lean principles? Finally, these common trends were used to develop guidelines for an effective mass customization strategy for industrialized homebuilders.

Case study findings: lean results and mass customization analysis

This section summarizes the extensive findings for one of the two plants included in the case study.

Company's background. The plant manufactures HUD-code homes for a moderate market segment. Production rate varies with orders, with a capacity of six floors (modules) per day. Production was running at capacity during the study.

Product choice offered. The plant offers their customers 47 different home models in configurations of single, double or triple (modules) wide. Floor plans range from 737 to 2,458 square feet, 2 to 6 bedrooms and 1 to 3 bathrooms. The plant allows customers to choose from a pre-determined set of standard options or features (e.g. six wallpaper styles) and offers several upgrade features (e.g. insulation packages, stainless steel appliances).

Lean implementation. The plant conducted an RPI event in the interior wall build area where interior (partition) and end walls are produced. Assembly takes place on four framing tables, three for partition walls and one for end walls). Assembly includes building the frame and installing vinyl covered drywall board (referred to as "S/R") on one side of the frame. The initial process flow is shown in Figure 2. All materials used in wall assembly (e.g. top and bottom plates, studs, rough opening framing components, and wallboard) were pre-cut to size in supporting workstations in the area. The initial layout, including equipment location, material staging, and material flows, is shown in a spaghetti diagram (Figure 3).

The over-riding issue in the wall build area was that it was unable to consistently keep pace with the main production line, creating a bottleneck to line flow and restricting overall plant capacity. The takt (cycle) time on the main line was 48 min, while the cycle time of the wall build area was 65 min during peak production periods. Various forms of waste were evident in the process. As evidenced by the spaghetti diagram (Figure 3), flows went in every direction, many were lengthy, and they often crossed other flows, creating congestion. Layout was a key issue. One chop saw was located near the raw material staging area (stud roller bed) and the cut lumber staging cart, while the other two saws required longer moves. The cut lumber staging cart served one framing table well, but not the other two interior wall tables. Although there was a designated area to stage raw wallboard (e.g. S/R roller bed), it was not fully used because of limited accessibility. Instead, material handlers often staged bundles of

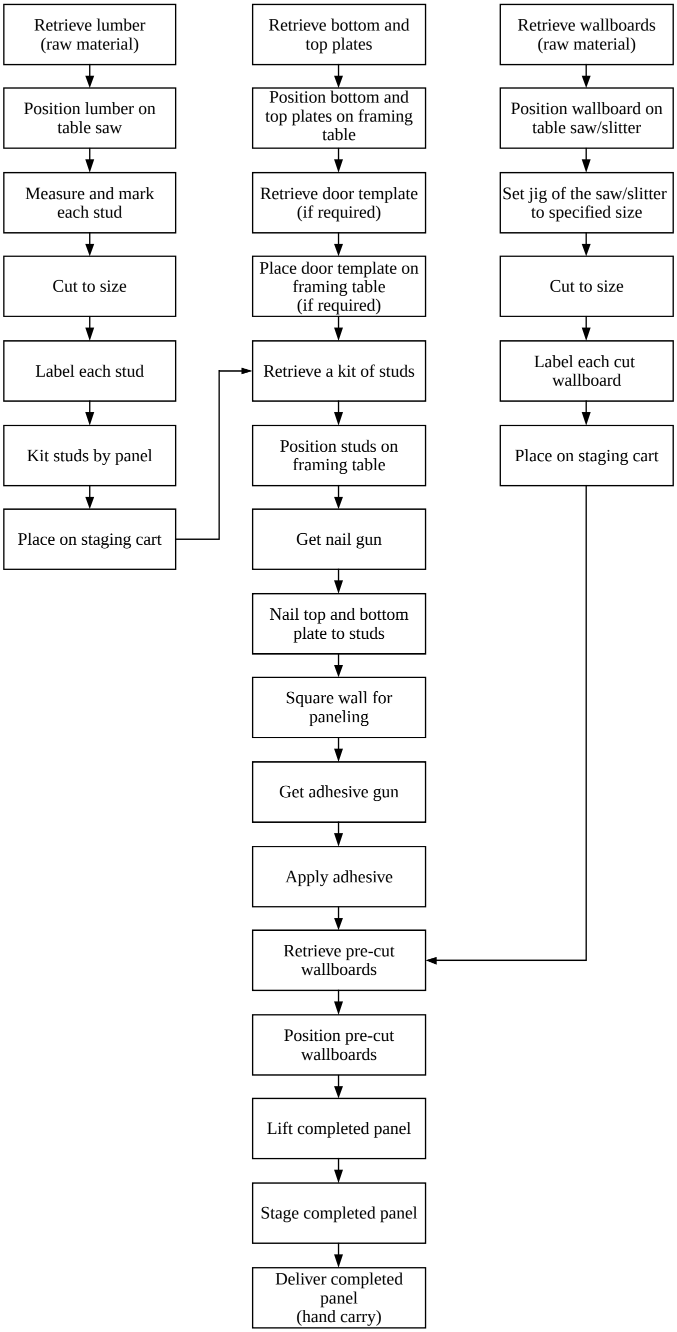


Figure 2.
Process flow chart of old process

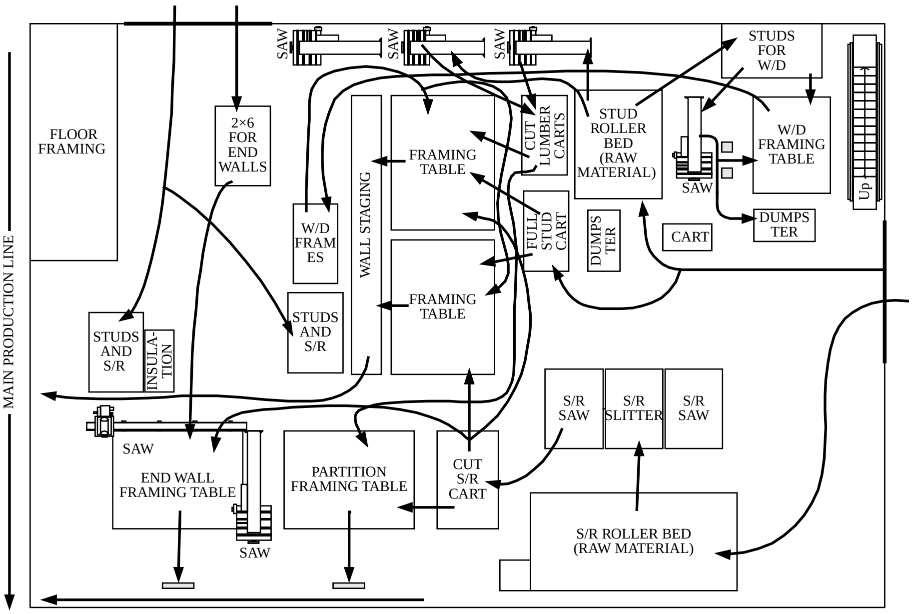


Figure 3.
Initial spaghetti diagram of interior wall build area

wallboard on the floor in any open space. This further congested the area. The staging area for the pre-cut wallboard (cut S/R cart) was close to two framing tables, but further from the other two and framers had to travel longer distances to retrieve materials. The L-shaped orientation of the framing tables limited use of the crane to only those tables on the lower side and forced framers on the central tables to drag finished walls through the middle of the wall build area to the main line. This caused further congestion in the area. Since the framing tables were viewed as the immediate bottleneck, framer movement of materials to the tables and finished panels to the line were considered critically important. Framers also had to find and sort the components in their kits as they positioned them on the tables.

Basic supporting activities were not efficient. For example, process instructions for the sawyers were not straight forward and no jigs were provided to aid in cutting. Sawyers were not always able to keep up with the framing tables, causing critical downtime on the already bottlenecked tables. Imbalances in panel assignments to the framing tables further bottlenecked panel flow to the main line. This became apparent when one table completed its assigned panels for one module and started building panels for the next module, while the other tables struggled to complete panels for the previous module. This situation suggested poor information flow between the supervisor and the workers and an overall lack of coordination. Workers relied heavily on the area supervisor because the process was not standardized.

The focus of the RPI event was to rearrange the layout to improve process flow. The improved layout (Figure 4) also promotes visual management because it was clutter free and well organized. Some of the changes accomplished in the RPI included:

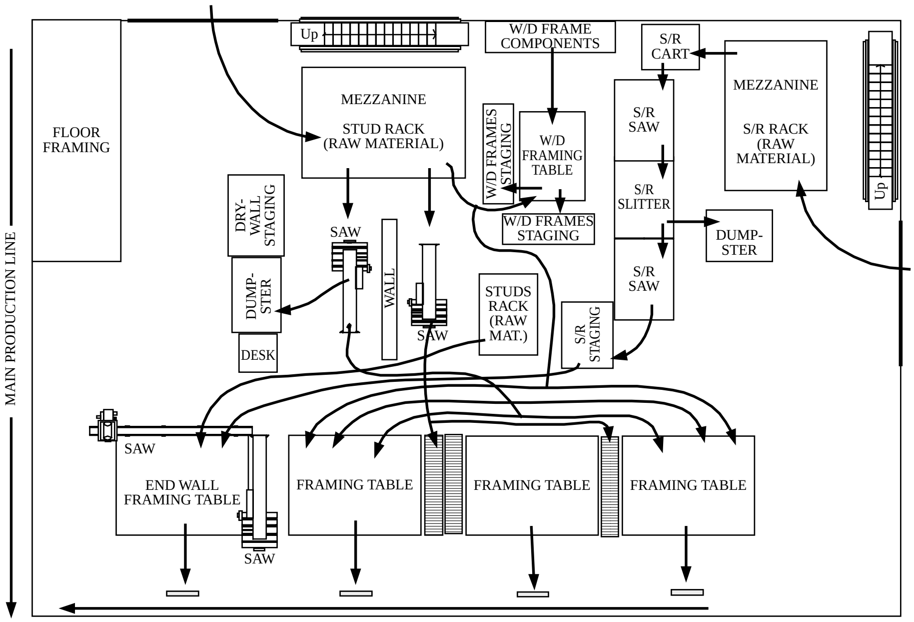


Figure 4.
Improved spaghetti diagram of interior wall build area

- The two central framing tables were moved and aligned with the lower two tables, allowing finished walls to be staged so that they were accessible by the bridge crane that was used to deliver finished walls to the main line.
- The stud cutting activity was rearranged to achieve a straight-line flow. The lumber storage rack was relocated on the upper wall to provide in-line flow for the material handler during delivery. Two chop saws were turned 90° and relocated directly below the storage racks. New pre-cut component staging bins were located directly adjacent to the framing tables (each bin can hold studs for up to ten panels). Sawyers place cut components directly in the bins, eliminating the need for framers to leave their tables to obtain components.
- Wallboard cutting was rearranged to smooth flow. Raw material was staged in a new rack that held six different colors of wallboard, two different sizes per color. The new rack is easy to replenish from the front and puts less strain on cutters as they pull material and transport it to the cutting tables (e.g. pulling over their heads). The saws/slitter was relocated away from the traffic path, facilitating wallboard handling. A dumpster was placed immediately behind the saws/slitter for scrap. Next to the saws/slitter a staging area for the cut wallboards was designated.
- Half of an existing mezzanine, used for insulation storage, was moved to open up floor space for the improved layout.
- Process documentation was improved for cutting wood components and jigs were provided to simplify cutting and improve quality.

- A new procedure and labeling system was developed to organize pre-cut materials in the wood staging bins at the framing tables. The procedure allows everyone in the area to visually monitor production performance at each table.
- Area supervision was trained to monitor the status of each table and the main production line and manage activities in the area to minimize disruptions to main line flow.

The plant spent $25,786 to improve the wall build area. The area is now synchronized with the main production line. Space was reduced by 12 percent. Drywall damage was reduced by 10 percent. Labor was reduced by about 30 percent – a labor savings of over $70,000 annually. These workers were transferred to other departments with labor needs, eliminating the need to hire and train three new workers.

Mass customization analysis. The impact of each dimension of choice on each lean production principle was assessed. Did the implementation of lean principles make it more difficult to offer product variety? Did offering product choice make it more difficult to implement lean principles? The following negative propositions were used to frame this analysis:

P1. Product choice makes continuous process flow more difficult.

P2. Product choice makes pull systems more difficult.

P3. Product choice makes leveling out the workload more difficult.

P4. Product choice makes the development of a quality culture more difficult.

P5. Product choice makes the development of standardized tasks more difficult.

P6. Product choice makes visual control more difficult.

P7. Product choice makes the use of technology (that serves people and process) more difficult.

There are several dimensions of product choice related to interior walls: quantity, size, wallpaper color, and number of window/door openings. The number of walls ranges from 14 to 27 per house, with a house consisting of 2 modules. There are a variety of interior wall sizes (heights and lengths) depending on the house model. Wall height varies with respect to the location within the house. Interior walls that are parallel to the end walls are sloped at the top to match the roof slope (e.g. wall studs are progressively shorter in length). The company offers six different wallpaper colors for interior walls. Usually, the homebuyer selects the wallpaper color and the house model. The quantity, size and the number of window/door openings are dictated by the house model:

P1. Product choice makes continuous process flow more difficult.

Typically, product choice causes work content and labor hours to vary. Labor hours vary with procedural changes associated with different choices (e.g. materials/components, varying dimensions and/or complexity of each configuration). This variation in cycle time makes it difficult to establish continuous flow as it limits the possibility of smooth hand-offs at the different stages of the production process. Together, with an increase in complexity, cycle time variation also increases the likelihood of quality problems, as workers hurry up, then wait. Product choice is also likely to require different production equipment and tools. This can make layouts more complex, resulting in inefficient space utilization and flow. Product choice may also increase staging requirements for raw materials and sub-assemblies, having similar negative impacts on space and flows.

The range of product choice in the wall build area benefited from the development of more continuous process flow. Nonetheless, the range of product choice and the complexity of activities required to achieve this choice did impact the lean implementation. Several important continuous flow concepts were critical:

- *Off-line parallel production* – From a lean perspective, the movement of wall build activities off the main line, while still providing continuous, but parallel flow, reduced main line, critical path cycle time. From a mass customization standpoint, it effectively disconnected the main line from any cycle time variability resulting from product choice. These advantages were obtained at the cost of dedicating floor space for the off-line activities.
- *Process improvement* – Process improvement in wall build not only improved productivity and quality, but also smoothed variability associated with product choice. The use of jigs for cutting wall-specific kits of studs and the use of templates for assembling door openings greatly improved productivity, increased quality, and helped to accommodate product choice without increasing any effort and without affecting the flow. From a mass customization standpoint, these jigs and templates virtually eliminated cycle time variability associated with product choice. A challenge for the lean improvement team was building cost-efficient wall jigs for the large number of unique wall configurations. As a first step, the lean team agreed to build jigs for the most frequently used walls.
- *Layout improvement* – Layout improvement in wall build facilitated continuous flow by reducing travel times, congestion and delays and reducing variability associated with product choice. The new layout in the wall build area moved equipment and materials closer together, shortening process flow. A critical part of this rearrangement was moving the two central framing tables under the crane, minimizing congestion. Providing controlled staging for pre-cut components and finished walls also facilitated continuous flow and limited the production of WIP inventory. From a mass customization standpoint, moving wall build activities closer together also reduced the variability associated with handling different quantities and configurations of walls. Moving the two central framing tables under the crane made it very easy to move larger numbers of larger panels to the line without disrupting other activities in the department. A challenge for the lean team was providing easily accessible staging locations for each color wallboard. Although it was difficult, it was accomplished by using multi-level racking.

In general, these results suggest that good concepts for lean, efficient continuous flow were also good concepts for (or easily accommodated) handling a range of product choice. Results showed that the creation of continuous process flow is feasible for different levels of product choice, but that the success may depend on redesigning the process and layout to eliminate all forms of waste and reduce the impact of product choice on cycle times and quality (e.g. reducing the variability caused by product choice). Thus, *P1* is rejected:

P2. Product choice makes pull systems more difficult.

The lean implementation in the wall build area used a build-to-order production control concept that incorporated component kitting by order. Individual walls are sequenced for production based on main line requirements. Walls are pulled to the line from the wall staging areas in the assembly sequence needed by the current module in the wall set workstation. Individual walls are built on framing tables when space opens up in the limited staging area adjacent to each table. Wall framers pull the next kit of components (representing the next wall needed on the line) from the component bin located next to each table. Space in each bin is limited to control production. Component cutters cut wood and wallboard components for the next wall needed on the line when space opens up in the respective component bins. They pull raw materials from stud and wallboard staging racks that provide one opening for each raw material. When material is near empty, material handlers replenish material from outside storage. This pull process assures that the right material will be available for each step of the process when it is needed, without oversupply.

Using this process, each raw material has a unique staging location. As product choice increases (e.g. wallboard colors) this scheme becomes more complex and less efficient. Note, however, that the lean team accommodated these choices by using multi-level racking. Note that stud components for all wall configurations were cut from the same stud material and, thus, did not add complexity. For pre-cut components and sub-assemblies, workers pull built-to-order kits, instead of unique part numbers. Pulling built-to-order kits provides a pull system without having to inventory and control every unique component and sub-assembly used in the process.

The continuous flow pull system was developed to assure that the right material was available when needed, without oversupply. Built-to-order kits were used to make the pull process tractable, given the many product configurations and component sizes. Staging and controlling unique raw materials was the greatest challenge, but successful solutions were developed by the lean implementation team. Thus, *P2* was rejected:

P3. Product choice makes leveling out the workload more difficult.

Typically, management does not schedule the main line to accommodate interior wall variation; other more important factors (e.g. area, roof complexity) are used instead. However, workload balancing was greatly improved as a result of process changes in the wall build area. The use of jigs eliminated much of the variability associated with choice in the wood component cutting process and templates took some of this variability off the framing tables. Framing table loading was leveled with the use of component staging bins. These bins were replenished with components by the sawyers, who filled bins as they became empty with parts for the next wall needed on the main line. These improvements helped to mitigate variation and facilitate the processing of product choice.

Workload leveling for the choice factors of interior walls was not accomplished on the main line, where it would be most effective given the other factors addressed. However, workload leveling was improved in the wall build area by other local process improvements which helped mitigate variation and facilitate the processing of product choice. Thus, *P3* is rejected:

P4. Product choice makes the development of a quality culture more difficult.

Product choice introduces variation which can result in reduced quality and more rework. However, building quality into the process helps prevent quality issues from occurring. Further, building quality into the process enables the quick identification of defects, their root cause and the development and implementation of corrective action. As a result, only products satisfying the quality standards will be passed on to the next process on the production line and eventually to the customer. This is particularly important when building new configurations or offering choice, because of the deterioration of production efficiency due to rework. Further, there is no buffer inventory to fall back on in case of rework.

In this case process optimization mitigated much of the potential quality problems associated with product choice. The wall build area optimized processes to not only increase productivity, but to greatly enhance product quality over the range of product choice offered in the area. Jigs and templates implemented were designed to improve productivity, better handle product choice variation, and at the same time serve as a method to build quality into the procedures. The use of jigs to cut studs supported the implementation of work standards, which encourage product consistency and maintain proper quality standards. The number of jigs required was dictated by the level of product choice offered (e.g. home models offered). Similarly, door templates provided a more standard method for building various rough openings on the framing tables. Product choice (the number of unique opening sizes) dictated the number of templates required. Thus, the jigs and templates encourage defect-free processes (Jidoka).

In summary, process optimization mitigated much of the potential quality problems associated with product choice. Thus, *P4* is rejected:

P5. Product choice makes the development of standardized tasks more difficult.

The wall build area adopted optimized processes that in turn standardized production methods over the range of product choice offered in the area. The use of jigs for pre-cutting wall components simplified and standardized the process for a wide range of wall configurations. The component bin at the framing tables and the procedures for its use resulted in a standardized process, regardless of the number and configuration of walls. In addition, this procedure also standardized the sequence of the walls to be built.

While increased product choice is likely to increase standard process documentation, this can be mitigated by proper process selection – developing and selecting processes that use standard tools and methods to produce the range of choice offered. Thus, *P5* is rejected:

P6. Product choice makes visual control more difficult.

In the case study, the implementation of two lean concepts mitigated most of the potential visual control problems associated with product choice: build-to-order kitting and layout optimization. Build-to-order kitting was effective in reducing the number of WIP components that needed to be staged and tracked. Kits of walls (lot size one) and wall components were staged and tracked rather than individual wall components. Layout optimization in the wall build area was highly successful in facilitating visual control. The re-layout of the wall build area organized materials and equipment around simple straight-line flows. It also eliminated random clutter and congestion. The primary challenge for the lean team was staging for wallboards, which eventually required more space and equipment to stage varieties of colors and sizes.

Product choice did challenge the lean team in organizing the area and implementing visual control, primarily in staging unique raw materials. However, using lean concepts such as build-to-order kitting and layout optimization mitigated most of the potential visual control problems associated with product choice. Thus, *P6* is rejected:

P7. Product choice makes the use of technology (that serves people and process) more difficult.

Product choice typically makes process technology (mechanization and automation) more expensive and less productive. However, the proper use of technology can serve people and processes, freeing workers from repetitive, strenuous and dangerous tasks, adding capacity and enhancing process quality.

The wall build area used only simple process technologies. However, these technologies yielded substantial benefits: increasing productivity, improving quality, reducing variability associated with choice, and reducing strenuous tasks. These innovations included the component cutting jigs and overhead crane.

Clearly, the need to accommodate product choice limited the use of process technology. However, the use of the simple technologies adopted profoundly affected the productivity and quality in the wall build area and better enabled the area to accommodate product choice offered. Thus, *P7* is rejected.

In general, the case study showed that product choice does not necessarily make the implementation of lean concepts more difficult. Some lean concepts, like workload balancing and standardizing tasks, clearly facilitated the handling of product choice. Other lean concepts, like creating a continuous process flow, can be made to work well, even with increased choice.

Industry guidelines

Findings from the case study are summarized in the following set of guidelines for implementing the seven lean principles while maximizing product choice:

- Move activities affected by customization off the main production line. Develop off-line parallel processes that are synchronized to main line flow, delivering sub-assemblies on a just-in-time basis. A similar approach is to designate an off-line "customization" station for custom work. This strategy works from a lean perspective because it reduces the main line, critical path cycle time and from a mass customization perspective because it effectively disconnects the main line from any cycle time variability due to product choice. This strategy can be used in other activities such as building porches and dormers or preparing wiring harnesses.
- Improve and standardize activities that are affected by product choice. Develop common methods, equipment and tools that simultaneously are highly efficient, assure quality, and minimize process cycle time variation due to product choice.

This strategy can be used in the trim department, by pre-cutting and pulling trim kits for windows and doors.

- Move equipment and materials closer together. Utilize straight line, L or U-shaped flows. From a lean perspective, this reduces travel waste such as excessive travel time, congestion delay, and related damage. From a mass customization perspective, it reduces the variability of cycle time associated with the number of trips or movements to get material for different product configurations. This strategy can be used in all the departments across the plant.
- Use continuous flow systems whenever reasonable. When production flow needs to be disconnected due to process variability, use limited queues with kanbans to drive production. When product choice or product architecture results in many components, consider pulling materials in built-to-order kits, instead of unique part numbers. This strategy can control inventories and insure sub-assembly availability, even as product choice increases. This strategy can be used in the floor department, by cutting and pulling floor joists as a kit. This strategy can be used in the trim department, by pre-cutting and pulling trim kits for windows and doors.

Conclusion

In general, there are some benefits to be realized from the use of some lean principles in a mass customization environment. This reflects the similarities of both mass customization and lean production as far as their goal to reach mass production efficiencies. Lean principles are not necessarily concerned with increasing product variety. Typically, product standardization is associated with efficiency, and customization with inefficiency and high costs. The literature reflects this dichotomy, often distinguishing between creativity and efficiency (Benner and Tushman, 2002). Certainly, the tradeoff between customer choice and productivity, between creativity and efficiency will be a critical element of business strategy for 21st century manufacturers. This research demonstrates that the use of lean principles can support mass customization in reducing the impact of these tradeoffs. More specifically, the case studies showed that product choice does not necessarily make the implementation of lean concepts more difficult. Some lean concepts, like workload balancing and standardizing tasks, clearly facilitated the handling of product choice. Other lean concepts, like creating a continuous process flow, can be made to work well, even with increased choice.

Results from the mass customization analysis showed the effects of product variety on each lean principle. The creation of continuous process flow is feasible for different levels of product choice, but the success may depend on redesigning the process and layout to eliminate all forms of waste and reduce the impact of product choice on cycle times and quality (e.g. reducing the variability caused by product choice) (Principle 1). The pull system helped to assure that the right material was available when needed, without oversupply. Built-to-order kits were used to make the pull process tractable, given the many product configurations and component sizes. This facilitated the synchronization of offline operations with the main line and prevented the overproduction of components. Staging and controlling unique raw materials was the greatest challenge, but successful solutions were developed by the lean implementation team (Principle 2). Workload leveling for the choice factors (interior walls) in the lean case study plant was not accomplished on the main line, where it would be most effective. Other more important factors (e.g. area and roof complexity) were used instead. Workload leveling was improved in the area by local process improvements. These improvements helped to mitigate variation and facilitate the processing of product choice. Similarly, Ballard and Howell's (1994) results demonstrated the importance of workload balance, by identifying variation and instability of the flow as the main cause of unbalanced activities between construction trades (Principle 3). Process optimization was used to mitigate much of the potential quality problems associated with product choice (Principle 4). Process standardization promoted continuous improvement and employee empowerment in the lean case study plant. While increased product choice is likely to increase standard process documentation, this can be mitigated by proper process selection – developing and selecting processes that use standard tools and methods to produce the range of choice offered (Principle 5). Product choice did challenge the lean teams in the case study plant. Organizing the area and implementing visual control, primarily in staging unique raw materials, was difficult. However, using lean concepts such as build-to-order kitting and layout optimization mitigated most of the potential visual control problems associated with product choice. Formoso and Santos (2002) studied some examples of visual controls in homebuilding, observing a positive correlation between visual controls and efficiency (Principle 6). The need to accommodate product choice in the case study plant limited the use of process technology. However, the use of the simple technologies adopted profoundly affected the productivity and quality in the wall build area and better enabled the area to accommodate product choice offered (Principle 7).

Results from the case study analysis suggested that good concepts for lean (e.g. efficient continuous flow, effective pull system, workload leveling, defect-free processes, standard tasks, good visual controls, and reliable technology) were also good concepts for (or easily accommodated) handling a range of product choice. Thus, lean concepts may be the method for homebuilders to achieve production efficiencies, while allowing product customization. Similarly, Tu *et al.* (2001) and Da Silveira *et al.* (2001) concluded that lean production is an important factor that supports mass customization.

Research findings are limited by the small number of plants involved in the case study. Future research should attempt to corroborate these findings by replicating this study in other departments and plants, including an extension to suppliers. In summary, this paper makes an important contribution to the understanding of both lean production and mass customization, identifying the lean principles that facilitate mass customization for industrialized homebuilders. Findings also provide useful guidelines for builders interested in better addressing specific customer needs, while managing the operational complexities resulting from product variety.

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