University of Alberta

AN INTEGRATED APPROACH TOWARD LEAN FOR PRODUCTION HOMEBUILDERS

by

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ABSTRACT

Homebuilding is widely regarded as the most analogous sector in the construction industry to automobile manufacturing. In the past decades, increasing interest from homebuilders has been seen to model the homebuilding process after manufacturing, particularly lean production, to improve productivity. However, differences inherent in the nature of the products prevent the direct implementation of lean principles and systems in the homebuilding industry. Project-oriented techniques used by the other sectors of construction are still dominant in homebuilding process planning and control. There is a clear need for an approach to integrate a lean production system into the homebuilding process and to overcome the challenges in lean implementation.

The purpose of this research is to develop a lean production approach for the North American homebuilding industry. Specifically, this research intends to provide a framework and a set of guidelines that can help production homebuilders to improve their efficiency through lean transformation. This study first investigated the current homebuilding process and then conducted a comparative study between the homebuilding and automobile industries. Based on the analysis, a lean homebuilding model was developed, and key lean strategies were identified to support lean implementation efforts.

Case study results revealed that a lean production system can be successfully applied to the homebuilding process, and lean strategies, such as continuous flow, pull system, production leveling, standardized work, investing in the people, and visual management were effective in improving a homebuilder's operation performance in terms of construction cycle time, process stability and house quality. The major

contribution of this dissertation is to provide production homebuilders a roadmap to developing their own lean production systems and lean implementation strategies. The research results are also anticipated to be a benchmark for future studies in the academic field and for the homebuilding industry.

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CHAPTER 1 – INTRODUCTION

1.1 BACKGROUND

1.1.1 Definition

Homebuilder is a vague concept referring to a broad range of private companies that provide services to construct homes. Homebuilders include both large corporations that build hundreds of homes each year and one-man companies that may only build one or two homes each year. To correctly describe their characteristics, homebuilders can be grouped into the following four categories in terms of their work volume:

1. Small volume builders construct 20 or less homes per year.
2. Custom builders construct homes precisely according to the individual needs of their customers.
3. Semi-custom builders work according to predesigned plans but allow customers to extensively modify the designs to suit their individual needs and wants.
4. Production builders normally produce hundreds of homes per year. Most of the construction is standardized with limited options.

The construction process of production homebuilders presents a unique management challenge (Bashford et al. 2005). The high volume and similarity in houses produced make the production homebuilding process similar to consumer goods manufacturing processes. Unlike small homebuilders, production homebuilding companies have strong professional and management teams and carry out a significant amount of research and development (R&D) activities. They have a better capacity to bear the cost and risk involved in process change, and the focus of their improvement efforts is not on individual technology, which may have a small impact per unit, but rather on the production system due to the large volume of housing they produced (Holmen Enterprises Ltd. 2001). Therefore, production homebuilders are most interested in process improvement and are most likely to develop and adopt innovations.

1.1.2 Overview

Homebuilding and renovation are important components of the Canadian economy, representing approximately $55.6 billion (5.3%) of Canada's annual GDP. In 2005, the Canadian residential construction industry reached its highest production level in almost two decades. A total of 238,830 new residential units were built, 62% of which were single-family and semi-detached homes. Home-ownership is a significant investment and an important way for Canadians to accumulate wealth. The 2001 Census of Canada indicated that the average Canadian household spent 21% of after-tax income on housing. Furthermore, approximately 67% of Canadian households own the dwellings in which they are living, and home equity accounts for more than half of the total net worth of the family (CMHC 2007).

Despite the dramatic increases in housing production and home ownership in recent years, the fundamentals of the homebuilding process have changed little since the 1920s, when the wood platform-frame structure became a standard building practice in North America, and no significant improvements in productivity have been observed (Zhang et al 2005). Today, a vast majority of homes are still constructed by manual labor, using the stick-built method. Though remarkable rationalization and benefits have been realized in other industrial sectors through replacing the traditional, craft-based production process with a standardized factory-based production system and through advancing manufacturing technologies and processes, the homebuilding industry has not undergone comprehensive industrialization and has a reputation of low productivity, high waste, and antiquated technology (O'Brien et al 2000). However, the current state of homebuilding practice also entails enormous potential for productivity improvement. For instance, in the Edmonton area the delivery of a typical single-family dwelling, from stake out to final inspection, takes between 180-210 workdays. In fact, only a small fraction of this time period is spent on real construction work. To highlight the problem, K. Hovnanian, a nation-wide homebuilder in the U.S., constructed a 2,000 ft^2 home in Lakewood, N.J., starting from slab, in just four and a half workdays, working from 7 a.m. to 5 p.m. (Sawyer 2006). The value-added ratio of the current homebuilding process was pegged at a mere 4%. (Value-added ratio is defined as the time devoted to operations that create value for the final customer divided by the total process time.)

The notion of modeling the homebuilding process after the manufacturing process is not novel. A factory-based production system involving volume-produced goods, capital equipment, disciplined labor and scientific management has historically demonstrated greater efficiency than a scattered craft-based enterprise system (Gann 1996). Industrialization efforts, such as manufactured housing, modular housing, panelized housing, and prefabricated structural components, have experienced limited and fragmented successes. Homebuilders are still struggling to find an effective model or path toward industrialization. The mass production model, which has enjoyed great success in the manufacturing sector, has not been viable for the homebuilding industry.

Since the early 1990s, however, research in the application of the manufacturing model to home-building has resurged, due to the popularization of a new manufacturing paradigm – lean production – which has replaced mass production as the industry benchmark. As a customer-driven system, the lean principle is more applicable than mass production to homebuilding. A high degree of customization and one-piece flow are the central objectives of lean production, but they are inherent features of the homebuilding industry. Key elements of lean thinking, including pull process, perfect first-time quality, waste minimization, continuous improvement, flexibility and long-term relationship with suppliers, seem to have been tailored for the homebuilding industry. However, major disparities still exist. Significant peculiarities, such as site production, temporary organization, variation in demand and high complexity of product, impede the lean techniques that have been used by manufacturing companies from being applied directly in the homebuilding industry. Homebuilders need a specific lean production system that encompasses the features and realities of the industry and a practical approach to realize this system.

1.1.3 Today's Challenge

In the past decade, Canada has seen dramatic changes in housing production. The decade began with the housing industry recovering from a cyclical trough that was reached in 1995 when housing starts in Canada fell to a low of 120,000 units (see Figure 1-1). As of 2001 starts had risen to 163,000 units in a sustained period of recovery. 2002 was a year of significant growth in housing market activity in Canada. Housing starts reached 205,000 units, representing a 26% increase over 2001. Rapid growth of the immigrant population, low mortgage rates, high employment levels, rising income and healthy consumer confidence supported high levels of housing starts across the country in six consecutive years (CMHC 2006). In 2008, the strong house price growth over the past decade cooled home ownership demand, and the deteriorated global economy made home buyers more cautious in house investment. Housing starts fell 7.1% to 211,060 units in 2008 and an additional 30% to 149,080 units in 2009 (CMHC 2010).

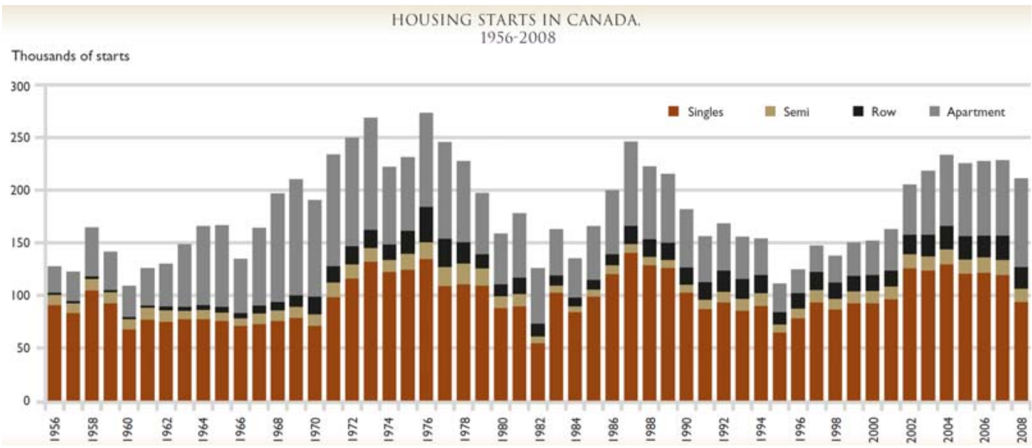


Figure 1-1: Housing Starts in Canada (1956-2008) (CMHC 2009a)

The decrease has been more pronounced in Alberta. In 2008 and 2009, the total housing starts declined by 40% and 30% respectively. The financial crisis and low oil price has tempered investment in the energy sector and resulted in a slowdown of the net migration into the province. Dramatic decline of demand led to a record high level of listings and new house inventory, which made competition in the home market fiercer. At last, the average price of a home in Alberta has tripled in the past ten years, significantly higher than the Canadian average. Considering the current global economic situation, potential buyers are cautious and hoping for price drops. In response to high inventory and aslow market, in 2009 housing starts in the Edmonton Census Metropolitan area were expected to decrease another 24% to 5,000 units (see Figure 1-2), following a 56% decline in 2008 (CMHC 2009b).

Figure 1-2: Total Housing Starts in Edmonton CMA (2003-2010) (CMHC 2009b)

1.2 NEEDS OF PRODUCTION HOMEBUILDERS

In order to enhance competitive advantage and win more market share in a slow market, production homebuilders need better control of the homebuilding process, which decides schedule, costs, price, profitability and quality of the end product. A better management system can easily make the difference between success/survival and failure in a highly competitive market.

The needs of production homebuilders in general can be categorized under three themes – economic, production management, and innovation (see Figure 1-3).

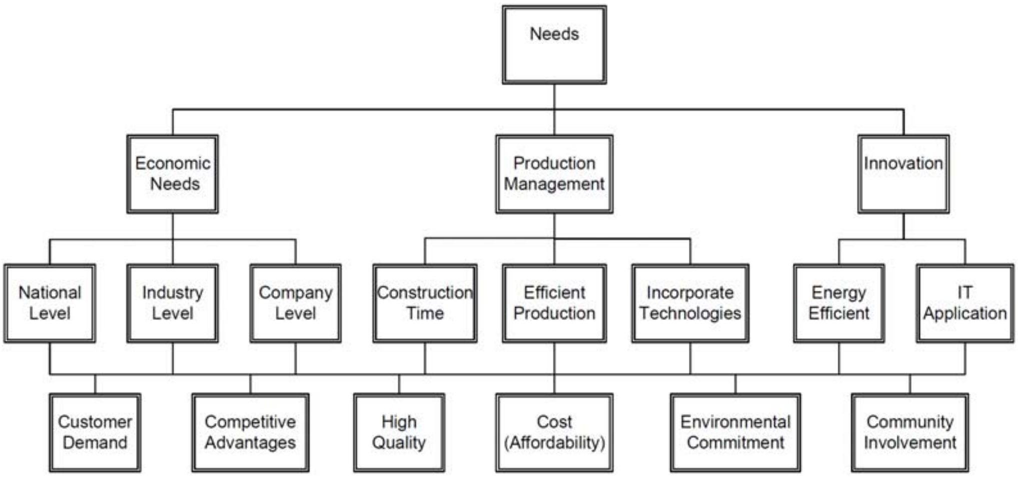
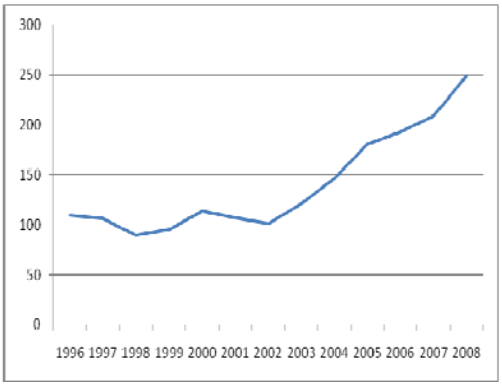


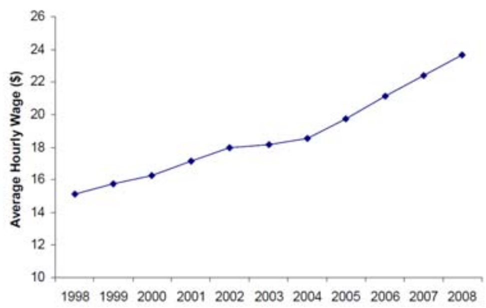
Figure 1-3: Research Needs

1. Economic Needs

1) National level: all industries are striving to cut costs to withstand the economic downturn.
2) Industry level: Starting in the second half of 2007, the housing market has turned into buyer market. Record high new and listing house inventory and low demand caused by a deteriorated economy have put significant pressure on housing prices. On the other hand, labor wages and commodity prices are still high due to the past economy booming (Figure 1-4). It is critical for the housing industry to reduce costs to enlarge the customer base and compete with existing house sellers.
3) Company level: An inevitable result of a buyer's market is price competition caused by excess of production capacity (supply) over demand. Low price strategy is a very powerful tool to stimulate demand and acquire market share. Although every production homebuilder tries to distinguish its product/service from others, location and price are still the top two decisive factors in house purchasing. Once the price competition starts, all companies have to match it in order to keep operating, and eventually companies with better management and lower costs will survive and gain more market share.



a. Commodity Price Index 1982-90=100 (Data Source: The Bank of Canada)



b. Alberta Average Hourly Wages (1998-2008) (Alberta Employment and Immigration 2009)

Figure 1-4: Commodity and Labor Costs

2. Production Management

1) Construction time: New homes have significant competitive advantages in layout design and energy efficiency, but a long waiting time and uncertainty in possession date make many potential buyers turn to existing houses. In the Edmonton area, a typical single family house normally takes more than one year from sale to possession, and no homebuilder can provide the exact possession date at the time of Purchase Agreement signing. To compete with existing house sellers, homebuilders need to reduce the construction time of new homes to three or four months, by increasing the certainty of the process.
2) Efficient production system: changed market conditions require innovative housing solutions such as flexible architectural design, better customer service and brand development, and value-added products. The current production system has to be reengineered to adapt to emerging customer needs with minimal lead time.
3) Incorporate technologies into home-building process: In the past decades, many new materials and equipment entered the market for residential housing, but only few of them have been widely used. Besides high initial costs, the fact that houses are located in random locations and performed by small trade contractors, who have only a temporary relationship with homebuilders, makes any technology that requires specific equipment or skill virtually inapplicable. There is a need for a practical method to incorporate those new technologies into the homebuilding process.

3. Innovation

4) The Canadian housing industry has seen growing buyer interest in energy efficient houses. It is a challenge for homebuilders to produce exceptional energy efficient houses without significantly increasing costs. Our industrial partner's vision is to provide NetZero ready homes at the same price of conventional houses by 2015. This goal can only be achieved by innovation, both in technology and management.
5) Advances in IT have dramatically changed the way that people do business. Builders are realizing that IT offers exciting opportunities to reduce cycle time and labor content, optimize the schedule, and deliver a more cost-effective,

durable product (NAHBRC 2000a). The key is to integrate IT with the homebuilding process while at the same time change the process to take advantage of the technology.

1.3 PROBLEM STATEMENT

The housing industry does not benefit greatly from advancements in technology and operations management. In fact, the characteristics of the housing industry have a negative impact on forming a culture of innovation. In a discussion paper prepared by Holmen Enterprises Ltd. (2001), the characteristics of the housing industry and their implications were summarized as follows:

- Low profit rate and the fragmentation of the industry limit the ability of homebuilders to invest in R&D and to take the risk of implementing new technology and management systems.
- A cyclical market makes the improvement efforts inefficient – "stop period" results in staff departures and long "re-learn" time.
- Most homebuilders do not have R&D personnel and their management staff does not have time to devote to innovation.
- Due to the temporary relationship between builders and trades, it is not of interest to builders to conduct research on subcontractors' work, and it is difficult to keep innovations proprietary and garner benefits from investments in R&D.
- The vast majority of homebuilders rely on subcontractors to perform all the construction work. Those independent small subcontractors are generally not interested in overall process improvement and tend to resist any changes on their work scope or skill requirements.

Homebuilders have a crucial need for a well-developed and proven production system, which integrates state-of-the-art construction engineering and manufacturing management techniques and is superior to the current system in terms of efficiency, affordability and environment.

The efforts to reengineer the homebuilding process by modeling the house production system after manufacturing have a long history in Europe and North America. A recent effort was made by Gann (1996) and Iwashita (2001), who endeavoured to introduce the practice of Japanese industrialized housing production to homebuilders in Europe and North America. Barlow et al. (2003) further analyzed the business model of major Japanese housing suppliers' using mass customization concepts. Due to the significant differences between the Japanese and North American housing markets, their efforts have been largely omitted by the housing industry. Under NAF-PATH program (a US initiative administered by the US Department of Housing and Urban Development (HUD), which aims to bring new technologies to the US homebuilding industry), the Housing Research Institute (HRI) at Arizona State University studied the current state of the Phoenix housing production system (Bashford et al. 2005) and suggested a new production control mechanism termed "even flow production" (Bashford et al. 2003). However, their research was based on aggregate data of a local industry, and the results were basically conceptual models validated by mathematical analysis or simulation models, not involving any homebuilder's practise.

The research presented in this dissertation has come from collaborative efforts between the University of Alberta and one of the largest homebuilders in Alberta, Landmark Group of Builders (LGB). As a researcher in the area of lean construction and then an employee of the company, I was invited to join the core lean implementation team, working with management and external Lean experts on establishing lean transformation strategies and developing a lean production model. To support the company's decisions, the company's actual homebuilding practice was documented and analyzed, using data collected through the company's production tracking system. The vision of this research was not to provide a ready-to-use model for a particular company, (in fact such a model does not exist,) but to develop a generic approach to guide the production homebuilders' Lean course. In the research, two fundamental questions are answered. First, how can we integrate the lean production system into the homebuilding process? Second, what are the challenges in the lean implementation and how are those challenges to be addressed?

After 3-year effort, a comprehensive approach integrating lean production and penalized construction has been developed and the collaboration company, by implementing the proposed lean homebuilding system, has significantly improved its homebuilding process in terms of construction time, quality, process stability and costs. Due to the similarity of the management models used by production homebuilders in North American, the author believes that the approach presented in this dissertation can be useful to guide other production homebuilders' Lean initiatives.

1.4 RESEARCH GOAL AND OBJECTIVES

The goal of this research is to develop a lean production approach for the North American homebuilding industry. More specifically, this research intends to provide a framework and a set of guidelines that can help production homebuilders to improve their efficiency through lean transformation. Specific objectives of the research include:

6) To develop a deeper understanding of the current homebuilding process.
7) To redesign the homebuilding process based on lean production principles.
8) To explore technologies needed to reduce the variability of the process, which is the prerequisite of lean transformation.
9) To indentify challenges in the implementation of the developed lean production system and develop solutions to those challenges.

1.5 RESEARCH METHODOLOGY

As a manufacturing paradigm, lean production is contrary to the conventional homebuilding process in both underlying management theories and operation control techniques. Today, there are still debates in the construction industry, the homebuilding industry in particular, on whether lean production is applicable for construction. In North America, the vast majority of production homebuilders are using traditional project management (PM) tools to control the homebuilding process. To promote the application of a lean production system and to implement the research results, the investigator has been actively involved in the operation of studied companies, developing lean application strategies, constructing a lean production model, and facilitating lean improvement efforts. Meanwhile, the lean transformation is characterized by gradual change in mindset and culture, which needs time and patience. The nature of the research work decided that a case-based, action research method was adopted.

1.5.1 Case-based, Action Research Method

The case-study method involves an in-depth, longitudinal (over a long period of time) examination of a single instance or event to explore causation in order to find underlying principles. It has been used for years across a variety of disciplines, especially in social science. Robert K. Yin defined the case study research method as *an empirical inquiry that examines contemporary phenomenon within its real-life context, when the boundaries between phenomenon and context are not clearly evident and in which multiple sources of evidence are used* (Yin 1984). Critics of case-study method claim that the study of a small number of samples may not provide enough ground for establishing reliability and generality of findings (Noor 2008). They believe that research results based on case studies are "localized" to a specific situation and difficult to reproduce by other researchers and even the initial researcher in another setting. Yet, case study has been continuously used by academic researchers with success in carefully planned and crafted studies of real-life situation, issues and problems.

To overcome the limitation of case-study method, the researcher clearly documented and compared the homebuilding process and production system on both the industry level and the company level. Production homebuilders are located in different market and regulation situations, and each has its own products, business strategies, competitive advantages, and production management system. However, if they follow the same basic homebuilding process and face similar challenges, the lean production model and implementation strategies developed in this research based on the practice of the collaboration company can be applied by other production homebuilders.

The action research method is a reflective process of progressive problem-solving, assisted or guided by professional researchers, with the aim of improving the environments within which the research is conducted (Susman and Evered 1978). Lean production, as a manufacturing model, is new for the practitioners in construction industry. Its implementation needs the collaborative efforts of both the investigator and the case-study company. As a designer and major provoker, the researcher actively worked with company's management to propose and evaluate the lean implementation course. Action research and case-study method are often companied when a new methodologies or approaches are the subject of the study.

1.5.2 Understand the Current Homebuilding Practice

In order to improve the current homebuilding process, a clear understanding and analysis of it is mandatory. This includes both the homebuilding process of the industry in general and the process of the collaboration company in particular. Developing this understanding and analyzing the current homebuilding practice included the following steps:

1) Reviewing the available literature on the homebuilding process and management systems.
2) Interviewing the management of the collaboration company to understand the company's production system and compare it to the literature review.
3) Collecting actual operational data to assess the performance of the current management system.
4) Map the homebuilding process using value stream mapping technique.

1.5.3 Develop a Lean Production Model for the Homebuilding Process

The presented research is based on the realization that a comprehensive lean approach is needed by the homebuilding industry to guide individual company's lean transformation. A lean production model developed in the context of the homebuilding process and the process of model development are two core elements of this approach. Three steps are involved in this area:

1) Conducting a comparative study to understand similarities and differences between the homebuilding and automobile industries and their impacts on lean implementation.
2) Developing possible solutions to address the differences and minimize the impacts. A significant body of research in the area of lean construction has focused on reducing workflow variability caused by complexity, one-of-a-kind and on-site construction. In general, two strategies are being proposed. The "product strategy" aims at eliminating the construction peculiarities by turning the building into factory-built products, whereas "process strategy" is intent on

improving workflow reliability through better planning and flow control (Bentelsen 2004). In the research, the advantages and disadvantages of two strategies were analyzed in the context of the homebuilding process and detailed solutions will be recommended.

3) Formulating a lean production model by redesigning the current homebuilding process using lean production principles and identified solutions. This was accomplished in collaboration with the collaboration company, by using value stream mapping.

1.5.4 Explore an Effective Approach to Implementing the Lean Production Model

Each production homebuilder has its own organizational structure, competencies and culture, which decide the way it manages its homebuilding processes. In order to achieve the full potential of the proposed lean production model, all participants involved in the homebuilding process have to change their behavior and way of thinking. A sound implementation plan is needed to create an environment where the proposed lean system can be applied and to minimize participants' resistance to change. Strategies used in this area include:

1) Exploring strategies and techniques needed to support the implementation of the proposed lean house production model. In past decades, numerous research efforts have developed lean production principles, strategies, and techniques based on the practices of Toyota and the other enterprises experiencing lean transformation. However, some of the lean strategies and techniques may not be applicable in construction due to the complex and dynamic nature of the construction process. The focus of the research in this area was twofold:
    - Lean production strategies and techniques that are relevant to the context of the homebuilding industry.
    - Construction techniques that can reduce the complex variability of the construction process.
2) Implementing the lean production model following the PDCA cycle.

- Plan: Develop kaizen plans. Based on the overall timeframe of lean transformation, each major step was divided into smaller increments with a responsible work group to ensure the successful completion.
- Do: Conduct the action items in kaizen plans. Multiple workgroups worked simultaneously on different kaizen plans. A solution was created through group efforts for each action item in the kaizen plan, and this solution was implemented and adjusted until the target process performs as planned.
- Check: Evaluate the results. Actual process data were collected before, during, and after the kaizen actions. Then those data were compared to verify improvement.
- Act: Make necessary adjustments to the original plan and identify future steps. This usually leads to a new kaizen plan and starts a new PDCA cycle. The nature of the lean improvement means that the efforts of improvement never stop.

3) Developing measurement metrics for assessing the results of lean production model implementation. The proposed production model must have clear advantages over the widely accepted current practice to overcome the resistance of the industry. How should we compare the two systems? Some traditional measurements, such as overall construction time and costs, of course, were used as a part of the metrics, but some factors neglected in conventional management practice, such as process predictability and management efforts, were also included.

1.6 SCOPE OF THE DISSERTATION

The dissertation scope covers analysis, methods, and steps to develop a lean production model for the homebuilding process. The model takes a flow view and addresses impacts of different operation factors on system stability, scheduling, and workforce management. Moreover, a practical approach for lean production model implementation is introduced based on the lean practice of the collaboration company. The effectiveness of the proposed lean production model is verified by comparing the operational data collected before and after the implementation. There is no common model for lean production. Every company must develop its own lean production system and find its own way of implementation. The research presented in the dissertation intends to provide a roadmap for production homebuilders to guide their lean initiatives. Figure 1-5 depicts the research methodology and the lean transformation steps taken by the collaboration company.

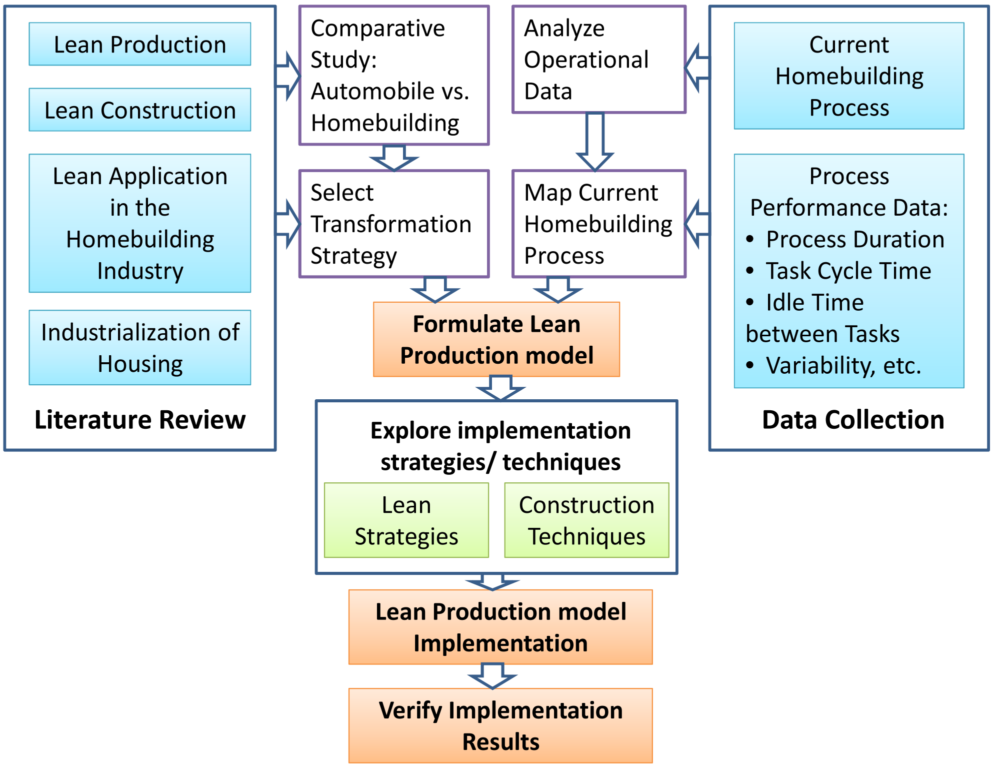


Figure 1-5: Research Process

1.7 DISSERTATION ORGANIZATION

This dissertation consists of six chapters. The first chapter discusses the research background, problems, objectives, and methodology.

Chapter 2 covers relevant literature topics including lean production system, lean construction, lean application in the homebuilding industry, and industrialized housing.

Chapter 3 includes three sections: (1) a comparative analysis of the similarities and differences between homebuilding and automobile production, (2) lean homebuilding model development using value stream mapping techniques, (3) creation of kaizen (continuous improvement) plans. Operation data collection and the work measurement system are presented to support the process mapping.

Chapter 4 introduces the key lean strategies taken by the case-study company in its lean implementation and the results of the proposed lean homebuilding model.

Chapter 5 describes the development and application of a panelized house system, including precast foundation panels and wood frame open panels. The industrialization of the homebuilding process significantly increases the process reliability and facilitates the application of a lean production system.

Chapter 6 includes a summary of the dissertation work and provides final discussion and recommendations for future work.

CHAPTER 2 – LITERATURE REVIEW

Lean construction may be one of the most controversial and confusing theory for construction practitioners that are only familiar with the current project-oriented management model. Although most of the lean concepts are straightforward and make a lot of sense, they contradict the system we have been using for decades. Construction and manufacturing are so different that it is hard for people to see a clear approach to implement lean ideas into their everyday work. It is quite common in the lean construction movement that people see Lean as a set of "tools" that assist in the identification and steady elimination of wastes, and only implement a few tools/principles on a selected part of the construction process. However, Toyota, the originator and world leader of lean production, kept telling us the key of the lean production system is not those tools and techniques. To be a lean enterprise requires a way of thinking that focuses on making the production flow through the entire process and a culture in which everyone is striving continuously to improve (Liker 2004). Being Lean, instead of doing Lean, involves a far deeper and more pervasive change in a company's business model and working process than most companies can imagine. It is essential for anyone who has enthusiasm for and commitment to Lean to fully understand the lean principles and culture they are based on.

2.1 LEAN PRODUCTION

Lean production derived from the Japanese manufacturing industry. Ohno, a manager, and Shingo, an industrial engineer, developed the Toyota Production System (TPS) for the Toyota Automotive Company on the basis of the mass production system invented by Henry Ford. The term Lean Production was first coined by John Krafcik (1988) and gained world-wide acceptance through the international best-selling book, *The Machine That Changed the World* (Womack et al. 1990).

The heart of lean production is eliminating non-value-adding waste from the business and manufacturing process. Toyota has identified seven major types of waste as follows (Womack and Jones 1996):

1) Defects mean rework and replacement, which waste time and effort.

2) Overproduction means producing goods or information earlier or in greater quantities than needed by the customer.
3) Excess inventory increases storage and transportation costs and risk of obsolescence. It also hides problems such as uneven flow, late delivery of materials, defects, equipment downtime, and long setup time.
4) Overprocessing costs money and effort without adding value to the customer.
5) Unnecessary movement includes any wasted motion workers have to perform during the cause of their work, such as looking for materials, reaching for tools, asking information, etc.
6) Unnecessary transportation includes inefficiently moving materials, work-in-process (WIP), or finished goods.
7) Waiting refers to both workers standing idle waiting for the finish of upstream activity, tools, supply, and parts and workers serving to watch an automated machine.

While having the same goal of eliminating waste, there are virtually two completely different approaches to achieving it. For many, both Lean and TPS can be seen as a loosely connected set of tools, such as Value Stream Mapping, 5S, Kanban (pull systems), and poka-yoke (error-proofing). The second approach focuses on improving the "flow" or smoothness of work, thereby steadily eliminating unevenness in the system instead of “waste reduction” per se. Real success comes from an improved process for identifying waste, understanding its root cause, and taking action to solve this cause. The advantage of the second approach is that it naturally takes a system-wide perspective, whereas a tools-based approach focus sometimes wrongly assumes this perspective.

Liker (2004) has summarized the following seven lean principles of building right process. These key principles drive the techniques and tools of a lean production system.

2.1.1 Establish a Continuous Flow to Expose Problems

The lean production system has two pillar concepts (see Figure 2.1) – Just-in-time (JIT) and in-station quality (autonomation). JIT means that products are only produced at the time they are needed and in the exact amount needed. This concept encompasses not only finished goods, but all materials or information delivered from the upstream operation to the downstream operation – internal customer. Establishing a continuous flow is the basic condition of JIT (Ohno 1988). Flow means that when the customer's order is received, the row material is ordered just for the ordered products. The material then flows immediately to the manufacturing plant and flows continuously through the production line, and then the finished products flow immediately to the customer. A perfectly production flow – smooth, continuous and just-in-time – eliminates overproduction, waiting and inventory; customer-valued features are the only ones produced, so there is no overprocessing – product design is simplified and effort is only expended on features the customer values. Of course, the perfect flow does not exist in reality. In Toyota, inventory buffers are also used in places where continuous flow is not possible. However, the idea of continuous flow and JIT provides a clear direction for using small lots to keep the material moving through the process without interruption.

Flow is at the heart of lean thinking because reduced cycle time will lead to better quality, lower costs, and high customer satisfaction. More importantly, continuous flow reduces inventory levels and exposes problems that demand immediate solutions. Other lean tools such as leveling production, standardized work, takt time, in-station quality, quick changeover, and preventative maintenance were invented to establish and maintain flow.

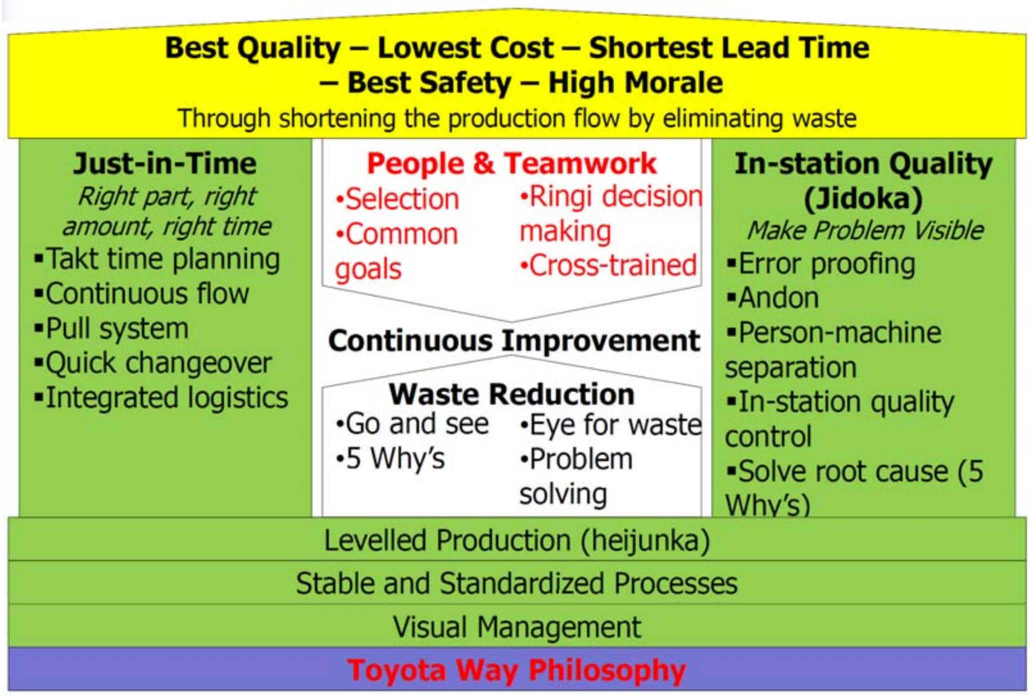


Figure 2-1: Lean Production System (Liker 2004)

2.1.2 Use Pull System to Avoid Overproduction

Kanban, a card that carries pickup, transfer and production information, may be the most well-known tool in the lean tool box. The entire material flow within Toyota and between Toyota and the cooperating companies is operated through kanban. When the inventory represented by a kanban is used, the card signals that more goods need to be produced. In this way the products are produced only at the time they are needed and in the exact amount needed. The idea of kanban came from the American supermarket system: stacking relatively small amounts of each product and replenishing inventory frequently based on what the customer actually takes away. Kanban is like the company's "nerve system," controlling material replenishment and production.

In order to fully understand kanban, people have to clearly understand its purpose and role. It is a way to create a pull system; its purpose is just-in-time. Kanban prevents overproduction, and as a result there is no need for extra inventory. Therefore, kanban becomes a powerful tool for exposing waste, because a JIT system asks for 100%

defect free products. If the upstream operation generates a defective part, the downstream operation has to stop the line.

2.1.3 Level the Production

One prerequisite of continuous flow is that each step in the process must have the capacity to produce the quantities needed at the time needed. In this case, if the demand of downstream operation is not even in terms of time and quantity, the upstream operation must have extra manpower and equipment to accommodate its requests. The greater the fluctuation in demand, the more excess capacity is required. For a synchronized pull production system, extra capacity has to be prepared at every point of the value stream. This leads to significant waste and will force the production into reactive mode, using overproduction and high level of inventory as buffer. The only realistic way to create a pull system with continuous flow is to "lower the peaks and raise the valleys" in production as much as possible so that the flow surface is smooth. In a lean production system, this is called production leveling.

Traditionally, people believe the unevenness of demand is simply the natural result of an uncontrollable market. Customer diversity forces manufacturers to produce small quantities of large varieties to satisfy the individual needs of each customer. When keeping market diversification while leveling production, it is important to avoid the use of a dedicated facility and equipment, so that different products can be produced on the same production line alternatively. The heijunka box (leveling box) is a sophisticated lean production tool for planning and leveling production volume and variety over a specific time period. As shown in Figure 2-2, the heijunka box has horizontal rows for each type of product and vertical columns for time intervals of production. Kanban cards are placed in slots corresponding to the pitch increments in which products are to be manufactured. (Pitch is the amount of time required for an upstream operation to release a predetermined pack-out quantity of work in process to a downstream operation. It can be calculated by multiplying takt time by the pack-out quantity). By mixing the production of different types of items, the lean production system keeps diversification and production leveling in harmony and still responds to customer orders in a timely manner.

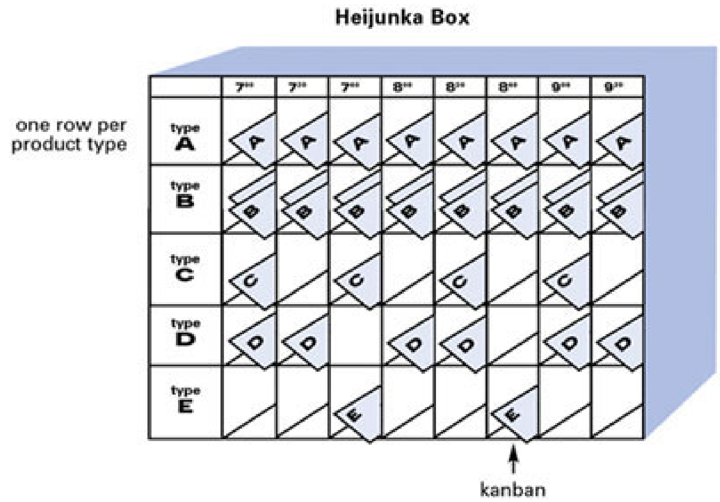


Figure 2-2: A Typical Heijunka Box (Jones 2006)

2.1.4 Get Quality Right the First Time

While most lean principles are common sense, a few of them contradict conventional wisdom. Stopping the assembly line to fix a problem is one of these few. When Toyota started its Georgetown, Kentucky, plant, it took months to "re-educate" management and workers that everyone has the responsibility to stop the line when he/she finds something out of standard. The idea behind this is that quality must be built in to the process. A systematic method is needed to detect defects when they occur so that the worker can fix the problem before the defect continues downstream. It is proven that solving quality problems at the source saves time and money downstream.

Undoubtedly, it is costly to stop the line, but it is necessary if we want to continuously improve the process. Stopping the line raises immediate attention to the problem and forces the team to go into intense problem-solving to identify the root cause and put a countermeasure in place. Lean production does not deny the importance of quality inspection, but believes inspected-in quality is a temporary quality and the most efficient way is to get quality right the first time. The only way to achieve that is to continuously improve the process and identify the root cause of every problem exposed to prevent it from reoccurring. The key tool here is "repeating Why five times."

2.1.5 Standardize Tasks and Processes

The foundation for flow and pull is a predictable and reliable production process. Workers must be able to produce to takt time and provide consistent performance in terms of cycle time and quality. This can only be achieved by standardized work – everyone does the same work the same way. The major tool in standardized work is the standard worksheet, which contains three elements – cycle time, work sequence and standard inventory. In a lean production plant, the workers are trained to follow a very detailed standardized procedure and there is strict discipline about time, cost, quality, etc. Virtually every minute, every movement of the day is structured and monitored. However, a rigid working procedure does not necessary stifle an individual's creativity. The key is in the way these standards are developed. In lean production, the standard worksheets record the best practice of workers – designed with the participation of the workforce, so they actually help people control their own work.

Standardized work is also the prerequisite of continuous improvement, since it is impossible to improve any process unless it is standardized. If everyone performs the operation in his/her own way, then any improvement will just add another variation that is occasionally used. The process has to be standardized, and thus stabilized, before any improvement can be made. Standardized work is also critical for quality. Without standard procedures ensuring consistency in the process, quality cannot be assured merely by inspection. By using a standard worksheet with clear instruction in sequence and key motion, workers can quickly learn the best way to perform their work without redoing a job or producing defective parts.

2.1.6 Make Things Visual

Visual control might be the most misunderstood concept in lean application. Many people have confused it with 5S (Sort, Set to order, Shine, Standardize and Sustain), another lean tool that aims at exposing and eliminating waste through neatly organized and labeled materials, tools and wastes, and maintaining a clean and shiny workplace. In fact, visual control has a much broader definition, which includes all communication devices used in the working environment to guide everyday decisions and to show whether the operation is normal or deviating from the standard. In today's world of computers, the tools used for visual control may have changed, but the rules remain the same:

- Using sample visual indicators to help people understand the situation (normal or abnormal) at a glance.
- Avoid techniques that distract workers' focus – best visual control device is right at workplace.
- Only provide information needed and put all key information on one sheet of paper.

2.1.7 Use Only Technology That Serves Process

The process should take precedence over technology. This is common sense but is difficult to do, particularly in this technological age. People have a tendency to jump around from one technology to another and hope that the cutting-edge technology can bring the company competitive advantages. However, lean thinking focuses heavily on the stability, reliability and predictability of the system and believes that the major approach for process improvement is people's continuous efforts. Any new technology must be thoroughly investigated and proven to be reliable and to add value to the process. If the technology is preferred, the impact of new technology on people, processes and value will be assessed. The technology will be rejected or put on hold if there is any chance to bringing adversely disruption to the existing process.

2.1.8 Create Lean Culture

In the past two decades, Lean has become popular in North America. Many companies have hired outside lean experts for either some form of lean training or kaizen (continuous improvement) events with fragmented results. There is a "Lean" cell here and some form of kanban system there. Some attempts have been made in Value Stream Mapping and a few process maps have been posted that no one really looks at. An andon system has been installed on the production, but nobody really uses it. Although, there are many signs of Lean on the shop floor, in truth, such companies are not truly implementing Lean. This failure is a result of management's inability to create a lean culture. Fujio Cho, former president of Toyota Motor Corporation, states that, *"Many good American companies have respect for individuals, and practice kaizen and other*

TPS tools. But what is important is having all the elements together as a system. It must be practiced every day in a very consistent manner – not in spurts – in a concrete way on the shop floor."

As shown in Figure 2-3, the hard part of implementing a lean transformation is dealing with the "soft" issues – culture change. Application of lean technologies and principles discussed above is only the beginning of a lean transformation. The true journey starts after the production process has changed and the production line has been reorganized. It is an internal change, a mental calibration. People need to live with lean philosophy and practice lean principles every day.

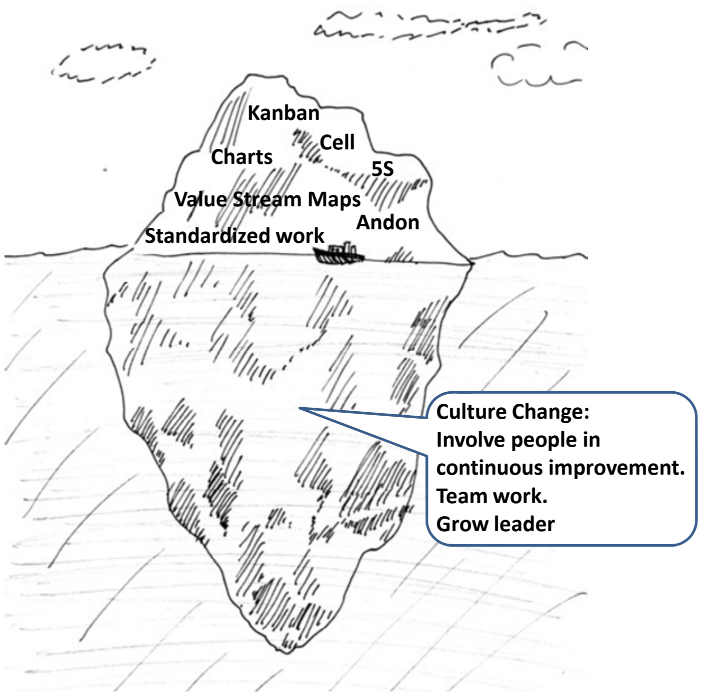


Figure 2-3: Illustration of Lean Transformation (Liker 2004)

Recently, lean culture has brought great attention from researchers and lean experts. Mann (2005) pointed out that culture is not a target to change but an idea arising from experience. Therefore, a company's culture is the result of its management system. In his book *Creating Lean Culture: Tools to Sustain Lean Conversions*, Mann detailed the following four principal elements of a lean management system.

- Leader standard work. Daily checklists to help line production leaders to focus on the process.
- Visual controls. Tracking charts that reflect expected and actual performance.

- Daily accountability process. A structured follow-up meeting to close gaps between actual results and expected performance.
- Discipline. Leaders consistently follow the lean process and teach it to others.

People are always at the heart of culture change. Liker (2004) provides three lean principles on developing exceptional people and partners:

- Grow leaders who exemplify the lean philosophy in everything they do and understand the actual work in detail.
- Select the right people and assimilate them into company's culture through continuous training and individual coaching.
- Form long-term partnership with suppliers and help them continuously improve their system.

2.2 LEAN CONSTRUCTION

Research on the implementation of Lean theory in construction began in 1992, when Lauri Koskela (1992) wrote a groundbreaking paper, "Application of the New Production Philosophy to Construction." In the paper, Koskela explains three different points of views on production: (1) a *transforming* of inputs to outputs; (2) a *flow* of information and materials; and (3) the generation of *value* to customers: also termed "TFV theory of production." Koskela (2000) points out that the construction industry is in general only using the transformation viewpoint and hopes that "the new TFV-concept will provide a new theoretical foundation for construction."

The debate about whether construction can be seen as a type of production and whether manufacturing model (or models) can be applied in construction has a long history. The unique characteristics of building products and construction activities make construction so different from discrete assembly industries that traditional mass production strategies are not applicable in the construction world. After lean production principles became the basis of best practice in manufacturing, researchers found some common ground between lean thinking and construction in production organization, such as make-to-order and one-piece flow. However, the lean production system, as a manufacturing paradigm developed in the auto industry, has some limitations, which means that it cannot be applied to construction directly. Today, arguments still exist that the lean production model has little relevance for most of the construction industry outside production housing (Winch 2003).

In the lean construction field, the research has so far focused on two parallel areas. Some researchers emphasize the importance in understanding construction as production and believe that the peculiarities of construction can be mitigated or even resolved through better process control and prefabrication. Other researchers claim that any management improvement and innovation has to be implemented within the context of the existing production situation, i.e. accommodating the particularities of construction, so their research efforts focus developing lean construction tools to manage the workflow within the construction process.

2.2.1 Particularities of Construction and Applicability of a Lean Production System

Compared to many other industrial sectors, construction is a unique type of project-oriented industry with many peculiarities that decide the course of production and the industry itself. Vrijhoef and Koskela (2005) identified three major differentiating characteristics: site production, temporary organization and one-of-a-kind product. They pointed out that these production particularities should be explained and understood with other interlinked levels: product and industry. The particularities on the three levels have a logical relation and reinforce each other in a complex interaction (see Figure 2-4), which make the reduction of particularities extremely difficult.

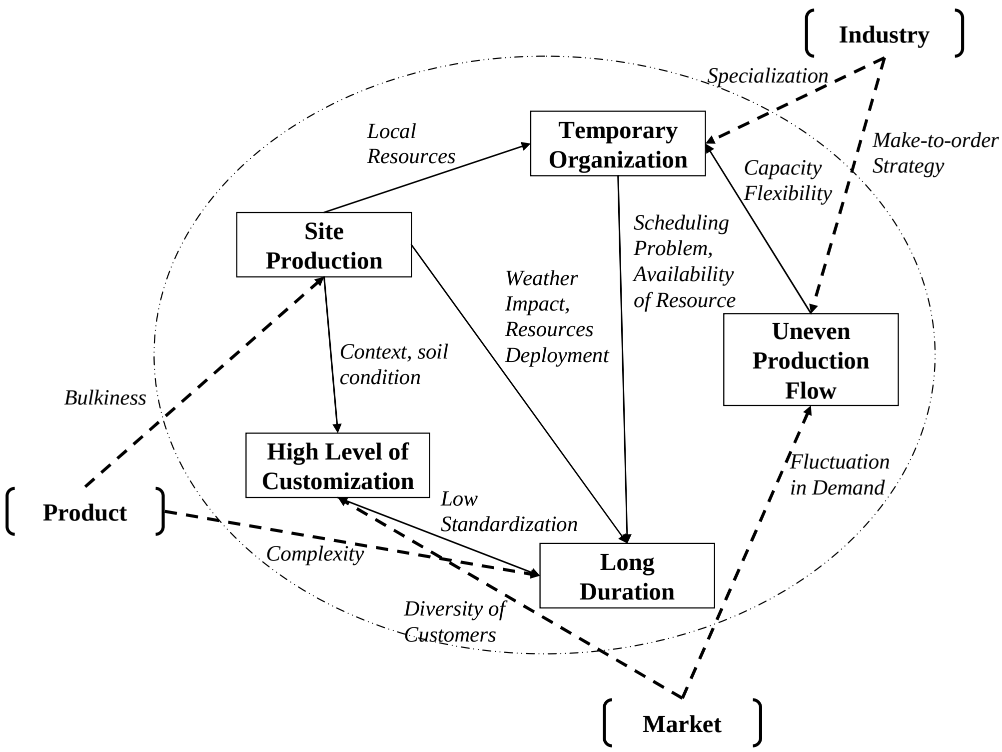


Figure 2-4: Particularities of Construction

Site production: Construction is an on-site production, as opposed to most discrete assembly industries, where products are produced in a fixed position and shipped to their final points of use. As a result, construction is subject to many location-specific factors such as site conditions, and building codes and regulations, which are often difficult to determine prior to actual production. Weather is another major factor that brings significant uncertainty to the construction process. Site-based production also increases the complexity of labor, machinery, and material deployment, and prevents batch production and automation.

One-of-a-kind production: One important characteristic of modern manufacturing is standardization. To minimize costs, it uses specialized equipment to produce standardized products with only limited levels of customization. In construction, most buildings are unique products with a different location, function and design, and demand job-specific construction methods and processes. This one-of-a-kind feature results in a dominant use of the project-based approach in the construction world, as opposed to a flow-based approach in manufacturing.

Temporary organization: The workforce in manufacturing generally enjoys great stability and has a long-term employment relationship with the company. In construction, conversely, most work is subcontracted to small- or mid-size trade contractors, which only have a temporary contractual relationship with the builder/general contractor for a specific project. The transient nature of the organization structure impedes knowledge transfer, training, and continuous improvement.

Long duration: Buildings are much more complex than most manufactured products. Depending on how parts are counted, a car is assembled from about 20,000 components, while a single-family house, the simplest type of building, is comprised of as many as 200,000 components (Gann 1996) and needs about 6-7 months for completion. The author considers the long duration as a major particularity due to the difficulties it brings to process analysis, planning and control.

Uneven production flow: The workload of construction fluctuates significantly on all levels. On the industrial level, the construction market is subject to cyclical trends. Economic conditions, interest rates, and land supply all greatly influence the market demands, and root-in-place property means that a building cannot be moved to an alternative customer. On a company level, the continuity of jobs depends on the results of competitive bids and each job has a completely different workload. While the current subcontracting-based system has provided construction companies flexible capacity (labor and equipment) to deal with the uncertainty in production flow, it creates more uncertainty and fluctuation in subcontractors' work flow. Uneven production flow has shaped the structure of the industry, but has been omitted by most researchers due to project viewpoints.

Although some manufacturing sectors also possess one or several of these characteristics, the combination of them all uniquely defines the construction industry (Ballard and Howell 1998a). Before moving on with the discussion of the applicability of a lean production system to construction, it is worthwhile to review the context of this manufacturing paradigm and its limitations. Lean production generally consists of two interrelated components – lean philosophy and lean techniques. In the automobile industry, these two components are perfectly integrated, while in other industries – even other sectors of the manufacturing industry – lean implementations are compromised to accommodate some of the inherent features of the given industry. In fact, while the fundamental principles of lean philosophy are universal, lean techniques primarily encompass the features and realities of mass production.

Manufacturing processes in general can be grouped into five categories as project, jobbing, batch, mass, or continuous, as shown in Figure 2-5. The automobile industry epitomizes mass production, where for any given model the lot size is in the hundreds of thousands. Although there are some minor variants due to customer selection, the production process in the assembly factory is essentially the same for all products. Due to the high volume of product, it is cost-effective to utilize specialized labor and equipment. The critical challenge in mass production control is the establishment and balancing of the production line so that the process will run smoothly and efficiently. Lean production was born in the context of the automobile industry, aimed at overcoming the drawbacks of mass production. The basic idea behind lean production is to produce only what is needed, when it is needed. This notion may seem simple, but its implementation requires an entirely new approach in terms of both organization and operation.

Lean production emphasizes one-piece continuous flow, which blurs the distinction between jobbing, batch, and mass productions, leading to a more productive and flexible form of mass production. However, the lean production system, as a manufacturing model, has the following limitations:

- Although some broader principles of lean thinking are considered to be universal, most lean techniques have been developed specifically for stable, repetitive production processes (Ohno 1998). Unless the process is stable, continuous flow cannot be realized, and lean tools such as cellular design, pull system, kanban system, leveled scheduling, mixed model scheduling and value stream mapping are not applicable.
- The effectiveness of lean production is contingent on stable gross output volumes (Womack et al. 1990). The flexibility that lean production offers is only within a stable gross output between different products, and cannot address fluctuations in gross output level.

- A fundamental requirement of the planning and implementation of lean production is the availability of accurate operation data. In manufacturing, cycle time and lead time are generally short and can be obtained by site observation, while for long-duration production processes such as construction, one finds great difficulty in collecting statistically meaningful data.

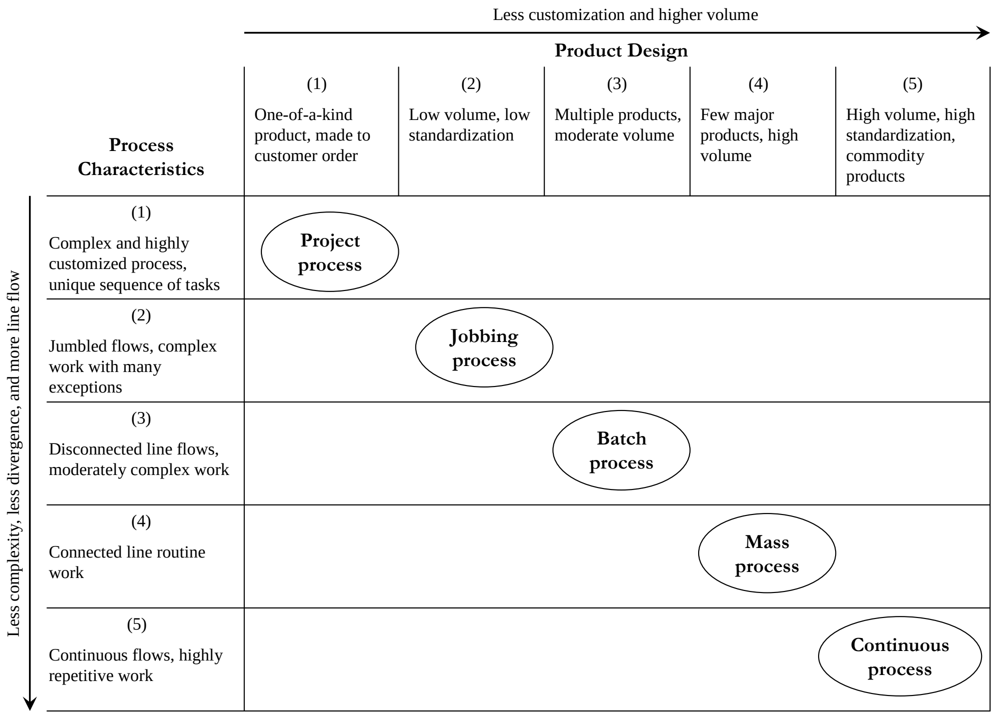


Figure 2-5 Process Model Matrix (Greasley 2006)

In the process model matrix (Figure 2-5), construction (project process) and automobile manufacturing (mass process) form the two extremes of the production process spectrum. The differences between these two industries are inherent in the nature of the respective markets they serve, and cannot be eliminated by a simple application of lean thinking. Winch (2003) argued that construction, in general, is a low volume, complex systems production and should enhance its project-based model by learning from manufacturing sectors that use a design-to-order or concept-to-order production strategy. Declaring the lean production system to be the single best system applicable to all manufacturing sectors, including construction, is an oversimplification.

Table 2-1 illustrates four basic manufacturing models and their application environments. Construction, along with the shipbuilding and aerospace industries, is typically associated with a concept-to-order strategy and has extremely low volume. A concept-to-order strategy also means that the producer has no control of the work flow. The automotive manufacturers generally use a make-to-forecast strategy and enjoy high volume in demand. Production homebuilders mostly use a make-to-order strategy, where customers make selections from a series of pre-designed options, but the volume of products is relatively low.

Table 2-1: Four Basic Manufacturing Models (Winch 2003)

Production Strategy / Production Volume	Concept-to-order Design-to-order	Make-to-order Make-to-forecast
Low-volume	Complex systems production	Lean production
High-volume	Component shop production	Mass production or lean production

Other researchers, represented by Bentelsen and Koskela (2005), argue that a lean production system, or at least most parts of lean philosophy, is applicable to construction. They claim that the traditional construction management practice has ignored the flow and repetitiveness in the construction process (in the view of participating companies), and consequently resulted in significant waste and process variation. Although the particularities of construction make the flow in construction is not as apparent and manageable as that in manufacturing, construction flow can still be improved through implementation of lean principles and tools.

2.2.2 Lean Project Delivery System

The Lean Construction Institute (LCI) agrees with Winch (2003) that construction is a complex systems production, but it believes that the basic principles of lean production can be applied to PM through tailored techniques. Based on this belief, LCI defines lean construction as "a production management-based approach to project delivery – a new way to design and build capital facilities" (LCI, 2007). Therefore, it focuses on the research of principles and techniques that applying the flow concept in PM, which leads to the development of Lean Project Delivery System™ (LPDS). As shown in Figure 2-6, the system consists of 11 modules, organized into five interconnected phases extending through the entire project life-cycle. Two function modules, production control and work structuring, support all five phases, and learning loops, a post-occupancy evaluation module, links the end of one project to the beginning of the next.

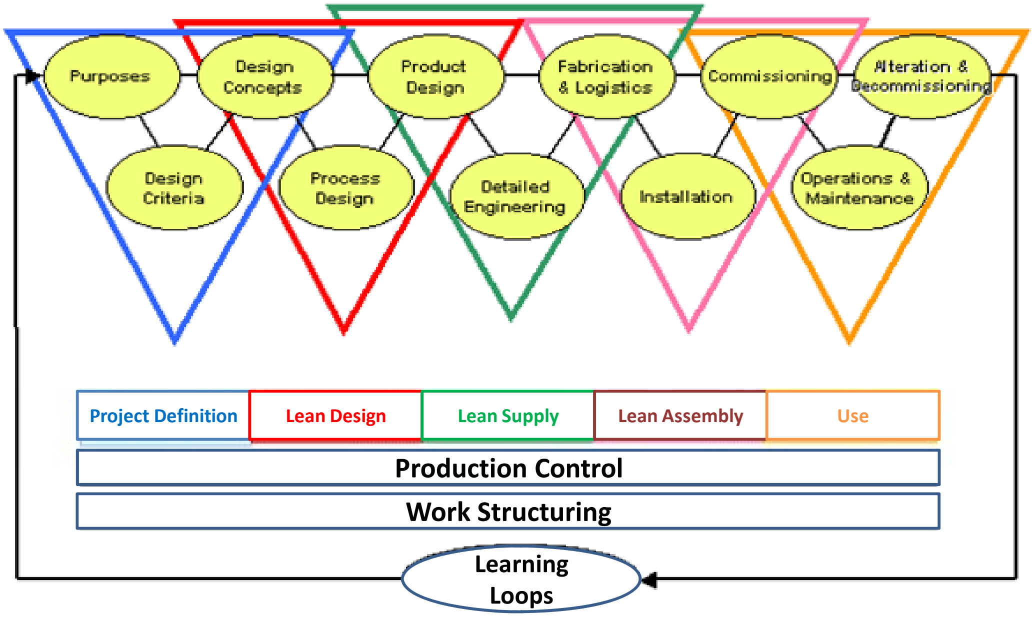


Figure 2-6: Lean Project Delivery System (Ballard 2000b)

Conventional PM is activity-centered. It breaks the project into a series of activities, estimates duration, cost and resource requirements for each activity, and then assigns/contracts activities to different subtrades. The execution of each activity is coordinated using a project schedule, and performance is monitored and compared to the schedule and budget. The traditional task management approach comes from the transformation viewpoint, which looks at production as a number of discrete small transformations, each independently adding value to the product (Koskela and Ballard 1998). Process optimization can be achieved by optimizing each separate transformation, and buffers, i.e. staging resources, are needed between transformations to keep the schedule.

LPDS differs from traditional PM in many ways (see Table 2-2). The most fundamental difference is that LPDS takes project view and focuses on making work flow reliable as opposed to improving productivity or reducing cost of individual activities. Key lean construction tools developed to achieve this goal are work structuring and production control.

Table 2-2: Comparison between LPDS and Traditional PM (LCI, 2007)

Lean Construction	Traditional Construction
Control	
Causing events to conform to plan – Steering	Monitoring against schedule and budget projections – Tracking
Optimization	
The entire project	A specific activity
Scheduling Viewpoint	
• "PULL" work schedule • Based on when its completion is required by a successor activity	• "PUSH" work schedule • Based on emphasizing required start dates for activities
Production System	
Flow production system	Conversion production system
Production Process	
Effectiveness	Efficiency
Performance Measurement	
Percent Plan Complete (PPC)	WBS, CPM, Earned Value
Customer Satisfaction	
Successor process satisfaction	Owner or final consumer satisfaction
Planning	
Learning	Knowing
Uncertainty	
Internal	External
Coordination	
Keeping a promise	Following orders
Goal of Supervision	
Reduce variation & Manage flow	Point speed & Productivity

Lean work structuring is an "operation and process design in alignment with product design, the structure of supply chains, the allocation of resources, and design-for-assembly efforts" with the goal of making "workflow more reliable and quick while delivering value to the customer" (Ballard 2000a). It answers the following questions (Ballard 1999):

- In what chunks will work be assigned to trade crews?

- How will work be sequenced?
- How will work be handed over from one trade to the next?
- Should two consecutive tasks be executed in a continuous flow process or should they be decoupled?
- What will be the size of decoupling buffers?
- When will tasks be done?

The current construction practice is piece-meal and product-oriented.

The phrase "work structuring" is borrowed from manufacturing. It originally refers to a set of operations management tools that help managers design an efficient working system that meets the requirement of the company and its technology and that satisfies the workers' individual needs (Chase et al. 2006). Job design and work measurements are two major components in work structuring, and the output of the work structuring process is standardized work. In a lean production system, work structuring has an important role, since it contributes to stabilizing the production performance and establishing a baseline for continuous improvement. In addition, some lean tools, such as JIT, job enrichment, team empowerment, work flexibility, and production leveling has been widely used in job design.

Work structuring in lean construction, however, integrates the ideas of job design, concurrent design or design for manufacturing, and 5-why problem-solving and aims at developing an elemental framework at the early design stage to guide the project delivery process (Tsao et al. 2004). Today's construction industry is fragmented. The design/build process is divided into a series of separate parts that are contracted to independent companies that only have responsibility for one or two parts and try to optimize their own operations only. To overcome the piece-meal, project-oriented contracting mentality, lean work structuring emphasizes the importance of involving general contractors, specialty trades and fabricators in the design process to develop product-process design and examine the problems that construction crews face with 5-why methods to develop alternative work structure. As a result, lean work structuring has much a boarder meaning than its origin in manufacturing, but the output is quite general and subject to constant change. The output of work structuring in lean construction are master and phase schedules, project contractual structure and supply chain configurations. Figure 2-7 illustrates the function of work structuring in lean project delivery.

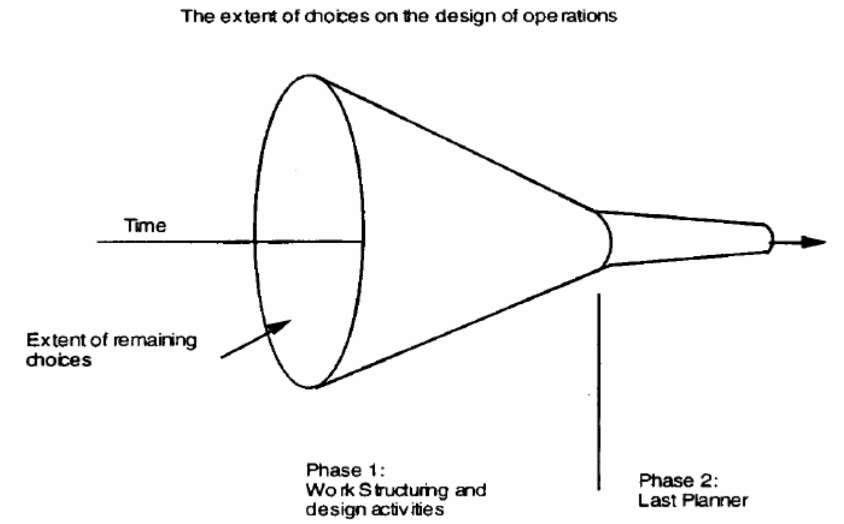


Figure 2-7: Work Structuring and Construction Process Design (Kim 2002)

Production control is also a manufacturing concept referring to the systematic approach to control the flow of a projected production. It usually includes aggregate planning, material requirements coordination, workload control, and production unit control. Ballard and Howell (1998b) first applied the production control concept to construction and developed a construction control system named Last Planner™. The system consists of three levels of scheduling, corresponding to manufacturing's (1) aggregate planning, (2) material coordination and capacity planning, and (3) operations scheduling. As shown in Figure 2-8, the scheduling levels are (1) "Master Schedule," which is developed in the design stage to show the completion date and major milestones of the project; (2) "Phase Look Ahead Schedule," which pulls the resource and generates early warning of problems; and (3) "Weekly Work Plans," which consist of tasks selected from Workable Backlog based on actual receipt of resources and completion of prerequisites. Stopping the line to fix problem, a lean principle, is interpreted here as making only quality assignments. The risk of not using available capacity and delaying the schedule forces management to deal with the problem immediately. Making only quality assignments also shields construction tasks from work flow uncertainty, and a stable work flow is one of the prerequisites of lean implementation and process improvement.

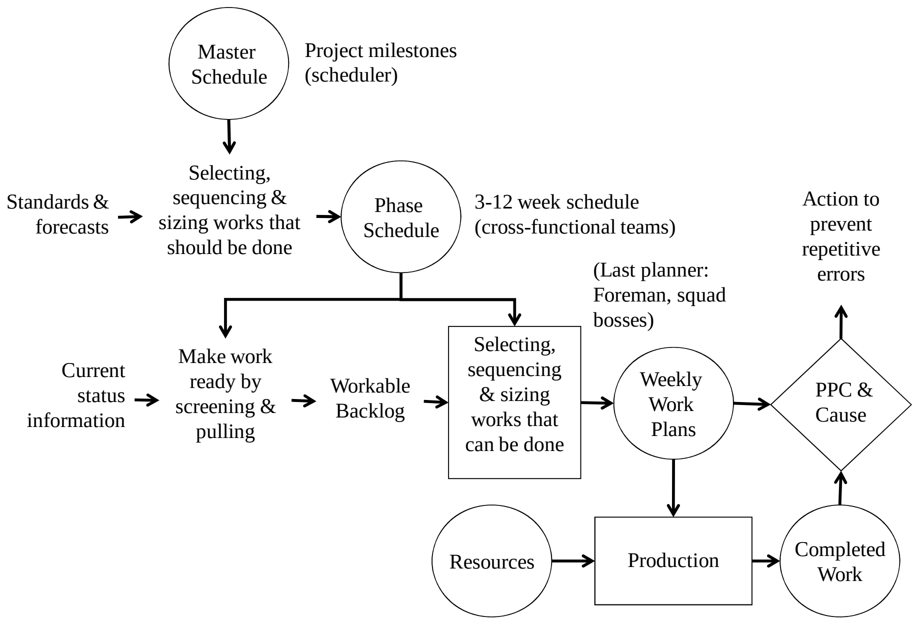


Figure 2-8: Last Planner System (Ballard 2000a)

Last Planner theory correctly identified that uncertainty is mainly caused by internal factors rather than external factors, and focused on the reduction of variation through process control and managing work flow (Kim 2002). However, the concept of "flow" in Last Planner differs from that in lean production. According to the lean construction glossary defined by the LCI, "(work) flow is the movement of information and materials through a network of production units, each of which processes them before releasing to those downstream." Lean production, on the other hand, understands flow on two different axes – operation and process. It seeks a continuous, stable and reliable flow on both operations – work stations, where work undertaken by men and machines – and process – products traveling through the production system. The Last Planner system focuses on improving the certainty of the process, represented by the improvement of percent plan complete (PPC), but neglects the flow of operations, the work flow of subcontractors.

While workflow variability reduction is widely accepted by lean construction researchers as one of the most important aspect in lean construction, some researchers claim that flexible capacity (labor and plant), which allow contractors to efficiently respond to variability, is equally important, if not more important, in construction due to the uncontrollable nature of construction conditions. Thomas et al. (2002) examined the data obtained from 14 concrete formwork projects and concluded that the variability in daily labor productivity is more highly correlated to project performance than the variability of workflow is. However, in this research, the project performance is evaluated by waste in workers' productivity (project waste index), as opposed to lean project delivery where project performance is measured in terms of project duration and costs. Although Thomas et al. (2002) did not give a clear recommendation on how to apply the capacity flexibility concept in construction, project performance should also be evaluated in terms of subcontractors' productivity and the variability on an operational level needs to be addressed.

2.3 LEAN APPLICATION IN THE HOMEBUILDING INDUSTRY

Homebuilding, represented by production homebuilders, is a unique sector of construction. In North America, houses are generally built repetitively on the basis of a small number of pre-designed models by specialized trade contractors (Bashford et al. 2003). As a result, the homebuilding process could be viewed in three different ways: a collection of many small individual projects, a big project with many repetitive units, or a production system with a flow of houses. Traditionally, housing construction is planned and controlled using the first view: many individual small projects. For each house, a site manager uses Work Breakdown Structure (WBS) to develop a list of activities that are sequenced and scheduled in a Gantt chart, and then these activities are assigned to various trade contractors or crews (Love 1995). Lumsden (1968) argues that the traditional PM technique is activity-oriented and not suitable for residential construction that involves many repetitive units. A resource-oriented technique, called Line-of-Balance (LOB), is proposed to provide continuous workflow for workforce moving from one repeating unit to another. Based on LOB technique, El-Rayes et al. (2002) further developed a scheduling and controlling system with consideration of common practical factors, including variation in duration, multiple crew usage, and resource availability. The idea to view the production of a homebuilding company as a production system is relatively new and falls under the lean construction domain.

In the past decade, there were three major research efforts on lean application in residential construction. First, the Science and Technology Policy Research Unit (SPRU) at the University of Sussex conducted a UK/Japan housing study project in the 1990s. The goal of the study was to "develop a better understanding of the ways in which each country's housing systems had developed and how the introduction of new technology might be used to improve quality and delivery of housing" (Iwashita 2001). A number of papers and reports were published as a consequence of this work. Another research effort was at Arizona State University. In collaboration with the Partnership for Advancing Technology in Housing (PATH) program, five major local homebuilders, the Home Builder Association of Central Arizona (HBACA) and the Housing Research Institute (HRI) at Arizona State University initiated an AzPath program aiming at building a culture and infrastructure of innovation for the housing industry (Sawhney 2004). "Implementation of Lean Thinking Concepts" is one of the major research areas of AzPath. The third research effort was on a so-called "product strategy" which aimed at reducing the complexity of construction by turning the building into a product manufactured in a factory where lean production can be applied and make the site-work mainly an installation (Bertelsen 2005). Housing has been regarded as the most suitable sector in construction for this approach.

2.3.1 UK/Japan Housing Study

Industrialized housing and mass customization were two majors area of this study. Gann (1996) introduced the success of Japanese industrialized housing producers, highlighting similarities and differences between industrialized housing and car manufacturing in terms of product development, R&D, supply chain coordination, marketing and sales. Great similarities can be found in the big house manufacturers, who have produced tens of thousands of homes a year, and automobile manufactures. Lean techniques, including JIT, quality circle, people and team work, and continuous improvement, are widely applied in these companies. However, wider customer choice and location-specific regulatory environments and site conditions require a much higher flexibility of housing production, so that some lean tools, such as kanban and error proofing, cannot be applied. In addition, more than half of the construction works have to be performed on site, which leads to high variability in the production process. The author also points out that although Japanese housing manufacturers set a good example of industrialized housing and knowledge transfer between housing and manufacturing industries, their success is also the result of unique features of the Japanese housing market, which is large and concentrated in urban areas.

In Japan, industrialized housing has approximately 20% of the market share. According to 1994 data, 46% of single-family houses were built by companies that constructed less than 10 dwellings annually. Iwashita's paper (2001) explained the operation strategies of those small contractors and their roles in the customized housing sector. Typically, small housing contractors operate in a small local market, dealing with the entire value stream including sales, material supply, construction management, construction, and maintenance. They use the traditional stick-built method and work with specialized trade people with whom they have had experience. No lean implementation efforts were observed. The author introduced an important player in the market, "super subcontractors," who worked directly for a production homebuilder and completed a subsystem of roofing, exterior finishing and carpentry works. The emergence of these super subcontractors allowed the large industrialized housing companies to outsource the construction function and focus on the sales, design and manufacturing functions. In the effort of developing suppliers and partners (a lean principle), large home producers help the formation of subcontractors and establish a long-term partnership with them.

Barlow was involved in four visits to Japan in 2000. The focus of his study was "the supply-chain management aspects of mass customization within a housebuilding context" (Barlow et al. 2003). As opposed to the common perception of manufactured housing, Japanese industrialized producers generally offer their customer a wide range of choice on design and specification levels. For example, a Japanese housing supplier typically has more than 300 standard designs in terms of floor plan and elevation, compared with well under 100 for typical UK or North American production homebuilders. However, the Japanese industrialized housing sector is not a homogeneous group. Different approaches were adopted to provide different levels of customization, as shown in Figure 2-9. Barlow's findings provide a new perspective of how to deliver high levels of customization in house design and specification while adopting standardization and prefabrication techniques.

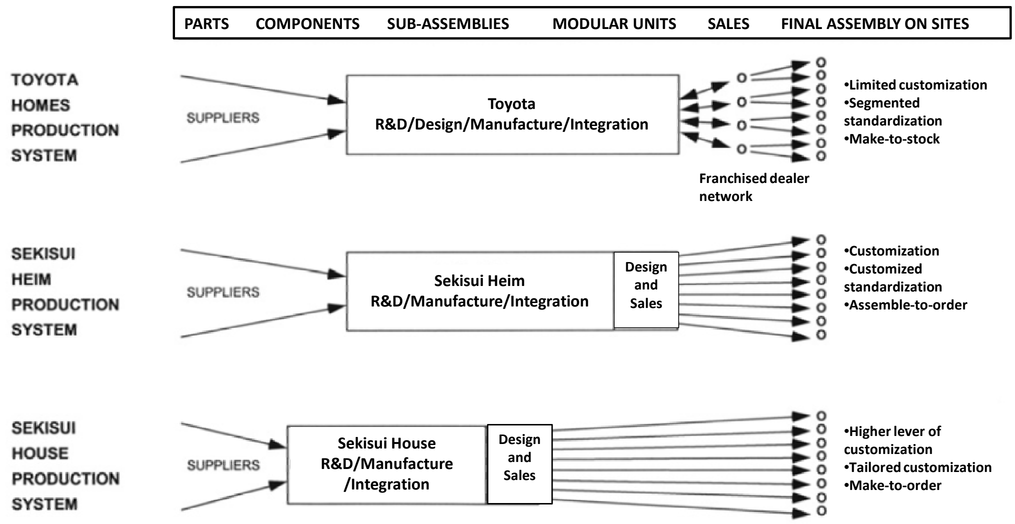


Figure 2-9: Supply Chain Models of Japanese Home Producers (Barlow et al 2003)

2.3.2 AzPath and Even Production Flow

The research activities of AzPath are based on the study of current practice of residential construction in the metropolitan area of Phoenix, AZ, and grouped into four interrelated areas: 1) Benchmarking time and cost of current industry practices; 2) Implementation of lean thinking concepts; 3) Application of supply chain management techniques; and 4) Using IT to improve coordination between trade contractors. Two important research results that have so far been published by AzPath are studies on even flow production (EFP) control techniques (Bashford et al. 2003) and housing construction cycle time (Bashford et al. 2005).

The concept of applying EFP in residential construction was first proposed by the U.S. National Association of Home Builders Research Centre (NAHB). The basic idea of EFP is simple: building homes to a standard schedule and releasing the same amount of houses into construction at a given time unit, such as one house per week, per day, or per 2 hours. As the author discussed before, the completion of a house involves a large number of independent trade contractors. Under current housing construction management strategies, the workflow of those subcontractors is extremely variable, which inevitably reduces the efficiency of homebuilding processes. The goal of EFP is to improve process reliability and predictability by setting a steady pace throughout the production process. As an assembly line is moving based on takt time, even flow allows sub-trades to move steadily from house to house according to a predetermined schedule, eliminating unexpected schedule changes that result in idle time of field crews. Meanwhile, a constant workflow, such as three houses per week, allows the trade contractors to plan and schedule their work and assign dedicated crew(s) to the homebuilder. Familiarity with the product and quality standards will definitely improve crews' productivity. A fixed schedule for every phase of construction, meaning no juggling trades and frequent schedule adjustments, significantly reduces the coordination efforts of field superintendents, and allows homebuilders to forecast precisely the home possession date, which improves customer satisfaction. In addition, EFP helps trade contractors more efficiently manage their manpower and eliminates idle time, since they don't need to deal with a possible peak. From a lean production perspective, even flow production can be seen as a housing construction version of production leveling and takt time planning.

In theory, EFP is straightforward and intuitively appealing, but in practice, a few difficult business decisions have to be made in order to apply EFP. First, one needs to look at the pace of home starts. It seems that the rate of home starts should be the same as the rate of sales. The problem is that sales rates vary all the time, and it is difficult to forecast future sales rates. If the pace of home starts has to be constantly adjusted to follow the sales rate, then there is no even flow. Second, one needs to look at the durations of activities in the schedule. In order to ensure the reliability of the schedule, activity durations should be determined by the largest homes or slowest crew. For example, the duration of framing should be 10 workdays, even though only the most complex model takes 10 workdays to be completed. However, longer activity durations result in houses sitting idle and may increase overall construction time. Weather is another issue. In an EFP system, on a day when weather or other "acts of God" prevent any home progress, all construction activities need to stop and that day is declared as non-workday. To reduced house idle time and mitigate the impact of weather, an alternative even flow strategy was adopted by some homebuilders. They release homes in constant pace to construction, but each activity in the process starts as soon as the proceeding activity is completed. Figure 2-10 illustrates those two strategies.

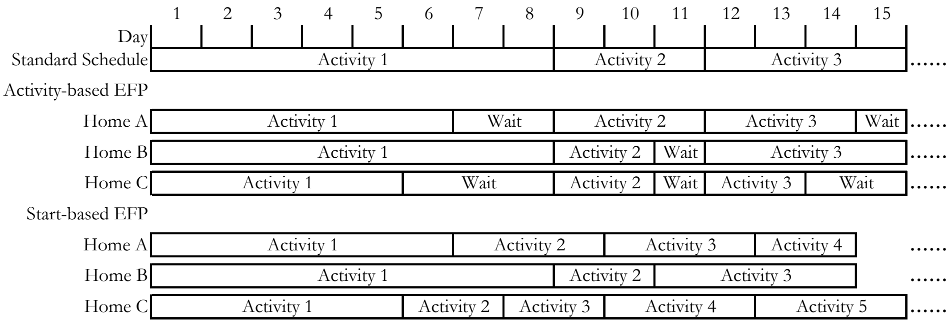


Figure 2-10: Schematic Representation of Two Even Flow Production Strategies

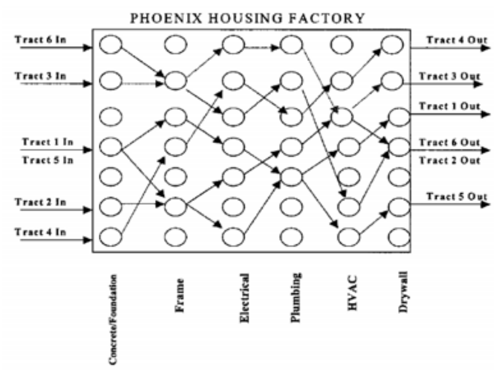
The contribution of AzPath's research is that it thoroughly investigated the implication of those two even flow production systems, maintaining even flow for each activity in the system (activity-based EFP) and only maintaining even flow for the first activity of the process (start-based EFP). Bashford et al. (2003) designed and simulated seven different scenarios, as shown in Table 2-3. The simulation results provided some importation insights on the even flow production.

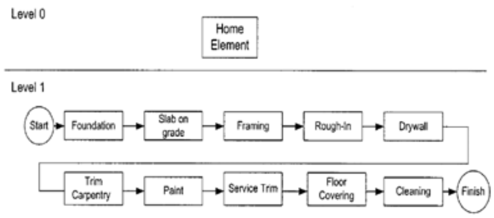
1) When construction starts follows sales, the standard deviation of work flow is equal to mean, implying that the pace of any given activity in the system is virtually unpredictable.
2) Activity-based EFP exhibits perfect flow control, resulting in even workload for trade contractors.
3) Compared with a random start pattern, start-based EFP only slightly improves flow reliability.
4) Even flow production methodology has no impact on the total project duration.
5) Improving the reliability of activity cycle time is the key for reducing both the variability of the process and the total project duration.

Table 2-3: Simulation on Even Flow Production Strategies (Bashford et al 2003)

	STARTS PER WEEK				
	1		2		
Strategy	Deterministic	Probabilistic	Deterministic	Probabilistic	Sales-based starts
Activity-based even flow	Scenario 1	—	Scenario 2	—	—
Start-based even flow	Scenario 3	Scenario 5	Scenario 4	Scenario 6	Scenario 7

Another research result of AzPath is also critical to this dissertation. The researchers at the University of Arizona conducted a thorough investigation of the residential construction industry in the metropolitan Phoenix area and developed a conceptual model for the residential production system on the industrial level, as shown in Figure 2-11a. In the model, houses on a tract of land are viewed as a product batch passing through a virtual factory with multiple pathways formed by trade contractors. The selection of the trade contractor (the pathway) is decided by each individual homebuilder and appears randomly from the system point of view. The Edmonton homebuilding market can be described using exactly the same model, except that the homebuilders in Edmonton usually subcontract their construction work by house instead of by tracts of homes. Figure 2-11b shows a simulation model consisting of 10 consolidated construction stages. This model was developed based on the inputs from several Phoenix homebuilders. In fact, the case-study company, LMB, followed almost the same construction process before its lean initiatives. The similarity between the homebuilding markets and homebuilding processes of Phoenix and Edmonton suggests that the North American homebuilding industry shares common characteristics and follows a similar management model. Any improvement efforts and research result done in one local area could be generalized for any market in North America.





a. Conceptual model of residential construction factory (Bashford et al. 2005)

b. Simulation model for homebuilding process (Bashford et al. 2003)

Figure 2-11: Homebuilding Models Developed by AzPath Research

2.3.3 Product Strategy in Lean Construction

Reducing workflow variability caused by complexity, and one-of-a-kind and on-site construction is a central tenet of lean construction (Ballard 2001). While Last

Planner and even flow production try to improve workflow reliability through better planning and control, some lean construction researchers proposed another approach to eliminate the peculiarity of construction by turning the building into factory-built products. They coined their approach as "product strategy," as opposed to the "process strategy" introduced earlier.

In fact, the product strategy is not new for residential construction, but is known under a different term, industrialization. The following section details the history and current state of industrialized housing. Unlike the automobile industry where the market is dominated by a few car manufacturers, industrialized housing has only achieved limited success in spite of a great number of attempts in the last decades. Koskela (2003) summarized four problems of industrialized construction, including longer flow due to more than two production locations, larger amount of design, higher requirement to construction quality (dimensional accuracy), and longer error correction cycle. He argued that elimination of complexity and variability through industrialization may cause other problems, and the total process of industrialized construction tends to be more complex than conventional on-site construction. However, complexity can only be defined in context, thus it would not be proper to directly compare the complexity of stick-built housing with that of industrialized housing (Hook and Stehn 2005). The complexity of prefabrication is caused by customization and on-site assembly rather than the peculiarities of construction, and can be managed by direct implementation of lean manufacturing principles. The key of the product strategy is to make prefabrication lean (Ballard and Arbulu 2004) and to find the right balance between standardization and customization (Gann 1996).

A survey conducted in four Swedish industrialized housing manufacturers showed that although industrial housing shared common features with manufacturing in terms of production control, stable and permanent workforce, and repetition of operations, its underpinning management culture was still based on traditional construction project mentality (Hook and Stehn 2009). Low worker motivation and involvement in built-in quality, problem-solving and continuous improvement make the implementation of lean production in industrialized housing as difficult as in on-site construction. The key of the applicability of lean principles and practices is not the production environment but the company culture and mentality of workers and managers.

2.4 INDUSTRILIZATION OF HOUSING

Ever since Henry Ford developed the revolutionary mass production system for car manufacturing, the housing industry has been seduced by the idea of producing houses using a mass production approach. Factory-based production, which involves economies of scale, fixed labor, a high level of automation, and tight managerial control, has long been perceived as more efficient than craft-based production like construction (Gann 1996). In the 1950s and '60s, some visionary architects initiated an industrialization movement in both Europe and America. Three main principles underpinned this movement: standardization, prefabrication and systems building (Crowley 1998). A number of high rise apartments featured large pre-fabricated panels, factory-made components, and standardized design to meet the rapid demands of low-cost housing (Herbert 1984). This early industrialization effort is widely seen as a failure for various reasons, including lack of customer-orientation, defects in structural integrity, severe quality problems in joints and thermal performance, and lack of maintenance. Although most of these problems were not caused by industrialization but by the pursuit of low costs and lack of management control, the construction industry tended to return to traditional housing. The only exception was manufactured housing in U.S. and factory-built housing in Japan and Nordic countries.

By the late 1990s, however, attention was again turning to the industrialization of residential construction. Lean construction has, of course, had a profound impact, particularly with the establishment of the International Group for Lean Construction and the Lean Construction Institute, which became the platform for information exchange in the area. The U.S. Department of Housing and Urban Development (HUD) launched the Partnership for Advancing Technology in Housing (PATH) program in 1998 and sponsored research on industrializing the residential construction site (O'Brien et al. 2000). This research then became the central part of a PATH roadmap – whole-house and building process redesign (NAHB 2002a).

2.4.1 Defining Industrialized Housing

Traditionally, the term industrialized housing is alternatively referred to as prefabrication, off-site construction, and factory-built. The underlying concept of all these terms is to accomplish most of the house production process in one or more plants and keep site work to a minimum (MHRA 2006). However, the key to industrialization is not moving assembly lines or producing products in factory, rather it is the production system itself that produces products efficiently. The manufacturing industry has achieved productivity gain through continuous innovation in the management and integration of key business processes across the supply chain. The change in the material transformation process is only an expression of the evolution of management thinking.

Inspired by the latest progress in operations management, Lessing et al. (2005) developed a comprehensive definition of industrialized housing, which consists of eight key characteristics:

1) A clear focus on customer value
2) Planning and control of the entire value stream
3) IT system to integrate all steps in the construction process
4) Reliable technical systems to support process
5) Off-site prefabrication of building components
6) Long-term relationship between participants
7) Supply chain management based on JIT
8) Systematic performance measuring and experience transfer

While off-site prefabrication is a key factor of industrialization, each of the above concepts must be developed to achieve the desired results. Homebuilders must improve their control of the supply chain and integrate design, prefabrication, site assembly, field work and market intelligence functions more effectively; this requires radical change in the whole process structure and management skills (Barlow 1999).

2.4.2 Industrialized Housing in the U.S.

Industrialized housing emerged on a large scale in the U.S. in early 1950s, when low-cost housing was much needed for returning veterans. Soon it evolved into manufactured homes, built completely in factory under Manufactured Home Construction and Safety Standards (HUD code). Since the HUD code was oriented toward temporary housing that could be transported on wheels rather than toward regular permanent houses, the quality standard and duration requirement were relatively low. Moreover, like the manufacturing industry, manufactured house producers employ unskilled or semi-skilled workers on high-cost, machinery-based assembly lines to produce houses continuously, and for each house, up to 75% of the construction work is completed in factories (NAHB 1998). Because it is costly to halt the production flow and reconfigure the assembly line, manufacturers prefer producing a few standard models in high volume. In addition, the requirements of transportation limited the size and shape of the houses. As a result, customers of manufactured housing benefit from lower costs that come from economies of scale and tighter managerial control, but at the expense of variety and choice. The average price of a double-section HUD-Code home is 25% less than that of a site-built home with same size. In late 1990s, manufactured housing reached its peak, representing approximately 20% of new single-family homes sold in the U.S. However, the trend has been changing rapidly since 2000, as shown in Figure 2-12. To compete with traditional stick-built methods, which offer great variety of design options, factory builders are facing big challenges in increasing design versatility, enhancing home performance, changing consumers' perception, and increasing productivity in the production process.

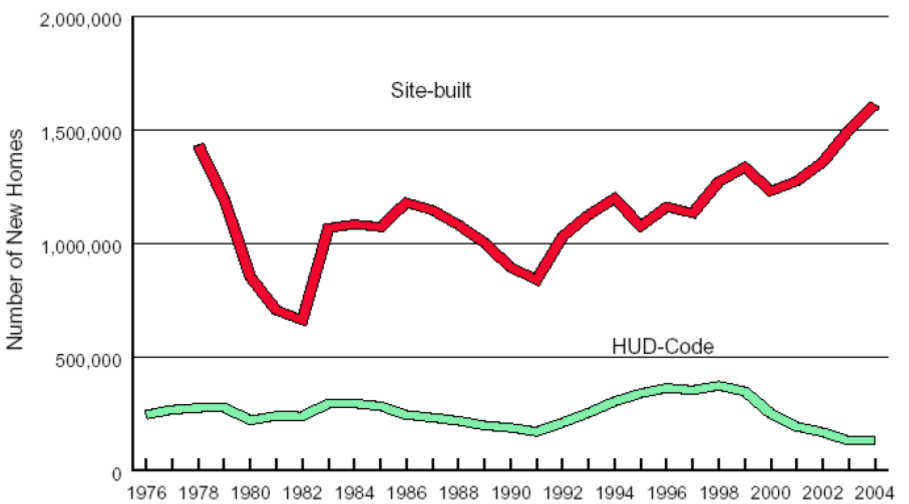


Figure 2-12: Housing Starts By Building Type (MHRA 2006)

In contrast to the down-trend of manufactured housing, the housing industry has seen a dynamic growth of two other segments of factory-built housing: modular and panelized construction. Many traditional manufactured home builders have diversified into modular homes and some homebuilding giants, such as Pulte Homes and Toll

Brothers Inc., have stepped into the field, building their own factories to produce basement/foundation wall panels, fabricated steel studs, structural floors and panelized interior and exterior walls (Sawyer 2006). The housing market boom in early 2000s drove homebuilders to invest in technology for prefabrication in order to improve productivity and reduce construction time.

In Pulte Homes' factory in Manassas, VA, the production line is driven by a computer-assisted manufacturing system. The parts are produced on a house-by-house basis. Each one in the line may vary from others as long as the design units, such as web depth and framing centers, meet Pulte's standard parameters. Then all components for each house envelope and interior partitions, completed with installed windows, are grouped and shipped to the site according to schedule. A typical 2000 sq.ft. single-family house can be assembled from foundation to dried-in in a week or less. Although panelized construction has significantly reduced construction time at the front, the remaining parts of the homebuilding process are still full of waste - another 90 to 120 days are needed to complete the house.

2.4.3 Industrialized Housing in Japan

The Japanese housing building industry has a long tradition of craft production based on woodworking skills. In the 1950s, several materials manufacturers began to produce and supply detached houses, hoping to exploit a new market for their excess production capacities, which resulted from the procurement boom caused by the Korean War (Matsumura 1994). At the beginning, these newcomers used the mass-production method to produce highly uniformed houses from a small range of standard components, but their products could not compete with conventional timber frame houses, which offered customers a great variety of choices. After the early failure, a few house manufacturers developed their own production systems and have grown into giants in industrialized housing. By the mid-'90s, the entire residential construction market was divided into three segments: 40% was produced by small local builders, using a combination of pre-cut timber and craft skills to build in small towns and rural areas; 40% by large contractors, usually making multiple occupancy dwellings; and 20% by various industrialized housing producers (Gann 1996). Five major factory-builders account for about a 80% share of the factory-built housing market (See Table 2-4).

Table 2-4: Japan's Top 5 Factory-Built Housing Companies (Gann 1996)

Company	Annual Throughout (1993)	Housing Products	Level of Factory Work (% of construction costs)
Sekisui House	70,000	Steel and timber-framed panelized houses	25-33%
Misawa Homes	50,000	Steel and timber-framed panelized houses	25-33%
Daiwa House	40,000	Steel frame panelized houses	25-33%
Sekisui Heim	34,000	Steel and timber-framed modular houses	35-40%
National House	32,000	Steel frame panelized houses	25-33%

The rapid growth of industrialized housing in Japan partially benefited from the unique characteristics of the Japanese market for new homes (Barlow et al. 2003), which include the following:

- High population density, rapid economic growth and urbanization made the local housing market large and stable enough to warrant the huge investment for housing factories. Unlike North American consumers, Japanese prefer new homes rather than second-hand housing – new homes represent approximately 80% of total house transactions.
- The shortages of skilled carpenters, depletion of indigenous supplies of timber, and the strict regulation of fire and earthquake protection increase the cost of traditional timber frame housing and enhance the advantages that the industrialized housing has in labor requirement, material purchase, and quality control.
- 75% newly built detached houses are commissioned by individuals and built on their own plot or on land purchased outside the transaction of houses. Therefore, the housing producers have to focus on improving their production processes to ensure their profitability.
- The customers' preference for high-quality and name-brand products gives room for industrialized housing, which generally is 8-10% more expensive than

traditional site-built housing but is known for its high level of quality and structural durability (Noguchi 2003).

- Most of the factory-based house producers in Japan have their origins in the manufacturing industry instead of traditional craft house building. The managers in these companies have solid backgrounds in manufacturing technologies and operations management.

Distinctive operation strategies and lean production systems also contributed to the success. Japanese factory-builders, as opposed to their American counterparts, aim at middle and luxury markets and make huge effort to improve the flexibility of the production system to cater to individual customer's choices. This is the reason that most of Japanese factory-builders adopt the panelized system instead of modular homes. Sekisui House, the largest housing producer in the world, combines design and sales activities to provide a high degree of customization to buyers. In sales offices, sales/design staff work with customers to develop customized designs based on catalogue design concepts. More than 300 standard designs in terms of elevation and floor plans are offered in the catalogue. (Gann 1996).

Cross-industry learning has occurred between factory-building companies and other industries. Sekisui has a long history of lean initiatives and process kaizen has become the company's culture – the way people do things every day (Hall 2008). In the company, every employee must report on their kaizen experience to his/her fellows twice a year, and part of management's standard work is to coach the "soft stuff": the value stream in process, work culture, team work, etc.

2.4.4 Industrialized Housing in Nordic Countries and Canada

In the last two decades, industrialized housing has dominated some of the national markets of Western European countries. One good example is Sweden. In 1983, 90% of new single-family homes were produced in factories. Government policy played important role in the progress of industrial housing. In the mid-'60s, Sweden decided to industrialize the nation's homebuilding industry, started subsidizing the mortgages and investing heavily on manufactured housing research. Now the Swedish industrialized housing industry has built its reputation on an exceptionally high standard of quality and energy efficiency. Meanwhile, a panelized building system and computer controlled production lines allow high flexibility in building design.

Denmark and Fenland are other two countries where more than 60% of homes have been provided by industrialized house producers. The dominant building system in those two countries is small wood-frame, highly insulated panels that can be handled either by workers or using a small crane. Larger panels and modular building have gained popularity in the past few years. The export orientation of these two economies and close relationship between housing industry and wood products industry made these two countries major players in the global market, exporting panelized homes and precut log houses.

The Canadian industrialized housing industry cannot compare in scale to that of the U.S., Japan and Nordic countries due to the small and low density housing market. Most of the manufacturers have experience in exporting precut, panelized, and modular building systems mainly to the U.S. and Japan. In the domestic market, industrialized housing accounts only for a small share in the urban housing market, but has competitive advantages over stick-built houses in rural housing and industrial camps, which are generally located in remote areas where skilled trade people are not available. Based on the author's study on two modular housing producers in Edmonton, no lean initiatives were observed in the companies. They generally use the same management method and techniques as stick-built housing to construct the building modules in the factory environment, as shown in Figure 2-13.

Figure 2-13: The Framing Station in an Edmonton Manufactured Housing Plant

2.5 COMPARATIVE STUDY BETWEEN AUTO-INDUSTRY AND HOMEBUILDING

The implementation of a lean production system in construction has met many difficulties, though one can argue that lean principles can be applied to any business. It is important to have a thorough understanding of the production environment of housing construction, and its differences and similarities to the automobile industry. The most obvious differences are in the nature of the product and market. Unlike the automobile market, where major manufacturers enjoy continuous and secured (in a certain time period) demand, the housing market is subject to consistent change caused by economy, land availability, variety of methods of financing and customers' preference. In addition, houses are bulky and location-specific (governed by a local building code and building permit review of the municipal administration). The economic distance of factory-built housing is 120-150 kilometers. Therefore, most production homebuilders, no matter what approach they use, traditional stick-built or factory-based, serve the local market, and extra production capacity caused by market fluctuation cannot be filled by demands from markets in other geographical areas.

Since the housing market in North America is not stable enough for a production builder to justify the large investment costs of a central factory and the high operation costs to maintain its own workforce, the homebuilding process is structured based on contracting. Homebuilders are actually not builders, but marketing companies and general contractors. All construction work is carried on by small subcontractors. A typical single-family home in Edmonton involves at least 30 trade contractors, undertaking about 90 distinct tasks. Each trade contractor works for multiple homebuilders and only has a temporary contractual relationship with any given homebuilder. The current practice provides the necessary flexibility for homebuilders to deal with the consistent change in market demand and risk is shared on a much boarder base with trade contractors. However, the transient nature of the organization structure sets homebuilding apart from manufacturing, in which companies establish permanent workforce and long-term relationship with their material suppliers, and significantly impedes knowledge transfer from manufacturing to the mainstream of housing production.

- Temporary contracting relationship between homebuilders and trades prevents homebuilders from investing in the training of their workforce, since workforce is not always available and also works for their competitors. Without training, any innovation in technologies and management becomes impossible.
- Small trade contractors perform their duty using craft skills, and have no motivation and capacity to develop and deploy new technology and capital equipments.
- The fragmented process structure hinders process control. Homebuilders have virtually no control over the completion of an individual construction task, and trade contractors generally try to maximize their interests rather than optimize the process.

Size and immobility of the final product and a fragmented process structure decide that houses are generally assembled at the point of consumption under many uncertainties such as weather and site conditions.

The level of standardization is another factor that makes housing differ from car manufacturing. The key factor that led to Henry Ford's innovation of the assembly line was the standardization and interchangeability of parts and the simplicity of attaching them to each other (Crowley 1998). Although there are numerous car models on the market to satisfy the individual needs of customers, this is realized by many international car makers competing in a local market. The parts of cars in a product family of an auto maker are highly standardized; even different product lines also share parts to achieve the economic scale and reduce operation costs. For example, Toyota's three major models of passenger cars, Corolla, Camry, and Lexus, are built on the same platform and its SUV model, RAV4, share more than 40% of its parts with other Toyota vehicles, including passenger cars (Liker 2006). On the contrary, a local housing market normally consists of a few major production homebuilders that provide a large variety of products and a number of small builders who build one-of-a-kind houses based on customers' orders. For instance, Landmark Homes, one of the largest production builders of single-family homes in Edmonton, has 15 base models and none of them accounts more than 20% of the total sales (Figure 2-14). Lessons from the 1960s systems building and the U.S.'s manufactured housing show that standardized volume-production, which leaves customers little if any choice on design and layouts, is not suitable for the homebuilding industry.

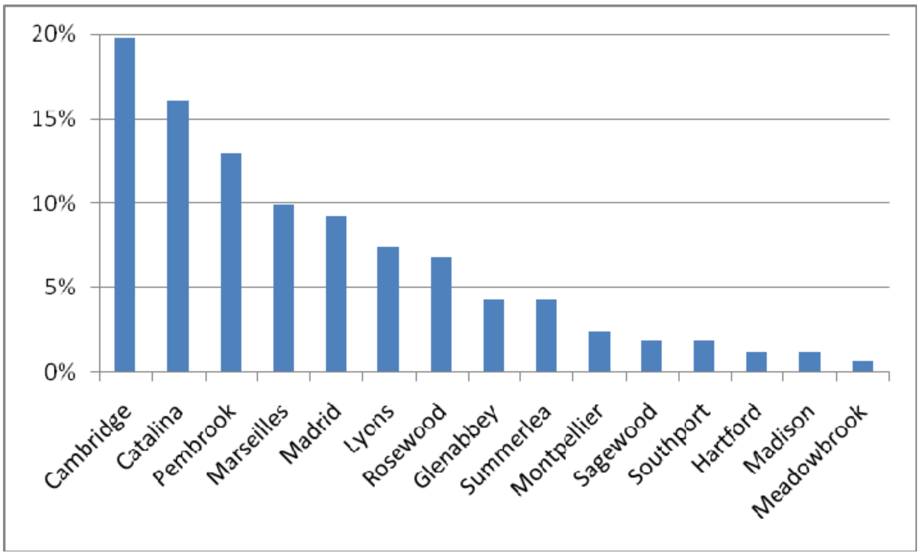


Figure 2-14: Models and Sales (Landmark Homes: Januray 1st – June 30th, 2009)

While there are considerable differences between the homebuilding and vehicle manufacturing industries, it is important to recognize that they also share a high number of similarities. First, they both sell directly to the final customer, rather than intermediate clients. Most purchasers are individuals lacking technical expertise to describe what they want, and make their purchases by choosing from a range of pre-designed options. The overall production volume is high for a production homebuilder. The collaboration company, for instance, builds more than 500 single-family and semidetached homes every year. Although these houses are in different models, they all have a similar structure and are built following the same sequence of operations. Variations in cycle times can be ignored in light of the long queue time. Thus, these 500 and more single-family and semidetached homes can be regarded as a single product family. This production volume matches the most specialized end of automobile production.

Second, production homebuilders and automakers use a similar production strategy. The determining factor in production strategy planning is to balance the trade-off between standardization (to facilitate the economics of repetitive production) and flexibility (to satisfy clients' demands for customization). Using the terminology of Hill (2000), this trade-off can be represented by the location of a "decoupling point," where the customer order enters the production system. The decoupling point separates the part of the supply chain based on planning from the part oriented towards customer order. As shown in Figure 2-15, the different locations of a decoupling point result in a spectrum of production strategies. At one end, automakers employ a "ship to forecast" or "make to forecast" strategy, producing cars and shipping them to dealers according to market forecast. At the other extreme, construction firms using a "design to order" strategy allow customers to express their requirements at the beginning of the information flow and produce the custom-designed product accordingly. Homebuilders, in the middle, use a combination of strategies to meet the different requirements of customers while protecting themselves from fluctuations in demand. The collaboration company, for one, constructs both speculative houses (built according to market forecast before any specific purchaser makes an order – i.e. make to forecast) and pre-sale houses (where work commences only after the customer selects and customizes a house model and places an order – i.e. make to order). In the first 6 months of 2009, 55% of the total sales of the collaboration company were speculative homes.

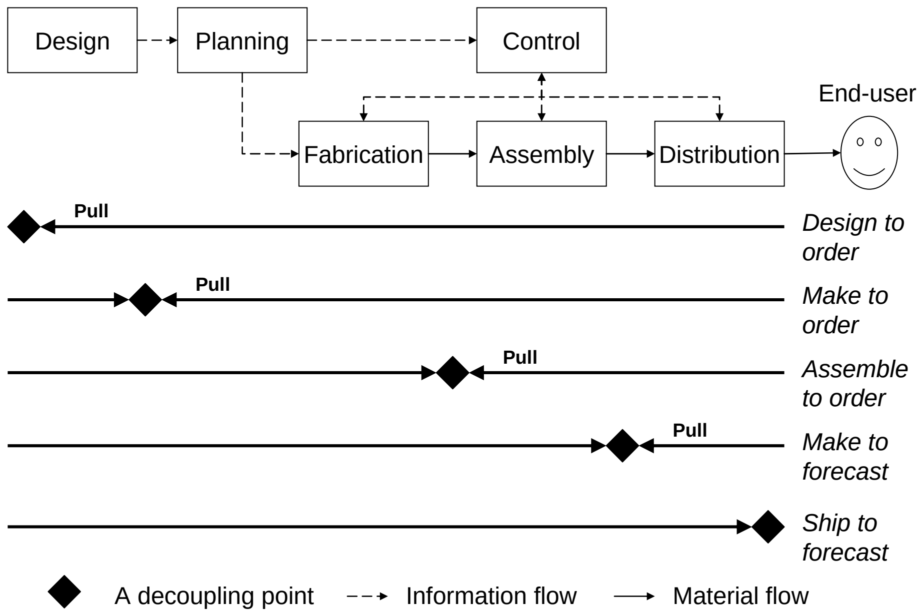


Figure 2-15: Production Strategies and Decoupling Point

Inspired by the similarities existing in the housing and automobile industries, many efforts were performed on industrialization housing, but most of these efforts failed due to the differences rooted in the product and market. The mass production model is simply irrelevant to a homebuilding process that requires a high level of flexibility and customization. The emergence of the lean production model has shed new light in this area. Toyota's objectives of creating continuous flow were to produce small quantities of many models (Ohno 1998). The lean production system uses a multi-skilled workforce at all levels of organization, highly flexible production lines, and a standardized working structure with continuous improvement to avoid the high costs of craft and the rigidness of mass production. The just-in-time pull system ensures that the customer needs is produced at the time the customer needs it.

In the past decade, the promise and benefits of lean production have been recognized by production homebuilders and some productivity improvements through lean implementation have been reported (Zhang et al 2005). However, the reported improvements are quite limited due to the inconsistent application of lean principles and tools. The differences between manufacturing and homebuilding make many believe that lean principles are only applicable to some specific areas. Nevertheless, the lean system must be taken as a whole. Lean principles must be supported by lean tools and be integrated into the entire homebuilding process. The homebuilding industry needs a proven approach that links together people, lean principles and tools to achieve a lean enterprise.

CHAPTER 3 – DEVELOPMENT OF A LEAN HOMEBUILDING MODEL

Homebuilding is widely regarded as the most analogous sector in the construction industry to automobile manufacturing, and this similarity bears great promise in terms of modeling homebuilding after manufacturing in order to improve productivity. However, due to the lack of necessary knowledge and tools, homebuilders still utilize the same techniques used by the other construction sectors to plan and control the homebuilding process. There is a clear need for developing a better production model for the homebuilding industry.

This need was recognized by the management of the collaboration company when it completed Lean 101 training in 2006. Then, the first question was how to develop this model and where to start. At the time, the Hole School of Construction Engineering and Management at the University of Alberta was invited to be involved in the company's lean efforts. Instead of picking and applying one or two lean techniques, researchers from the University of Alberta recommended to start with analyzing the current process and work out an overarching lean transformation plan. Value Stream Management, a tool for process mapping and lean implementation plan development, was identified as the lean technique that was most suitable for this goal.

3.1 VALUE STREAM MANAGEMENT

Value Stream Management (VSM) originated from Toyota Motor Company's Material and Information Flow Mapping and then became the most commonly used tool for lean planning. It is designed to help lean system practitioners plan and link lean initiatives based on systematic data capture and process documentation (Tapping et al. 2002). The core elements of VSM are value stream maps. The current state map describes the existing situation of a company's internal and/or external production process (value stream), and guides the lean team to systematically analyze the process, identifying hidden problems and existing wastes. The future map shows a redesign of the production process that incorporates lean concepts and tools. VSM allows the lean team to look at the production process or system as a whole rather than just optimizing individual tasks. The advantages of VSM were summarized as follows (Rother and Shook 2003):

- It visualizes the actual material and information flow, providing an effective tool for clear and concise communication.
- Mapping and lean measurements expose wastes.
- By integrating lean principles and techniques into the future map, VSM becomes the blueprint of lean transformation. Management review and reporting are incorporated.
- It is a qualitative tool but describes quantitative details of the flow.

In the past decade, VSM has been adopted for use in a wide variety of situations, from manufacturing to heath care to banking. Although the display format and work steps of VSM change depending on the characteristics of the industry and the firm's production technology, skill set and corporate culture, the fundamentals of VSM consists of six steps (Tapping et al. 2002):

1) Choose the Value Stream

A "value stream" is a series of activities required to bring a product or service from its raw state through to the customer. It usually covers the "door-to-door" production flow inside a plant, but is also used to map the product flow passing through multiple production facilities. Since a manufacturing plant usually fabricates multiple products, each by a unique transforming process, the product family with the highest production volume is generally selected as the target on which to focus improvements.

2) Map the Current State

The goal of current state mapping is to create a clear picture of the existing production process and to expose wastes. Therefore, the collection of first-hand, real-time data is critical in this step. Special icons and format of data boxes and arrows are used to describe the material and information flows.

3) Determine Lean Metrics

Once the current production state has been documented, the key performance indicators (KPI), which drive continuous improvement and waste elimination, must then be identified. The most effective way to motivate workers to contribute to a lean initiative is to provide them with a simple way of understanding the results of their efforts. Lean metrics provides specific measures of individual operation as well as a total measure for the entire value stream. The most common KPI in lean metrics for manufacturing companies include inventory turns, defective sigma level, total work-in-progress (WIP), total cycle time or total value-adding time (VAT), total lead-time, up-time, on-time delivery, overall equipment efficiency, and first-time-through capacity.

4) Map the Future State

The future state map is based on the analysis of the current value stream. It represents the ideal state that a company will attempt to realize over a certain period of time. In order to develop this new flow, Rother and Shook (2003) formulated the following guidelines:

- Produce according to the specified takt time;
- Develop a continuous flow whenever possible;
- Use a "supermarket" (kanban) to manage production where a continuous flow is not possible;
- Create a "pull" system; and
- Level the product mix at the pacemaker operation.

5) Develop Kaizen Plans

A kaizen plan is a detailed implementation schedule for the main elements and actions to be accomplished in the lean implementation. It plots out which tasks are to be performed, when these tasks will need to be completed, which tools should be utilized, and who will be responsible to carry them out. Solid planning is essential for a successful lean transformation.

6) Implement Kaizen Plans

Lean transformation cannot succeed without commitment from people at all levels of the company. Kaizen activities have an impact on virtually everyone connected to the target value stream. People are reluctant to change, even change for the better. The key of kaizen plan implementation is communication. Make sure that all stakeholders know what is going on and why. Let the people at frontline take the ownership of those lean initiatives.

3.2 VALUE STREAM SELECTION AND PHASES OF MODEL DEVELOPMENT

Prior to the commencement of value stream mapping, two management decisions need to be made: (1) select a value stream, and (2) decide on the level of mapping. Unlike manufacturing companies, production homebuilders are generally considered to only have one product family. Although houses are different, they are built following similar steps and utilizing the same sub-trade pool. The challenge is that the housing construction process is complex, involving dozens of trade contractors and consisting of hundreds of construction activities. A single map encompassing the entire process would be too large and cumbersome for a VSM team to handle. In fact, a rule of thumb for VSM is that the target value stream should include no more than 12 tasks (or process stations). A feasible solution is to divide the entire production flow into stages, with each stage considered as an independent value stream in a supply chain. Another reason to compartmentalize the construction process is that the process is too long to be synchronized with one takt time. For example, it is obvious that the capacity of excavation trades working at the beginning of the process needs to match the current pace of sales, but for finishing trades at the tail end of the process, it is virtually impossible to synchronize their production pace to the pace of sales that has occurred a few months prior. The analysis of historical data shows that sales fluctuate significantly from month to month. Therefore, the total production duration of the target process should be shorter than one month.

The level of mapping is another important issue to be considered in defining the value stream. In manufacturing, mapping generally begins at the level of the production process in a single plant, with the activity box indicating a continuous product flow. In other words, the tasks in the map are divided at the places where the product flow stops and in-process inventory accumulates. In construction, the houses (products) do not move along a production line but, rather, workers move from one house (product) to another. Thus, the operations of a trade contractor can be regarded as a continuous flow and would be shown with one activity box on the map.

After considering the size requirement of the value stream map, total production duration, and the logical relationship between construction activities, the entire house production process of the collaboration company was divided into five stages, as shown in Table 3-1. The summary data shown in the table were based on the production data collected in early 2007 – approximately 400 houses for each task.

Table 3-1: Construction Stages and Descriptive Statistics (Landmark Homes, 2007)

	Stage 1 Foundation	Stage 2 Lock-up	Stage 3 Rough-in & Drywall	Stage 4 Pre-finals	Stage 5 Finals
Start Task	Stake out	Main floor capping	Plumbing rough-in	Prime vacuum	Tile flooring
End Task	Drill and pour garage & sidewalk piles	Roofing	Drywall taping	Hard floor vacuum	Occupation
Number of Tasks on main stream	9	10	11	13	20
Actual Duration Average (calender day)	73	31	54	42	26
Standard Deviation	35	14	20	14	7
Coefficient of Variation	48%	45%	37%	33%	27%
Scheduled Duration (calendar day)	20	25	22	18	16
Difference (Actual - Schedule)	53	6	32	24	10

In collaboration with management of the company, a four-phase method was adopted to develop the lean production model.

1) Work with representatives from construction management and all major subcontractors to draw a process flowchart of the entire homebuilding process. A VSM session conducted at this level can identify the areas where waste has accumulated and problems with handoffs occur over and over.
2) Five workgroups consisting of construction managers and related subcontractors work on five construction stages to map the current state of each construction stage. Mapping is conducted at construction activity level and data collected in the production tracking system are used to calculate the key attributes of tasks. This type of VSM pinpoints hidden problems and existing waste.
3) A future state map is created by each working group. The major challenge of this phase is how to apply lean principles to the homebuilding process and identify the lean tools and improvement methods. The future state map shows where these tools and methods are to be used.
4) Compile five future state maps into a future process chart, which becomes the overarching goal of company's lean implementation.

3.3 FLOWCHART OF THE CURRENT HOMEBUILDING PROCESS

The collaboration company started the lean production model development project with two 2-day workshops, which gathered all the company's management, construction managers, site managers and representatives from major subtrades. Each workshop targeted half of the homebuilding process. An external lean expert facilitated the workshop, and the author provided technical support, including documenting the discussion results and validating the flowchart with actual operations data.

A process flowchart, instead of Value Stream Map, was selected as the first step in lean production model development due to the following reasons:

- Process flowchart is a common type of chart used widely in engineering and business to document, analyze and manage processes. The chart is self-explanatory – it shows the steps as various boxes and shows their order by connecting those boxes with arrows. No training is needed to understand or develop the flowchart.
- The focus of the flowchart is to document a process flow. It provides a big picture of the process, but does not involve a detailed description of each step. This feature makes it an ideal tool for large group mapping sessions, where actual operations data are not always available.
- As a high-level process map, it facilitates communication between all stakeholders by carrying overall objectives and a focus on the initial areas of improvement.

Figure 3-1 and 3-2 show the process charts that were developed in the VSM workshops of the collaboration company. The focus of the mapping was on labor flow, with each box in the map representing a construction task. The duration of each task and waiting time between the tasks were estimated based on the experience of site managers and related subtrades' representatives. As shown in Table 3-2, the estimate in the flowchart provided a much better description of the actual situation than the standard schedule did. The difference between estimate and actual construction time can be explained by the tendency of people to exclude abnormal situations, which leads to high deviation and longer construction times (see Table 3-1). At the end of each workshop, a team consisting of site managers and representatives of major subtrades was assigned to each construction stage to verify the corresponding section of the flowchart and to further develop the value stream maps and improvement plans for that stage. The author joined the developing efforts of lean teams that targeted Stage 1 and Stage 2, and was responsible for cross-examining the value stream maps developed by all five teams and compiling them into an overall process map.

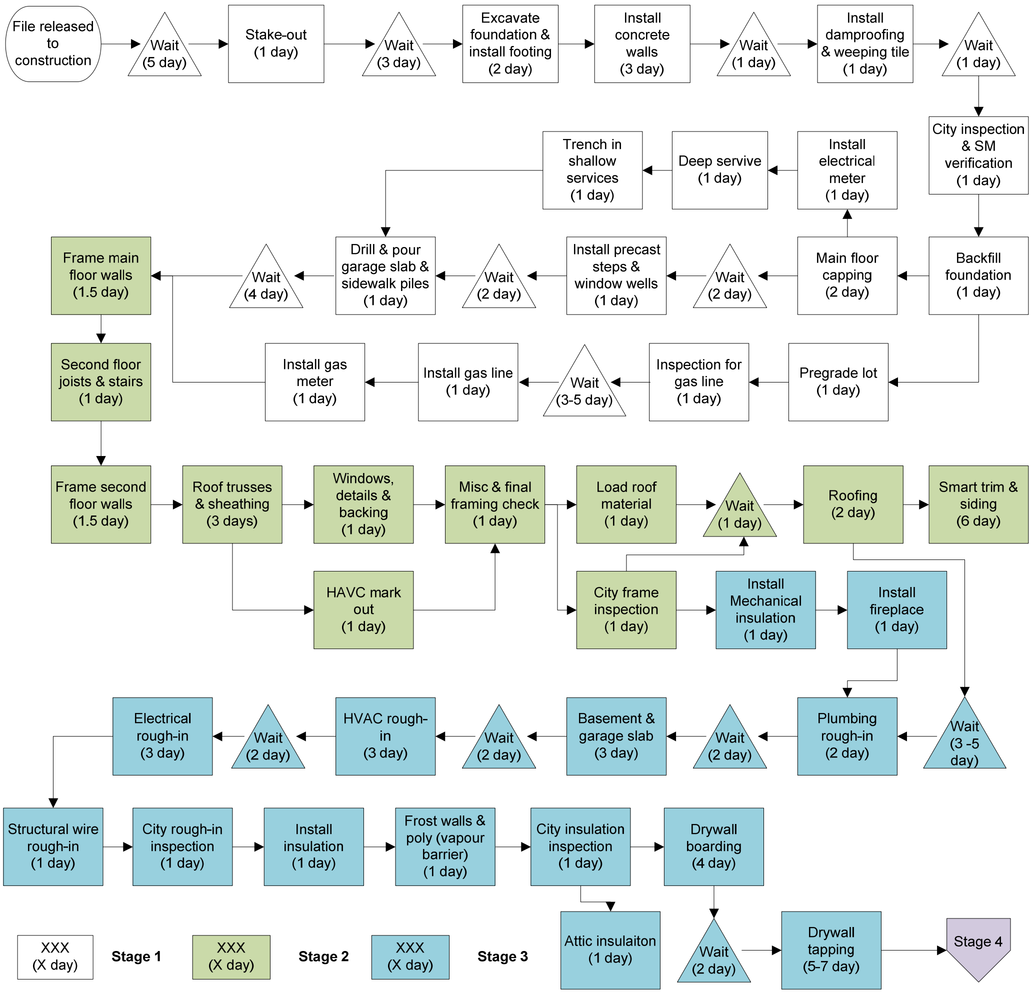


Figure 3-1: Homebuilding Process Flowchart (Stages 1-3, Landmark Homes)

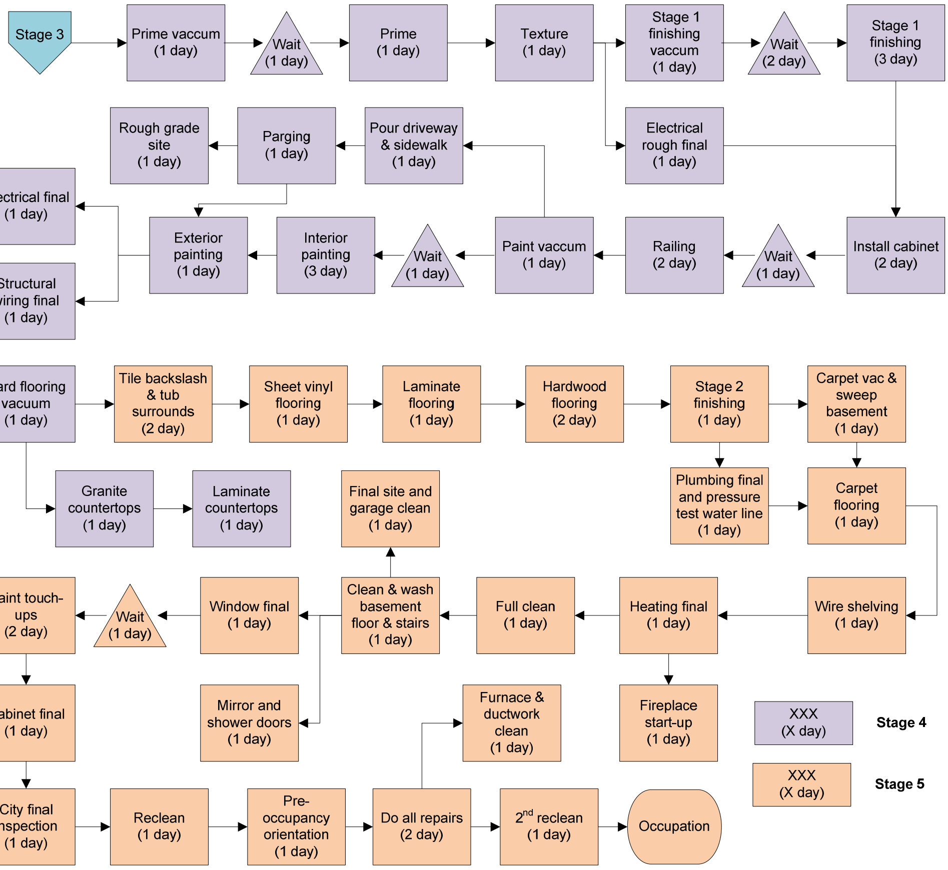


Figure 3-2: Homebuilding Process Flowchart (Stages 4 and 5, Landmark Homes)

Table 3-2: Construction Cycle Time Comparison (Landmark Homes, 2007)

	Stage 1 Foundation	Stage 2 Lock-up	Stage 3 Rough-in & Drywall	Stage 4 Pre-finals	Stage 5 Finals	Total
Estimated Construction Time (working day)	31	18	36	23	23	131
Estimated Construction Time (calendar day)	43	25	50	32	32	182
Actual Construction Time Average (calender day)	75	31	54	42	26	228
Construction Time in Standard Schedule(calendar day)	22	25	22	18	16	103

3.4 DATA COLLECTION AND KEY MEASUREMENTS

As a quantitative tool, VSM uses a list of descriptive statistics to depict the current state of the process and to determine what the future state will be. In VSM exercises, one of the most important steps is to collect detailed, real-time data related to the value stream. A common rule is to bring a stopwatch while walking along the actual pathways of material and information flow, and to rely only on information obtained firsthand. However, most of the construction tasks are lengthy and have high variability in task durations and queuing times. Complexities in the construction process make it virtually impossible for an individual researcher to collect sufficient data merely through site observations. The collaboration company has an intranet-based production tracking system, in which site managers record the booking date, confirmed start date, actual start date, and actual finish date of every task in the construction process (Figure 3-3). Based on the data exported from the tracking system, the author developed a data analysis tool to calculate basic operations measurements. Figure 3-4 shows the system structure of the developed data processing tool. Operational data are extracted from the intranet of the collaboration company through open database connectivity (ODBC) and saved in a raw data table. The analysis module calculates the statistical attributes required by VSM, such as cycle time (CT), lead time (LT), waiting time between tasks (WT) and percent started on schedule (PSS). The system provides the capacity to calculate the descriptive statistics of data in any given time period or geographical area, as shown in Figure 3-5. This system is now used by the management of the collaboration company to monitor the current projects in construction and evaluate the performance of site managers.

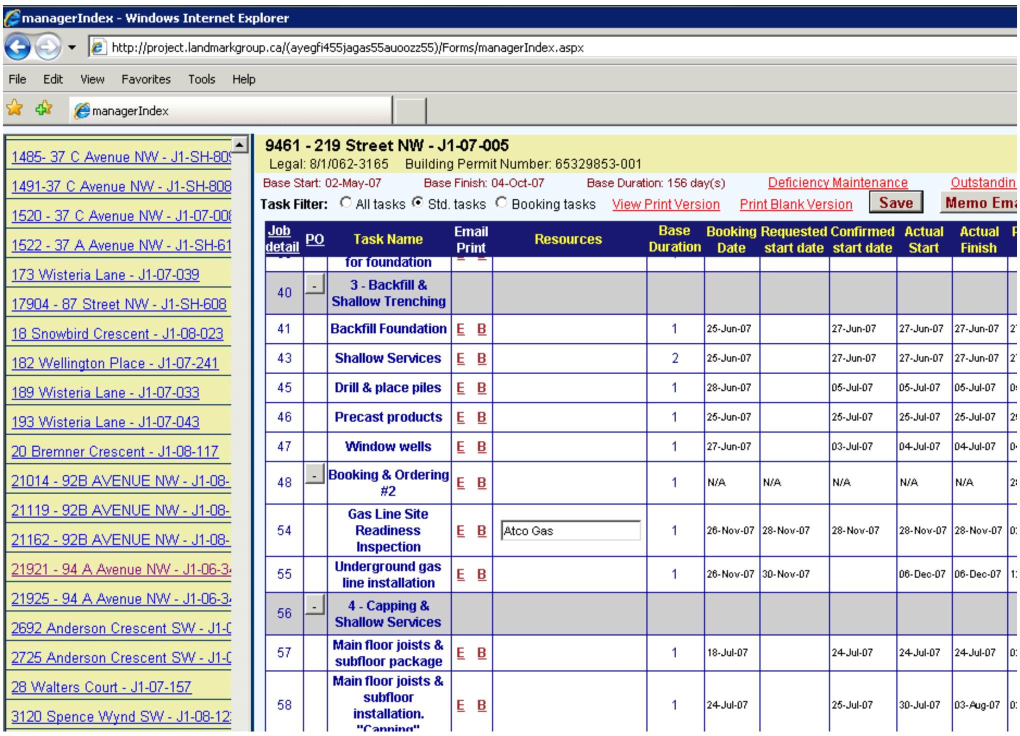


Figure 3-3: Snapshot of LGB's Construction Production Tracking System (Partial)

A major factor impeding the application of VSM to the main construction stream at the operational level is that key concepts/elements used in VSM, such as cycle time, change-over time, up-time and inventory, are defined in the context of manufacturing and seem non-applicable to construction. To apply VSM in construction, the author redefined most of the concepts used in traditional VSM and designed a new measurement PSS, as shown in Table 3-3. After discussion, the management of the company and core lean implementation team selected six key attributes, including cycle time (CT), changeover time (CO), lead time (LT), yield rate (Y), percent schedule started (PPS) and waiting time (WT). Since no historical record is available on changeover time, and yield rate, they were estimated by site managers and related subtrades through group discussion. The other four attributes were calculated by the author using a data analysis system.

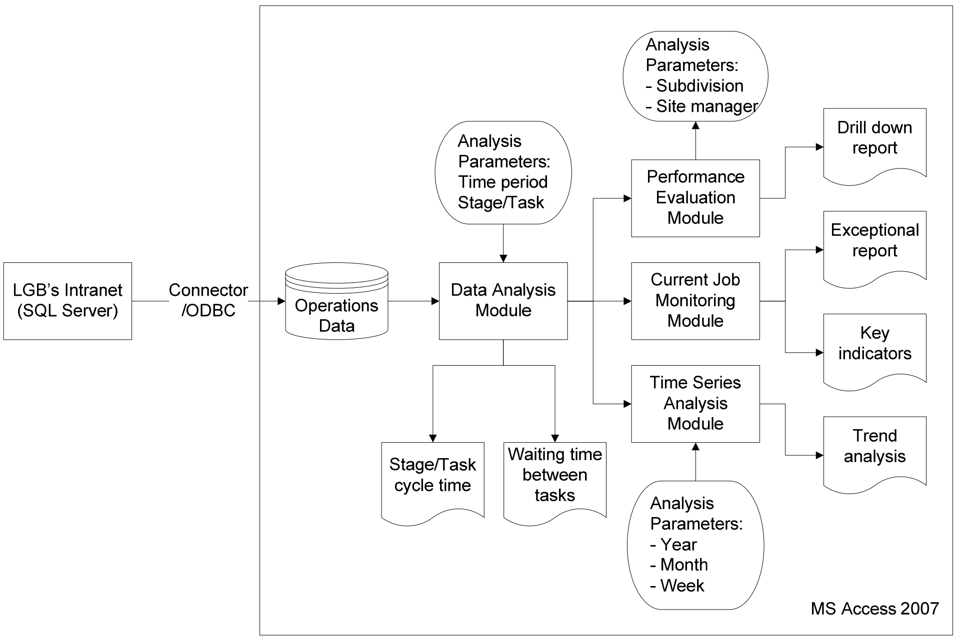


Figure 3-4: Data Analysis System Structure

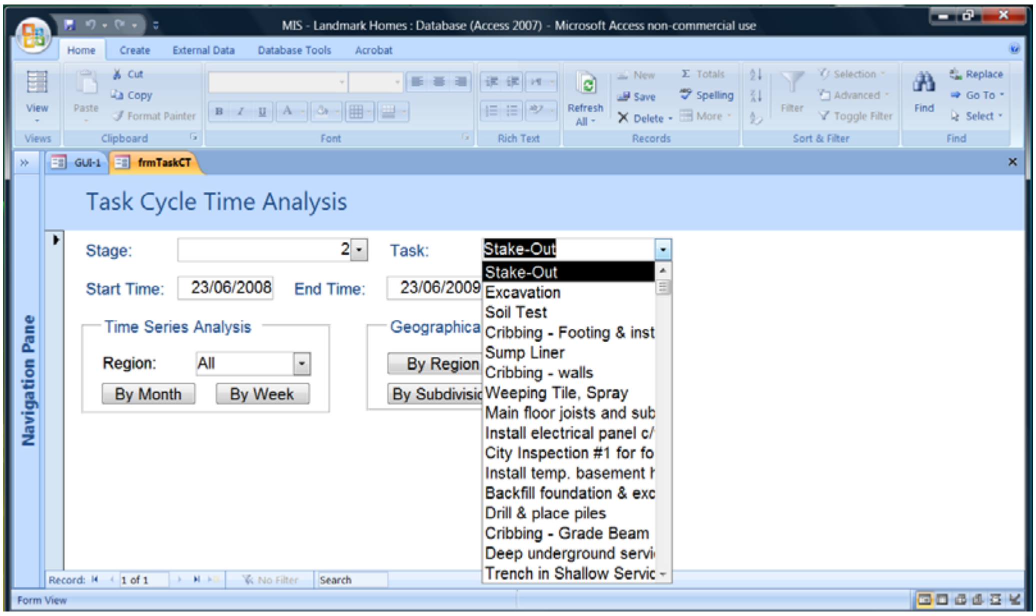


Figure 3-5: User Interface of Task Cycle Time Calculaiton

Table 3-3: VSM Key Elements (Yu et al 2009)

Key Concepts	Definitions	Formula
Cycle Time (CT)	The duration that a sub-trade needs to complete its work package.	CT = Actual finish date - Actual start date
Lead Time (LT)	The time that a sub-trade needs to deploy its crew to a given job.	LT = Confirmed start date - Booking date
Waiting Time (WT)	The time that elapses between one task being completed to the next task being started. In lean system, WT serves as a time buffer to shield downnstream crews from upstream variability.	WT = Actual start date of task i+1 - Actual finish date of task i
Available Production Time (APT)	The number of workdays available for trade contractors doing the construction.	APT = 365 - Weekends - Holidays
Changeover Time	The time that a crew needs to switch from working at one house to another, including demobilization and mobilization.	
Uptime	A measure of the proportion of APT that is actually used on construction, in percentage.	Uptime = (APT - Bad weather days - Changeover time) / APT
Work-in-process (WIP)	Number of uncompleted houses in the value stream, including the houses in construction and those standing idle waiting for sub-trades.	
In-process inventory / Supermarket	The backlog of ready houses that stands idle waiting for the start of a given task. In lean system, it serves as a buffer to protect the continuous workflow of downnstream crews.	Number of houses in inventory (NOI) = WT / Operational takt time
Yield	The percentage of houses that go through an operation correctly, without any rework.	
Takt time	Takt time is the rate at which a homebuilder must build houses to satisfy customer demand.	
Operational takt time	It is the actual takt time used in process leveling. It considers the influences of system problems, such as bad weather, rework, changeover, and so on.	Operational takt time = Takt time / Uptime
Number of crews (NOC)	The number of teams that are working parallelly on the same task.	NOC = CT / Operational takt time
Percent Schedule Started (PSS)	A measure of the proportion of start-date promises made by sub-trades that are delivered on time, in percentage.	PSS = Number of tasks started on schedule / Total number of tasks

3.5 VALUE STREAM MAPPING (CASE A – STAGE 1)

Stage 1 is the most problematic segment. The scheduled duration of Stage 1 is 20 days, but houses actually spend an average of 73 days (365% of the scheduled duration) in this stage. In addition, a large standard deviation (35 days) indicates that the construction process in Stage 1 was not effectively controlled and that a high potential exists to reduce construction time by redesigning the process.

Figure 3-6 is the current state map of Stage 1, which was drawn up in July 2007. The conventional approach of residential construction management is based upon a management model which views the construction process as a series of tasks to be completed in sequence (Bashford et al. 2005), and each house is scheduled and managed individually as a small project using a Gantt chart or Critical Path Method (CPM). The map shows the main flow of Stage 1 where 11 trade crews (represented by activity boxes) are involved. VSM provided an opportunity to view the construction process in a whole new light. Each trade can be seen as a work station and the construction process becomes a production line. Instead of looking at the process as a series of tasks occurring at an individual house, the production system is regarded as houses going through a set of operations performed by trade contractors.

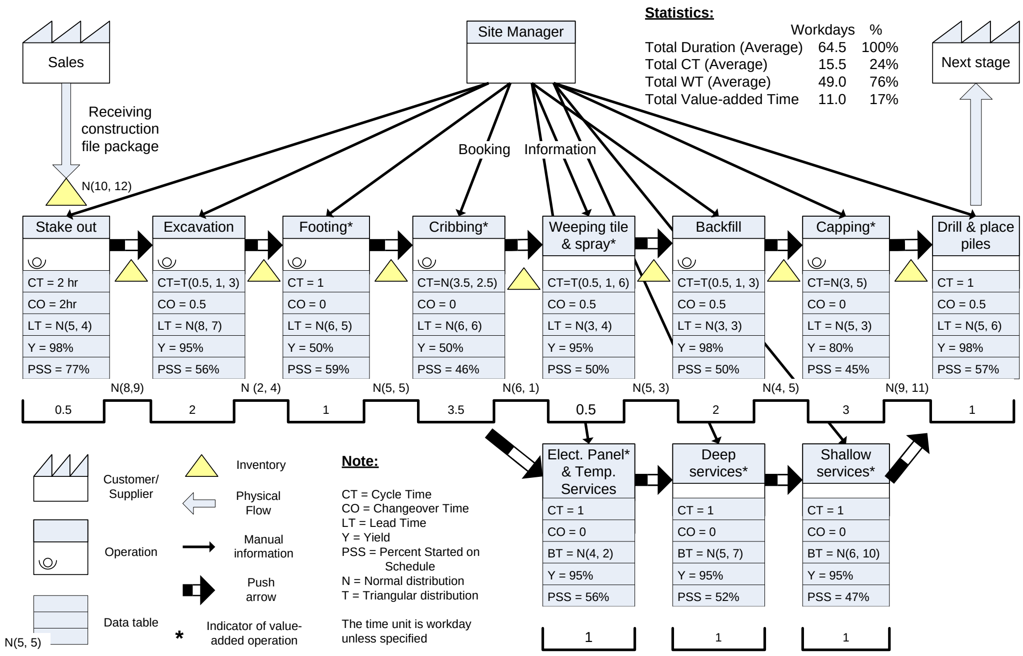


Figure 3-6: Current State Map (Stage 1, Landmark Homes)

Unlike in typical value stream maps used in the manufacturing industry, attributes of each task are not a constant but are expressed in the form of distribution in order to reflect high variability in the construction process. Site managers are the center of production control. Due to the unpredictability of both the market and the construction process, homebuilding is essentially a "make-to-order" business. No overall production schedule exists in the homebuilding company, and construction is triggered when the file of a new house is released by sales. Subsequently, the responsible site manager starts booking material and sub-trades and tries to push the process as quickly as possible. Meanwhile, no look-ahead schedule is available for trade contractors. The booking information is generally issued by site managers via phone or fax on a task-by-task basis.

Upon drawing up the current state map, several wastes can be identified immediately. In this case, the first observation was that waiting times were very lengthy. The total duration of Stage 1 was 64.5 workdays, but waiting time accounted for 49 workdays. This means that houses in construction stood idle about 76% of the time, with no construction activity on site. According to a study done in the U.S., on average, every day a house sits empty costs $291 (Caldeira 1998). One apparent cause of the long waiting time was the high level of variability of the process. The lead times and cycle times of tasks in the map varied greatly. Six of 11 tasks had lead times with a standard deviation in excess of five days, and the cycle times of five tasks must be described using statistical distributions. In current practice, site managers booked the downstream subtrade immediately following confirmation of the start date of the upstream tasks. The intention of this practice was to shorten construction duration by overlapping lead time and task cycle time, but the actual result was that nearly half of the tasks could not begin on the scheduled start date (the average PSS on the current state map is 54%). The temporary nature of the contract relationship between the homebuilder and trade contractors magnified any delay in the schedule through a ripple effect. For example, bad weather (e.g. heavy rain) prevented the excavation from commencing on the confirmed date for a given house. Since the excavation sub-trade had already scheduled other jobs in consecutive days for other homebuilders, the delayed job had to be rescheduled to the end of its working schedule. Moreover, since the downstream task (in this example, pouring of footings) could not begin until the excavation was complete, the site manager had to cancel original bookings and attempted to get new commitments based on the newly scheduled excavation date. However, from the perspective of the footing contractor, a sudden schedule change meant that it must find a new job fitting for that time slot in a very short period of time. Thus, over-booking (i.e. sub-trades accept jobs exceeding their capacity) had become common practice. Consequently, a greater number of tasks failed to begin on the scheduled start date, and lead time became even more unpredictable.

Second, variations in cycle time were relatively high, especially for tasks whose cycle times were described in distributions. Site managers had reported that the major cause of high variation was not workload differences between house models, but the manner in which sub-trades carried out their respective jobs. They had the tendency to deploy their crews continuously on new jobs where a large quantity of work was available, leaving uncompleted, minor details to rework crews. These rework crews followed separate working schedules and usually arrived several days later to finish the job. Quality problems were another cause of a high variation in cycle time. It had not been rare, for example, that the crews who installed the main floor spent one day cleaning the beam pockets and leveling the top of the foundation walls.

Based on the analysis of current practice, the workgroup determined that the lean initiative goal for Stage 1 was increasing productivity by stabilizing the process, reducing lead time, and eliminating defects. Accordingly, the lean metrics shown in Table 3-4 were developed in order to quantify this goal and track progress.

Table 3-4: Lean Metrics (Stage 1)

Metrics	Baseline	Goal*
Variation of production CT (workdays)	Up to 5	1
Total waiting time (workdays)	50	25
Value-added ratio	17%	25%
Average percent started at schedule (PSS)	45% - 77%	90%
Yield	50% - 98%	100%

* Goal was decided after future state mapping.

The focus of future state mapping is to eliminate the root causes of wastes and to link the value stream in a smooth flow. Unlike manufacturing, where the fundamental problem is overproduction caused by "batch and push" (Womack and Jones 1996), the homebuilding industry suffers most from variability. Unpredictability of the process causes all kinds of waste, not just of long lead times and excess inventory.

Uncompleted houses are vulnerable to weather, requiring temporary protection; to pilferage, requiring security and extra materials; and to vandalism, causing rework. Variability also results in fluctuation of the production flow. This means that homebuilders need to sustain a large workforce pool and cannot provide stable work flows to trade contractors. In order to reduce the variability of the process, the following four measures were taken in the future state mapping (Figure 3-7): establishing a production flow and synchronizing it to takt time; leveling production at pacemaker task; restructuring work; and improving operation reliability with work standardization and total quality management.

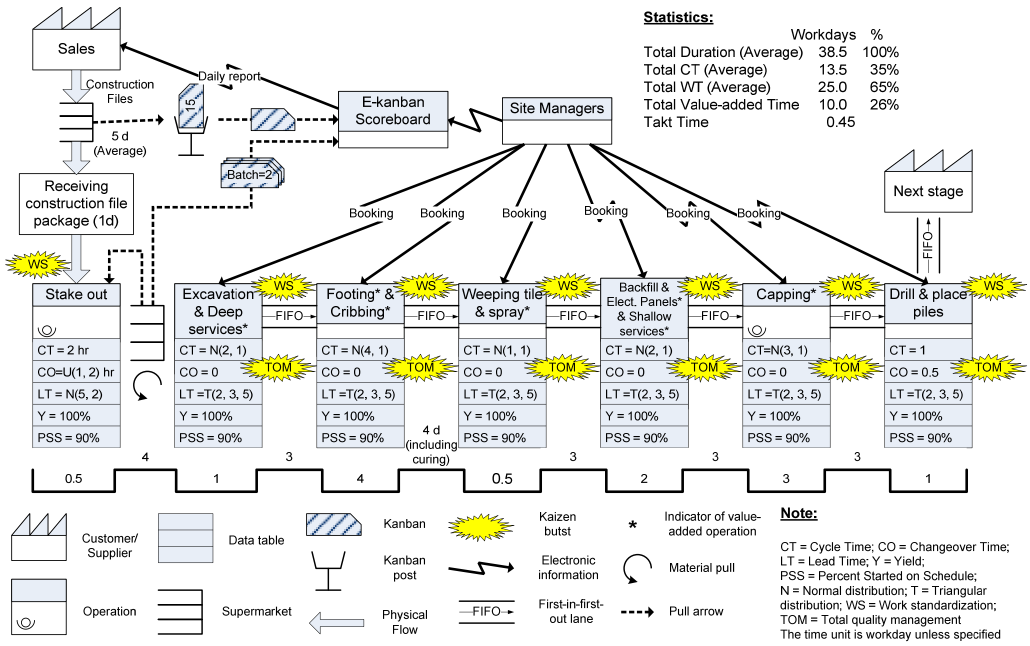


Figure 3-7: Future State Map (Stage 1, Landmark Homes)

FIFO-Lane-Based Flow and Its Synchronization

In manufacturing, continuous flow forms the centerpiece of the lean production system and is regarded as the most effective way of production. Nevertheless, the production system built on continuous flow can only be used for a reliable process. As the system is fully synchronized, any small delay or breakdown in one operation will result in halting the entire system. Housing construction is a site-based production (as opposed to factory-based manufacturing). Weather and site conditions have a significant impact on the execution of construction activities, so variation in task duration is unavoidable. In addition, the housing construction process is a long process involving more than 60 work "packages" (tasks). Connecting all the tasks into a continuous flow would make the system very fragile. Finally, construction work is performed by various trade contractors who have individual interests and are almost exclusively concerned with the efficient execution of their individual tasks (Bashford 2004). Therefore, keeping an excess capacity buffer to overcome minor flow fluctuation is not practical for homebuilders.

Another important lean tool, supermarket-based pull flow, is also non-applicable in house construction. A pull-flow system is controlled by the pacemaker task, where customer orders enter the production system. In manufacturing, the pacemaker is typically the most downstream task in the value stream, and the production pace of all upstream tasks is "pulled" by the pacemaker. In house construction, the pacemaker acts at the beginning of the process. In order to develop a stable flow from the pacemaker task to the downstream end of the value stream, a FIFO (first in, first out) -lane-based flow system is proposed based on the theory of last planner described by Ballard (2000).

With the help of statistical analysis, the construction manager of the company can predict with great certainty the total number of houses that will enter the production system in the course of a given month, but it is virtually impossible for site managers to know with any certainty what the state of a given house will be more than a week into the future; there are simply too many variables that can affect the readiness of a particular job. The fundamental idea of the proposed system is to stabilize and reduce lead time by guaranteeing trade contractors' working load. In practice, this is realized using agreed capacity, a commitment between a homebuilder and its trade partner on the number of jobs (kanban slots) that a sub-trade will perform each week. For example, a homebuilder might predict that about 40 houses would enter the production system next month, and it might have two trade partners working for a given task. Next, a trade booking agreement is signed between the company and each trade partner. Assuming that one trade contractor has agreed to provide six kanban slots weekly, and the other four, a typical booking scenario would be the one shown in Figure 3-8. Site managers release specific job information following the completion of the preceding task and load a kanban slot. The capacity agreement in fact forms a

FIFO lane, and the jobs released are the inventory on the lane. This way, the FIFO lane links two separate tasks into a stable flow. In the future state map, the cycle time (CT) and changeover time (CO) of each task remain the same as those in the current state map, and the waiting time (WT) reflects the length of the FIFO lane.

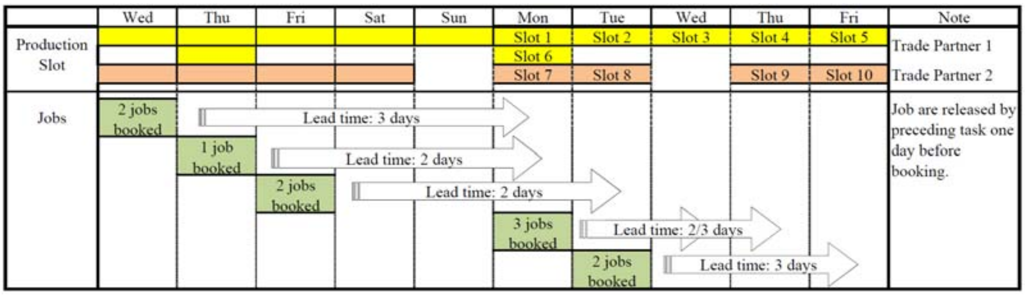


Figure 3-8: A Typical Scenario of Lean Booking

The number of kanban slots is decided by takt time, which is a function of customer demand. In the cooperating company, it usually takes 30 to 45 days from the customer signing the purchase agreement to the release of the file package to construction, so the average volume of sales in the past two months is used to determine the takt time of the system. In the first two months of 2007, the sales volumes of the company, including pre-sales and spec houses, were 47 and 42 respectively. Since 22 workdays are available in March, the takt time is 0.49 workdays. In practice, the downtime was estimated as 5%, and the agreed capacity of each task was designated as 10. By reserving the same number of kanban slots for each of the tasks in the value stream, the production paces of working stations are synchronized.

The FIFO-lane-based approach is different from other scheduling techniques for repetitive construction activities, such as LOB (Line-of-Balance), due to its ability to deal with the dynamic work flow — i.e., new houses can enter into the production system continuously — and high variation in productivity. In this system, consecutive tasks are de-coupled by the FIFO lane so that each task only deals with variations caused by the preceding task, which can be accommodated by adding a time buffer (WT) between tasks. For instance, the task called "Excavation and deep service" has a one-day standard deviation in cycle time and a possible two-day delay in booking time; thus, a three-day waiting time for the next task can effectively control the flow fluctuations caused by variations in the present task. In addition, the system is very flexible. Either party can change the agreed capacity from time to time, provided that advanced notice is given (in practice, the agreed upon notice time for capacity change is two weeks).

Production Leveling

In the conventional production management approach, the volume of jobs performed typically occurs unevenly over time. Figure 3-9(a) shows the monthly volume of files released to construction in 2006, and Figure 3-9(b) shows a typical record of the number of released files over a one-month period. The causes of this large fluctuation were unpredictability of sales and a pushed production management. Flow fluctuation causes several problems for a synchronized production system:

- There is no sense of takt time, and it is difficult to decide the capacity requirement.
- When peaks and valleys frequently appear, filling the agreed kanban slots consistently becomes a heavy burden.
- An erratic flow makes the production difficult to monitor – "Is the situation normal or not?"

In order to avoid these problems, the production control must lower the peaks and raise the valleys in the workload as much as possible so that the flow surface is smooth. This practice is referred to as production leveling or "even production flow."

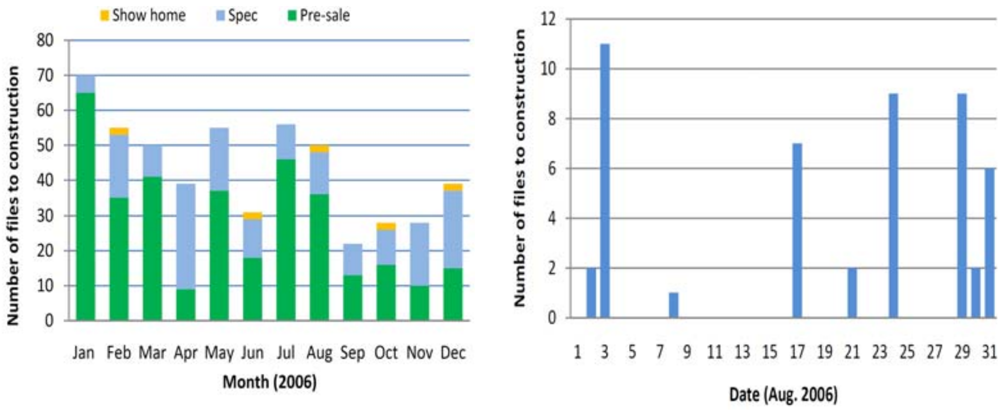


Figure 3-9: Typical Record of Files Released to Construction (Landmark Homes)

Bashford et al. (2003) has described two common even production flow strategies (activity-based and start-based) and discussed their implications for the housing industry using simulation. In this research, these two strategies were combined and implemented in an innovative way. On the one hand, tasks connected by the FIFO-based lanes form an activity-based even flow system. Unlike fixed schedules, where a long duration for each task must be chosen to ensure that the duration will not be exceeded, a booking system based on the agreed capacity had the capability to accommodate minor variation so that time buffers between construction tasks were significantly reduced. On the other hand, a supermarket-based pull system was established between the pacemaker task (excavation) and sales as a decoupling buffer (Ballard et al. 2003). The sales department typically releases the files of pre-sale houses to the first supermarket, while the downstream task withdraws the files. Once the number of files in the supermarket reaches the upper limit, sales must stop releasing; when the number reaches the lower limit, sales releases the files of show homes and spec houses in small and consistent quantities until the files of pre-sale houses are available. The upper and lower limits are decided based on the historical analysis of sales variability. In this research, they were set to 15 and five homes (7.5 and 2.5 workdays inventory) respectively.

Work Restructuring

It is apparent that waiting time can be effectively abated by reducing the number of handovers. In an extreme case, if the entire value stream could be completed by a single crew, the house would pass directly from one task to the next in a continuous flow, without any waiting time in between. The factor that prevents the same crew working continuously in a house throughout the value stream is that different tasks require different skills and equipment. Although multi-skilling and the use of cross-functional teams were shown to be effective in reducing variability, and thus improving flow (Ballard 2001), the reality is that the vast majority of trade contractors are specialized in one type of job.

A feasible solution is to examine adjacent tasks and consider the possibility of integrating them into one work package to be performed by a single working team. The footing and cribbing tasks, for instance, require a similar skill set (framing and concrete pouring) and can easily be completed by one crew. Historically, these two tasks have been performed separately, because it is more productive to pour footings in batches (where multiple footings are poured within a subdivision at one time), and wall forms are always moved around with the cribbing crew. On the future state map, these two tasks are combined into one work package with an expected cycle time of four workdays. Compared to a savings of three workdays of waiting time, the possible cost increase due to the small amount of concrete pouring and under-utilization of wall forms is minor. The same strategy was also used for electrical panel installation and shallow services which were both electrical jobs. In fact, this work package was further integrated with backfill tasks to be contracted to a cross-functional team. The electrical, cable and telephone (shallow service) lines are approximately three feet below finished grade. By installing them at the same time as backfill, the trenching operation is eliminated, and the quality of backfill is ensured. A similar consideration led to the integration of task excavation and deep services (water and sanitary) which are situated at approximately nine feet underground.

Process Improvement Measures

The production process on the future state map exhibits significant overall improvements. Total construction duration of the value stream decreases from 65.5 workdays to 38.5 workdays, amounting to a reduction of 27 workdays or over five weeks. The percentage of waiting time drops from 76% to 65%, and the value-added ratio increases from 17% to 26%. However, achieving the material flow envisioned in the future state map requires the amount of inventory on FIFO lanes to be stabilized ideally around six houses (i.e. three workdays lead time) and never less than four, so as to ensure that sub-trades receive notice at least two workdays ahead. Based on the statistical analysis, PSS needs to be improved from the current 45%-77% range to a upward amount of 90%, with standard deviation of cycle time for each task reduced to one workday. Therefore, the probability that the cycle times of any two homes in a series of six are longer than the average cycle time by more than one workday is below 10%. Although the actual probability of a shortage of jobs in the FIFO lane to fill the kanban slots might be much lower due to the possible completion of previous delayed jobs, focused attention on improving the reliability of the operation of sub-trades will be required. In practice, the following kaizen foci were proposed by the core lean team:

- Work standardization – The work scope and quality standards of each task are clarified in written documents and distributed to related sub-trades. The goal is "100% ready handover."
- Total quality management – Trade contractors are required to control quality at the source, completing all repair work before workers leave the site, while site

managers are required to check quality as the construction is in progress. The goal is "100% first-time-through."

- Long-term partnership with trade contractors – Lean implementation involves significant behavioural changes in all parties linked to the system. It will take time to build up trust between parties, train workers, and change the mindset of personnel.

These items are marked on the future state map using a kaizen lightening burst icon. An advantage of VSM is that the process improvement efforts become subordinate to the value stream design, as opposed to stand-alone improvement activities, so that the lean team can focus on the improvements that have real impact on overall process performance.

Information flow is another important issue in VSM. Without a fundamental change in information management, it would be very difficult to operate a lean value stream. Unlike a manufacturing production line, construction crews move from one house to another that may be located miles away. Visual control cannot be applied in housing construction the same way that it is in manufacturing. Using the concept of the heijunka box, the author proposed an internet-based "e-kanban" system, with a column of kanban slots for each workday and a row of kanban slots for each trade contractor. Site managers place a kanban with the link of job information (detailed address and technical drawings) into a desired kanban slot when a job is ready. The corresponding trade contractor then withdraws this kanban via the internet and allocates a crew to the job. If a slot is not loaded two days prior to its start date, or if a kanban is not withdrawn until the start date, the construction manager will be aware of a production problem.

3.6 VALUE STREAM MAPPING (CASE B – STAGE 2)

Compared to Stage 1, Stage 2 is much simpler. Eleven tasks in the flowchart involve only five trade contractors and thus can be grouped into four work packages: framing, roofing, trim work and siding. However, the collaboration company had almost lost control of Stage 2 when the company began the VSM in 2007. Since 2002, Alberta had experienced robust economic growth driven by high energy prices and resource development. Rapid increase in population and people's income boosted the demand on housing. In late 2006 and early 2007, the Alberta housing market reached its peak. New housing starts in Edmonton metropolitan area hit a historical high of 14,970 units in 2006 and 14,888 units in 2007, almost twice the number in 2001 (City of Edmonton 2008). This volume severely strained the capacity of trade contractors and the supply of the construction labor force. Bashford et al. (2005) studied the relationship between production system loading and project cycle time in residential construction. In reality, the situation was much worse than that predicted using the mathematical model. Part of the reason is that the housing production system is not an isolated system. The high-paying jobs in the oil sands industry attracted workers moving from residential construction to industrial construction projects. Figure 3-10 shows the current state map that was drawn in August 2007 using the data of 292 single-family houses that were constructed by the collaboration company in the first 7 months of 2007. The duration of Stage 2 (50 workdays) had doubled that of 2005 and 2006 (31 calendar days as shown in Table 3-1).

An obvious reason for the prolonged stage duration was the long waiting time between tasks, which accounted for 50% of the total duration (25 workdays). The discussion at the VSM session of the Stage 2 workgroup had the same conclusion as that of the Stage 1 workgroup: the root cause of long waiting time was the high variability of the construction process. Site managers further pointed out that although the average lead time was one week, the variation of lead time was high and only less than half the jobs had started according to the confirmed schedule date. The actual start time of a task of a given job was virtually unpredictable. In order to ensure the site was ready when the next crew came to the job, site managers had to book the next trade after a task had started. For long duration tasks, such as framing and siding, since the variation of cycle time was several days, the working request of the next task was generally issued in the last two or three days before completion. The statistics obtained from data analysis affirmed the site managers' comments: the average waiting time after roofing was the same with the standard lead time of trim work and siding, and the average waiting time after framing was three days longer than the standard lead time of roofing.

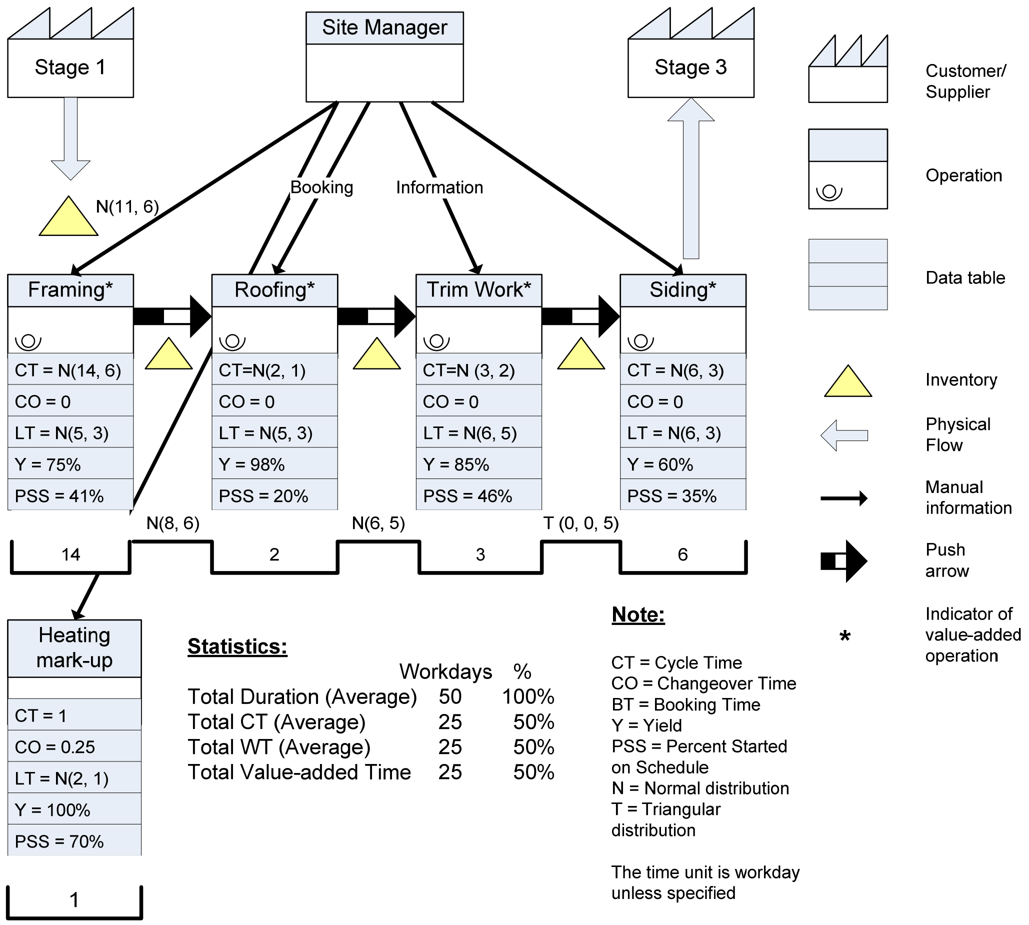


Figure 3-10: Current State Map (Stage 2, Landmark Homes)

Waste also existed in the task's cycle time. The average cycle time of framing was 14 workdays, but the estimated duration of framing was nine workdays (see Figure 3-1). In order to maximize their interests and reduce the risk of being idle, subcontractors always intend to receive bookings at or even more than their capacity. In a booming market, they often started a new job before the job that they had been doing was completed. Working two or more jobs simultaneously causes long cycle time and high variation. Therefore, the actual value-added-ratio of the process was much lower than 50%, the number shown in the map.

Quality was also a big issue here, especially for framing and siding. The 75% yield rate of framing did not mean that only 25% of jobs had defects. In fact, every job had defects, and the 75% yield rate meant that on average, 25% of items in framing checks failed. The standard framing checklist of the collaboration company has 237 items

(Figure 3-11). A 25% fail rate meant that on average 59 errors were found on every framing job. Low quality led to significant waste in the process. In general, site managers had to do framing check two or three times for every job, and framing crews had to go back to the job and spend another one or two days to repair the errors found in the framing check.

Landmark Homes (Edmonton)

Framing Checklist					
CAPPING					
Job Address				**Site Manager:**	
Job Number:				**Framing Contractor:**	
Date Inspected:				**Date Re-Inspected:**	
Area of Home		**Framers Check**	**Site Manager**	**Description**	
Basement					
Teleposts correct type in proper locations, centered on beam & plumb. No more than 3" of thread showing.No less than 1".					
Beams are level & straight.					
Beam pockets are filled with solid blocking					
Solid point load blocking through joist space to beam and foundation wall. (Under doors and large windows)					
Headers above basement windows (required for windows over 4 feet)as per joist layout					
Main Floor Joist System					
Beams are sized as per plan.					
Engineered joist & beam package installed as per manufacturers layout. Check for plumbing hits.					
Joist hangars installed as per manufacturers detail, joists glued in seat and screwed. Excess glue cleaned off.					
Backer blocking installed at all joist hanger locations as per manufacturers detail.					
Squash blocks installed, one on each side of EVERY joist where it bears on a beam or at point load.					
Floor sheathing glued and screwed					
Lateral bracing installed as per manufacturers specifications shown on blueprint and/or layout					
2x6 cantilever blocking installed on flat for insulation					
Sand/concrete access location & size as per blueprint (if applicable)					
Stairwell correct size & location.					
If walk-out, ensure correct window RO's and in correct location, all sheathing nailed, walls level, plumb and square.					
Install cantilever insulated pan.					
Basement stairs installed securely and properly with poly between stair and frost wall.					
2"x8" Handrail backing installed at 28" o/c from nosing.					
Bearring walls triple plated wraped in poly on footing.					
Proper backing for drywall in stairwell					
Headroom 6'-8" when possible otherwise minimum 6'-5".					
Backing for baseboard in between all studs.					

Signed:_______________________ (Site Manager)   Signed: __________________________ (Framing Contractor)   Date: ____________

Figure 3-11: Landmark Homes' Framing Checklist (Page 1)

In the VSM session, new ideas like in-process quality control, "100% ready 100% of the time" and continuous workflow to dedicated crews were proposed to reduce stage cycle time and improve product quality. The basic idea of preventive quality control is that site managers check quality when crews are still working at the site. For instance, site managers check the main floor walls and second floor system when the crew is framing the 2nd floor walls, check the 2nd floor walls when the crew is constructing the roof, and check the roof when the crew is installing backings. Preventive quality control increases the number of quality checks and thus the workload of site managers, but the quality problems are identified and corrected when crews are still working on site, so it may save the crews' time on rework. The "100% ready 100% of the time" rule use the same strategy of the Last Planner System, i.e. site managers only book the jobs that will be 100% ready (site, materials, etc.) for sub-trades by the scheduled start dates, and thus the downstream task is shielded from the variability in the upstream process. When trust has been established between trade contractors and a homebuilder, the trade contractors will pre-schedule their crew for the job and stop overbooking.

The goal of providing continuous work flow is to establish a long-term partnership with subcontractors. The collaboration company commits to provide continuous work flow to selected trade crews, and those crews will work exclusively for the collaboration company. Dedicated crews will ensure the availability of a workforce and improve product quality and process reliability.

While these ideas are promising, the workgroup and the management of the company realized that for long-term improvement, radical changes in construction technology and work structure were necessary. Two such initiatives were prefabrication and job integration. As a production homebuilder that provides a broad spectrum of housing products, including multiple-family row houses, start housing, mainstream single-family houses, and high-end customized mansions, the management of collaboration company believed that a panelized building system was the only way to meet such diverse needs in the market. Although the practices of industrialized housing in Japan and Western Europe provide useful lessons and prove the effectiveness of the technology, all those successes were achieved in different market situations and with different products. How to integrate panelized construction into the building process was challenging. No success story in North America had been reported in this area. A few large production homebuilders in the U.S. adopted similar approaches (Sawyer 2006), but no operation details were available.

Following the lean principle that any new technology must be thoroughly evaluated and proven through direct experimentation in a pilot area before it is used in the present process (Liker 2004), the collaboration company developed a three-phase plan as a guideline for implementing the technology:

- Phase I: A pilot plant will be established to produce wood-frame open wall panels, floor panels and roof segments. All houses built by Landmark Homes (Edmonton), a member of the collaboration company that specializes in mainstream single-family houses, will use the panelized system. The impact of the new technology to the existing process will be analyzed, and the improved process will be standardized.
- Phase II: A production division will be established based on the pilot plant. The division will produce insulated open panels and perform all major construction tasks in Stage 2, including framing, roofing and siding. The idea of job integration came from the concept of sequential procedure (Gibert 1991), which regards the construction process as a successive realization of an autonomous sequence. Each sequence is a large work package containing tasks grouped by functions of the building. A few super-subcontractors performing large packages of continuous work without interference will improve the reliability of the process and reduce the management overhead.
- Phase III: The production division will produce a closed wall panel system, and thus electrical rough-in, smart wiring, and drywall will be integrated into its work scope. All members of the collaboration company will use the panelized system and standard process for building envelope construction.

Considering that the time frame to implement future state map was 18 months, the Stage 2 future map was developed based on Phase II, as shown in Figure 3-12.

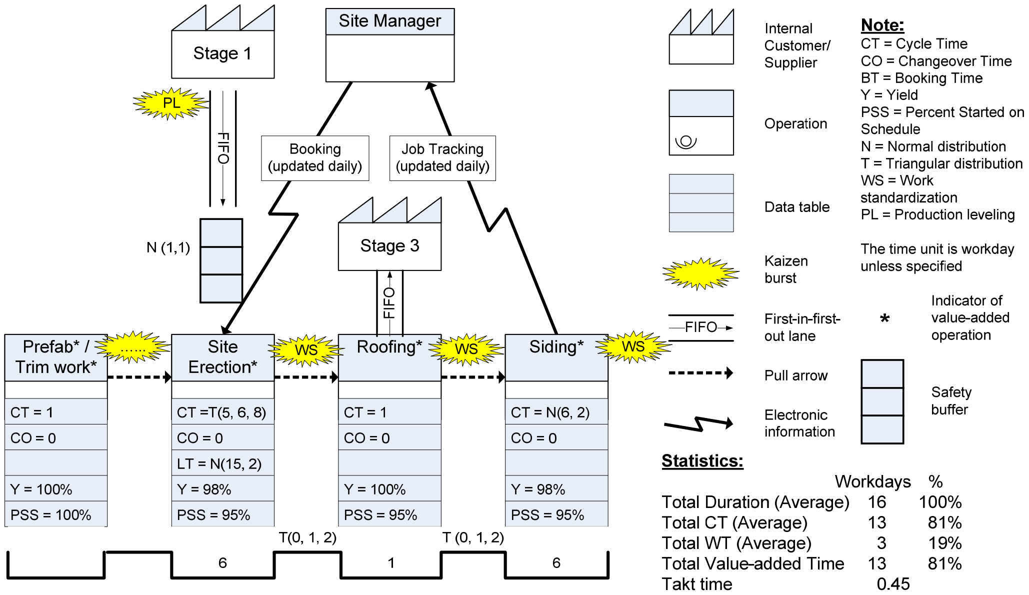


Figure 3-12: Future State Map (Stage 2, Landmark Homes)

In the new process, Stage 2 is one work package. Site managers inform the production division the date that a job can be ready for framing start. After receiving the framing request, the scheduler checks the production schedules and puts the job into the closest available time slot. Then he or she sends the confirmed schedule date to the site manager and books all required materials and equipments. Once the erection date has been set up, the production schedule of the job is fixed. The wall and floor panels and roof segments is prefabricated in the shop one day before erection, and the house is erected on the framing start day. All windows, doors and trim work are installed in the factory. The HVAC openings are also cut in the plant according to drawings, and thus heating mark-out (a non-value-added activity) is eliminated. It is estimated that a three-man crew can complete the framing of a 2,000 sq.ft. single-family house in six workdays, including one day of erection. Roof shingles are loaded onto the roof on the framing check day, and roofers show up on the eighth workday and siding starts on the tenth workday. The total duration of Stage 2 is three weeks. The process is triggered by the framing start date, but pulled by the completion date of siding. A one-day buffer is scheduled between the on-site tasks to accommodate possible delays caused by weather, equipment breakdown, rework, etc. Theoretical analysis showed that prefabrication could effectively mitigate construction peculiarities and thus bring the construction process to the same starting point as manufacturing. A stable and reliable process allows the direct application of lean principles and tools, which will significantly reduce wastes and improve productivity. Table 3-5 summarizes the current situation and goals of lean initiatives.

Table 3-5: Lean Metrics (Stage 2)

Metrics	Baseline	Goal*
Variation of production CT (workdays)	Up to 6	< 2
Total stage duration (workdays)	50	16
Total waiting time (workdays)	25	3
Average percent started at schedule (PSS)	20% - 46%	> 95%
Yield	60% - 98%	> 98%

Some lean principles and tools used in Stage 2 have already been discussed in the previous section, and more details will be introduced in the next chapter. A factory-based sub-process (Stage 2) completely changes the rules of construction management and asks for a higher level of process control. For instance, all construction activities in Stage 2 are triggered by one event, the framing request, but the lead time of the framing start is three weeks. A longer lead time is necessary for prefabrication, because the lead times for materials like windows, doors and trusses are 10-12 workdays, and the plant needs time to adjust its capacity based on demand fluctuation. However, a long lead time means a high level of process control. Site managers need to know the exact date when the site can be ready for framing at excavation day. Once the framing start date is confirmed and a job is located in the production schedule, that date cannot be changed. Since all the schedules, including schedules of wall production, floor production, roof production, crane, truck and trailers, field framing crew, roofing crew and siding crew, are balanced and synchronized, change in one job will disturb the entire system and result in a non-continuous work flow. For that reason, the prefabrication plant has a two-week frozen production window. If the framing start date of one job is delayed for whatever reason, the wall and floor panels and roof segments will be produced according to the schedule and stored in the yard, and the site work will be taken out from the crane, transportation, and field crews' work schedules. Remarkable wastes are caused by double handling finished products and the idle time of equipment and field crews.

3.7 FUTURE STATE FLOW CHART AND KAIZEN PLAN

VSM is a powerful tool for lean planning and communication for management, but it is too complex for workers and most small trade contractors. In order to make sure that everyone involved in the process knows what is happening and why, the collaboration company created a future state flowchart to visually show the goal of lean transformation and developed an 18-month kaizen plan to guide and coordinate efforts of process improvement.

3.7.1 Future State Flowchart

The future state flowchart is a simplified summary of the future value stream maps of five stages. It shows the time standard for every major construction activity and the relationship between and work sequence of those activities. Thus, site managers and trade contractors can have a big picture of the entire process and know what the ideal or normal situation should be.

The future state flowchart, as shown in Figures 3-13 and 3-14, targeted to reduce the overall duration of the construction process to 149 calendar days (106.5 workdays or 5 months). Compared to the current process flowchart, the construction duration was reduced by 19% (25 workdays), mostly by eliminating waiting time. The target seemed quite conservative, but considering the real situation of early 2007, the improvement was actually substantial. Due to the soaring housing market and lack of skilled trades, the average duration of 213 single-family homes completed by the collaboration company in the first six months of 2007 was 294 days. Thus, the collaboration company was in fact targeting to cut the overall construction duration by half.

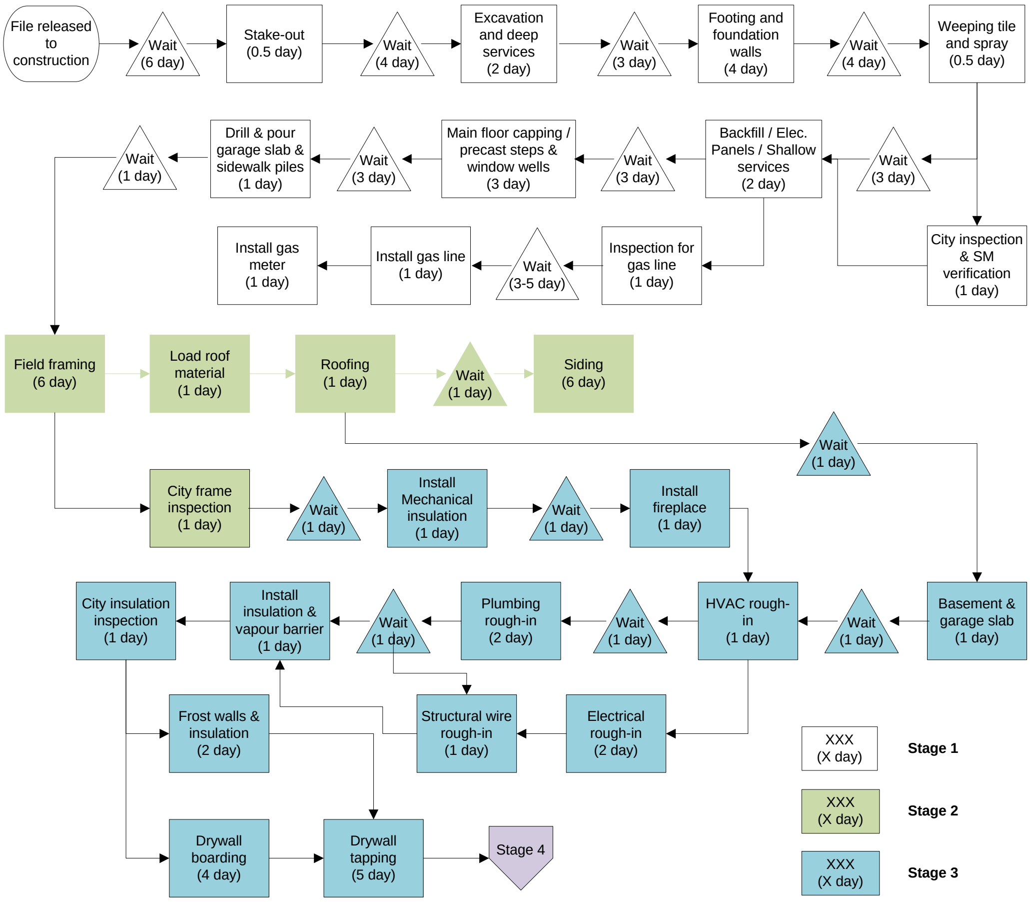


Figure 3-13: Future State Flowchart (Stages 1 to 3)

The focus of Stages 3 to 5 was increasing process reliability through production control. After roofing and siding (Stage 2) are completed, the house basically becomes a controlled environment; the biggest unpredictable and uncontrollable factor in on-site construction – weather – is not an issue any more. In addition, most tasks in Stages 3 to 5 take less than one day to finish and the size of the house does not have a big impact on the cycle time. Now the key to eliminating waiting time is to ensure that trades show up on the job at the scheduled day. The following three factors are critical to achieve this goal:

- Make sure that the site is 100% ready 100% of the time. After confidence has been built, trades will not overbook jobs to avoid idle time caused by sudden schedule changes.

- Standardize the construction process to increase predictability, so site managers can book trades two to three weeks ahead to ensure the availability of a workforce.
- Even production flow to create continuous workflow for regular trade-contractors who have long-term partnerships with the company.

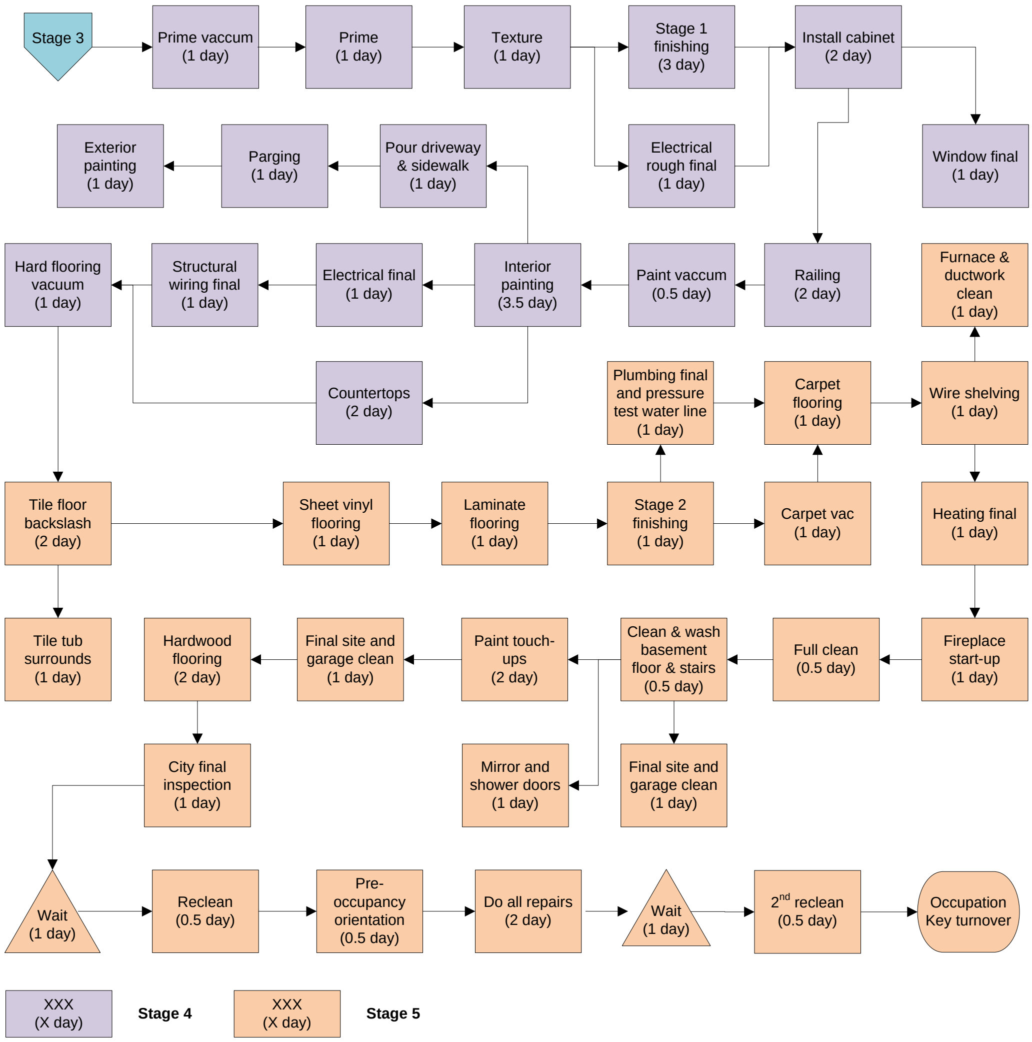


Figure 3-14: Future State Flowchart (Stages 4 & 5)

3.7.2 Kaizen (Continuous Improvement) Plans

The future state process flowchart had set a clear goal for lean improvement. After a series of company and trade meetings, the "5-month delivery cycle" was understood and accepted by everyone in the company and all trade contractors. However, lean implementation is a long-term job, and the concepts shown in the future state map cannot be implemented all at once. A comprehensive planning is necessary to break the implementation into smaller steps and to set milestones of improvements.

The five workgroups worked independently to create a kaizen plan for their target stage. Instead of focusing on implementing techniques identified in VSM sessions, the workgroups were required to envision the planning process as building a series of connected flow and to find the best answers to the following three questions:

- How to create a continuous process flow.
- How to improve the flow reliability.
- How to level production.

A four-step process recommended by Tapping et al. (2002) was adopted by all five workgroups in their kaizen planning:

1) Review the future state map and create a yearly kaizen plan.
2) Determine milestones (start and finish dates) for each main improvement event and develop a kaizen milestone chart.
3) Complete the VSM storyboard. (In the case of the collaboration company, the VSM storyboard was made on the company level for the entire construction process. The storyboard was posted in the board room of the company, as shown in Figure 3-15.)
4) Present the kaizen plan to management and obtain approval.

The objective of yearly kaizen plans is to provide a high-level structure for lean application. The workgroup started with defining major lean implement elements required to achieve the future state, and then the implementing sequence of these elements were decided. After this, the start and finish dates were assigned to each element, and the timeframe was presented in a kaizen milestone chart using predefined symbols. Figure 3-16 shows the yearly kaizen milestone chart developed by workgroup 1 (Stage 1). In the collaboration company, the kaizen milestone chart was reviewed every two weeks by the workgroup to monitor the progress of lean implementation. Open triangles would be added on the chart to indicate actual start dates and closed triangles to signify actual completion dates.

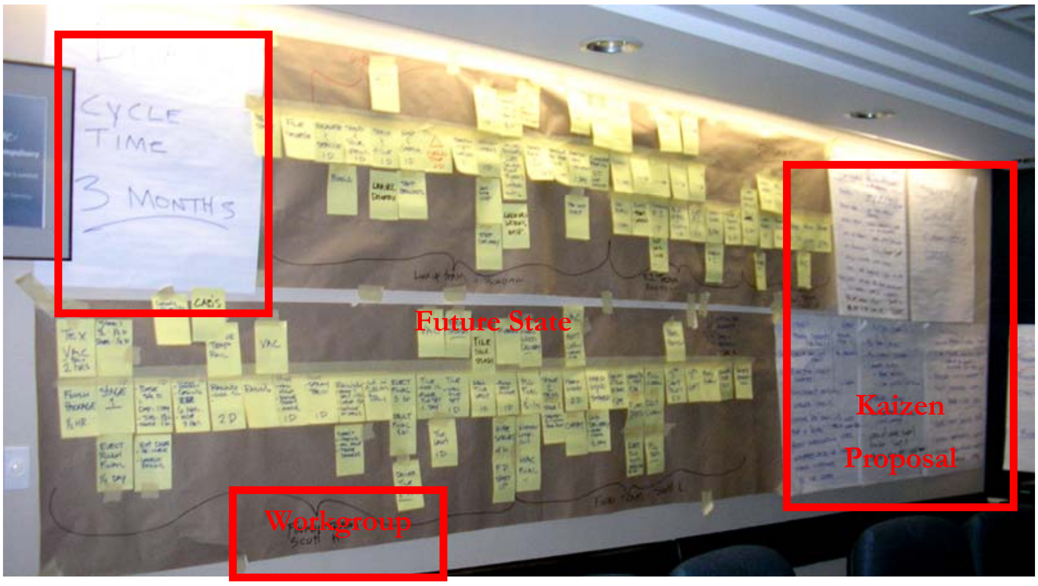


Figure 3-15: Lean Implementation Story Board (Landmark Homes 2009)

YEARLY KAIZEN PLAN

Value Stream: Stage 1 | **Value Stream Team:** Bohdan, Slav, Ali, Barry, Haitao | **Date:** Aug 10, 07 | **Page** 1 **of** 1

Item	Task	Goal	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
	Continuous Flow													
1	Takt time development		- - -	- - -										
2	FIFO-lane-based flow	All trades	- - -	- - -	- - -	- - -								
3	E-kanban storeboard			- - -										
4	Capacity adjustment mechanism	All trades		- - -	- - -	- - -	- - -	- - -						
5	Waiting time reduction	< 25 days						- - -	- - -	- - -	- - -			
	Flow reliability	PSS>90%												
6	Standardized work package	All tasks					- - -	- - -	- - -	- - -	- - -	- - -		
7	Work restructure	One super contractor							- - -	- - -	- - -	- - -	- - -	
8	Total quality control	Yield > 95%					- - -	- - -	- - -	- - -				
9	Cycle time reduction	90% within time standard								- - -	- - -	- - -	- - -	- - -
	Production leveling	Variation<20%												
10	Supermarket-based pull flow (file release-excavation)			- - -	- - -	- - -	- - -	- - -	- - -					

△ = Start Date   - - - - = Expected   ▲ = Completed

Figure 3-16: Yearly Kaizen Plan (Workgroup 1)

CHAPTER 4 – LEAN HOMEBUILDING MODEL IMPLEMENTATION AND CONTINUOUS IMPROVEMENT

Lean implementation leads to significant changes in the working process and in the production organization. These changes impact virtually everyone in the company and all the trade contractors. Change – even change for the better – is difficult for most people; it is critical for lean transformation to drive fear away from the workplace and motivate people to change their working habits (Tapping et al. 2002). The construction industry has relied on and been characterized by the traditional construction project culture for decades. Based on a study on lean application in the Swedish industrialized housing industry, Hook and Stehn (2009) summarized the fundamental impact of current construction culture on lean application as fellow:

- low motivation and awareness of build-in quality, standardized work, flow and continuous improvement;
- problems are solved based on experience, seldom thoroughly analyzed and documented; and
- ad hoc solutions and a low responsibility for production process and system.

As a production homebuilder with 30 years of history, the collaboration company experienced the same type of difficulties in lean transformation, i.e. the hard-to-change project culture and mentality of workers and managers.

4.1 ORGANIZATION STRUCTURE OF THE COLLABORATION COMPANY

The collaboration company of this study is a leading homebuilder in Alberta. In the Edmonton area, it has five subsidiary companies, each specialized in a sub-market including apartment buildings, semidetached and row houses, starter homes, single-family houses, and high-end customized homes. Landmark Homes (Edmonton) is the flagship of the group and has constructed more than 400 single-family homes each year in 2005 and 2006, accounting for about 40% of the overall sales of the group. The collaboration company's lean initiatives started in Landmark Homes in early 2007 and then gradually spread to other companies in the group.

The collaboration company is a typical production homebuilder in North America whose core business is sales and construction management. It is not involved in land development and has no construction workforce. Figure 4-1 shows the organizational structure of the collaboration company. The president of the collaboration company has more than 40 years' experience in the homebuilding business, but no experience in manufacturing. As the founder and strategic leader of the company, he is enthusiastic for innovation. He believes that factory-built housing will be the future of the homebuilding industry and has a passion to transform the collaboration company a traditional homebuilding company to a lean housing manufacturer. All general managers of subsidiary companies are company veterans, having worked in the collaboration company more than 10 years. None of them has any experience manufacturing and lean production. Due to different management style, they had different attitudes towards lean initiatives. There were 10 construction managers and about 25 site managers (superintendents) in the five companies. Most of them came up from the trades and managed the construction process based on their experiences. As a production homebuilder that constructed more than 1,000 units per year, the collaboration company worked with hundreds of subcontractors. Most of them specialized in one task and worked in one or two subdivisions. In July 2007, the collaboration company was working with as many as 147 subcontractors in 31 subdivisions.

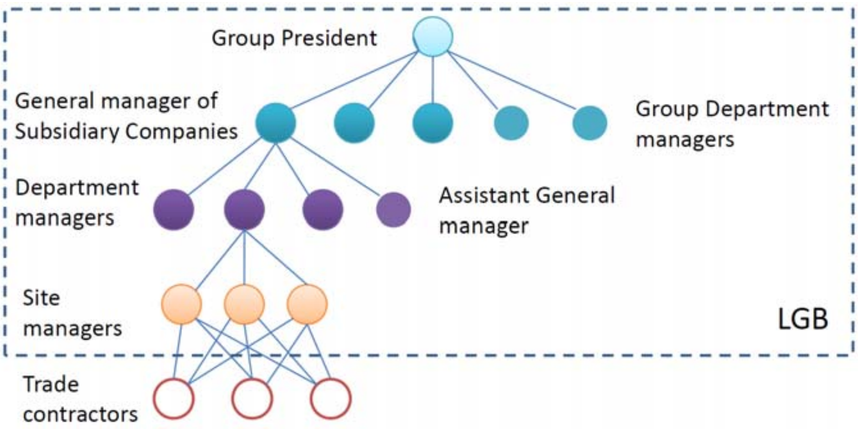


Figure 4-1: Organizational Structure of the Collaboration Company

Before the researchers from University of Alberta introduced lean production concepts to the collaboration company, the management of the company had been barely aware of lean. After a lean consultant from the manufacturing industry had completed the lean training classes, the management team and construction managers were aware of lean theoretically, but the subcontractors had no chance to take any lean training. In fact, most of the subtrades were not interested in learning lean concepts and principles. They just wanted to know the requirements of homebuilders and to follow the system.

4.2. MANAGEMENT COMMITMENT

For many people, lean implementation seems like another short-term program, but it is not. Toyota spent over 30 years developing a lean manufacturing system, and they continue to perfect it. The success of lean implementation depends on the long-term commitment of top management. "The most important factors for success are patience, a focus on long-term rather than short-term results, reinvestment in people, product, and plant, and an unforgiving commitment to quality," says Robert McCurry, former executive V.P. of Toyota Motor Corp. The collaboration company's management shows its commitment to lean implementation through the following:

- Allocating sufficient time and resources for lean training.
- Engaging external lean consultants to facilitate VSM process.
- Spending time to lead lean activities.
- Including lean activities into construction managers and site managers' work scope.
- Investing in lean techniques, such as a panel prefabrication plant, e-kanban scoreboard, etc.
- Sharing the benefit of lean implementation with trade contractors.

4.2.1 Develop People and Partners

In the preface of The Toyota Way (Liker 2004), the author quoted Fujio Cho, president of Toyota Motor Company, to explain the uniqueness of the lean production system. Mr. Cho said "The key to the Toyota Way and what makes Toyota stand out is not any of the individual elements. … But what is important is having all the elements together as a system. It must be practiced every day in a very consistent manner – not in spurts."

Obviously, the Toyota Way cannot be achieved by hiring an external lean expert to conduct several lean workshops and facilitate VSM sessions or by appointing a lean champion to be responsible for lean events and value stream map implementation. Developing people who live with the lean philosophy and cultivating an environment of learning and continuous improvement are the key.

The collaboration company kicked off its lean journey with a series of lean training workshops. First, key management personnel of the group, including all general managers of the subsidiary companies, attended a one-day training workshop (Lean 101) led by an external lean expert. The workshop introduced basic concepts of lean, such as eight types of wastes and flow, and explained commonly-used lean tools, including standardized work, 5S, visual control, workforce practices, quick changeover, takt time management, quality at the source, pull flow (JIT), kanban, production leveling and total production maintenance. The workshop also served as the kick-off meeting to solicit organizational buy-in. Then, all employees in the company were required to take Lean 101 training to get familiar with lean concepts and principles. A simulation (airplane game) that tied together key lean concepts was an important part of this training.

The training of construction managers and site superintendents is extremely important, because the process and system are ultimately supported and managed by them. Their role is much more than that of a supervisor; they need to lead the way. Lean production has much higher expectation of mid-level managers. They must not only have the knowledge and skills to manage and coordinate construction jobs, but also have the ability to solve problems, facilitate team work, encourage continuous improvement, and teach others. Those "soft" skills cannot be taught in the classroom and have to be learned by doing. In six months, the lean expert had attended weekly lean meetings and numerous workgroup meetings to coach people on how to observe a process, define problems, find out root causes, communicate and facilitate the meeting, work in a team, develop standards, and so on. External experts have their limitations. They do not have the necessary job knowledge and normally do not have the time to be involved in day-to-day operations and problem solving. They are outsiders to the company and not in the management loop. Due to these limitations, external lean experts cannot provide a lean solution for the company or take the leading role in lean implementation. Their role is mostly a coach and advisor who help in training people and kicking off lean initiatives. However, in the early stage of lean transformation, significant investment in lean consulting is necessary due to the lack of lean knowledge and skills inside the organization.

Getting buy-in from subcontractors is indispensable for lean transformation of production homebuilders. Since virtually all construction works are performed by various subcontractors, mapping and planning are worthless unless consensus with subcontractors can be achieved. At the beginning of the one-day flowcharting workshop, the lean expert quickly went through the key concepts of lean and introduced the VSM technique so that the representatives of major subcontractors knew what was happening in the meeting. Since a majority of trades only had a temporary relationship with homebuilders and the turnover rate was high, it was difficult to justify the investment in providing training to subcontractors. Moreover, lean production is different from the current project-based practice in many ways. It was not easy to persuade subcontractors to follow a new system while the entire industry was still on the old track. A solution is to grow super-subcontractors that live with the same lean philosophies.

A good example of this strategy is the Great Canadian Renovation and Construction Corporation (GC). In early 2007, Great Canadian Roofing Corporation was one of the 43 major subcontractors working with Landmark Homes. It took about 80% of roofing, 40% of framing and 35% of siding jobs of Landmark Homes. At that time, Landmark Homes was subcontracting jobs to five framing, two roofing and six siding companies in its 31 subdivisions. In late 2007, the collaboration company formed a strategic partnership with Great Canadian Roofing Corporation and established a joint venture company, Great Canadian Renovation and Construction Corporation, which specialized in panelized construction. Now GC has become a super-subcontractor for the group and carries all the framing, siding, and roofing jobs of three major group companies. Regarding GC as an extension of the company, the collaboration company invested heavily in integrating the working process with that of GC and providing support for GC's lean initiatives. In fact, the author currently spends 50% of working time with GC as a lean analyst. A detailed introduction and discussion of GC's lean implementation are included in Chapter 5. So far, the collaboration company has five super-subcontractors carrying restructured work packages: excavation-foundation, framing-roofing-siding, plumbing, electrical-structural wiring, and insulation-drywall.

Following lean principles to develop partners and suppliers involves a fundamental change in mentality. Conventionally, homebuilders maintain a large subcontractor pool and contract work to the lowest bidder. It is believed that subcontractors have an inherent motivation to improve their processes and productivity to survive and grow in a competitive market. In fact, this belief is simply wrong for the following reasons:

- Most of the trade contractors are founded and led by people who used to be trade workers. They know the industry well and have the necessary technical skills, but lack training in management required for process improvement.
- The vast majority of subcontractors are small companies. They do not have the necessary resources for long-term improvement efforts nor the ability to take the risk of innovation.
- Trade contractors are basically service providers. Any innovation or change must get buy-in from homebuilders. Without a mentality change in the management of homebuilding companies, changes like work restructuring and super-subcontracting cannot happen.

The key to building long-term partnerships is for the homebuilders to not look at trade contractors as external service providers. Rather they should be viewed as an extension of the homebuilding company, and the company should work with them to develop an integrated production system. Therefore, construction works are not commodities to be sourced on the market through open bidding, but services provided by highly capable suppliers that have the same company culture and are working in one production system. In *The Toyota Way*, Liker (2004) suggested a supply chain needs hierarchy as shown in Figure 4-1. Currently, the collaboration company has established a stable relationship with all its trade contractors, with fair business relationships, stable processes, and clear expectations, but for super-subcontractors, the collaboration is working to achieve a higher level in the hierarchy – to develop enabling systems and to learn together as one enterprise.

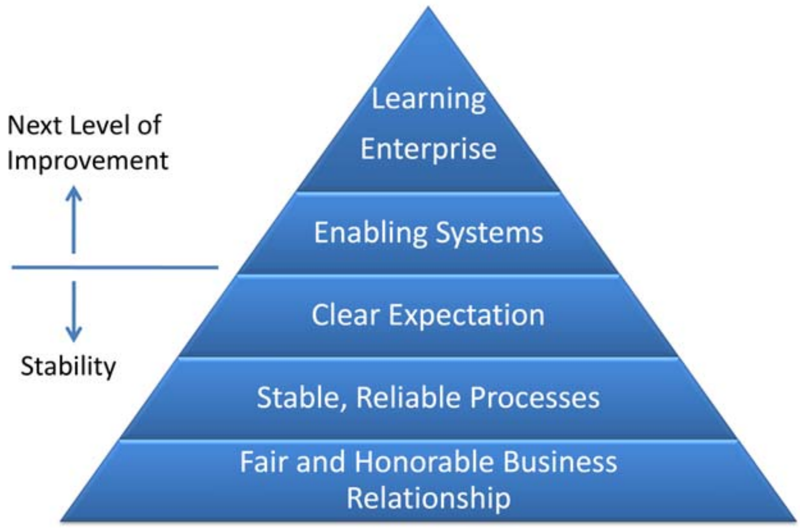


Figure 4-1: Supply Chain Needs Hierarchy (Liker 2004)

4.2.2 Base Management Decision on Long-Term Thinking

Principle #1 in *The Toyota Way* is to "base your management decisions on a long-term philosophy, even at the expense of short-term financial goals" (Liker 2004). Long-term thinking is considered as the foundation of the Toyota Way (see Figure 4-2). Management must recognize that the lean journey is an adventure involving many unforeseen problems and short-term pains. It is critical to keep the big picture in mind and not to let problems and failures stop the process.

Lean implementation in the collaboration company also confronted numerous difficulties and even failures. Due to significant differences between the homebuilding and manufacturing industries, and lack of examples of precedents in the industry, the collaboration company's lean initiatives had to adopt a trial-and-error approach – each kaizen event was an experiment. People learned from mistakes and revised the kaizen plans to try again. In fact, most of the kaizen plans were revised several times in the 18-month lean implementation period and the ultimate process and future state map were quite different. However, the management's commitment to lean and the five-month delivery cycle goal never changed. The top management of the company has a clear vision that lean production through industrialization is the future of housing production and is the only approach to moving customer service to another level –

three-month delivery and "net-zero ready" houses. The 18-month lean implementation is only the first stage towards this goal.

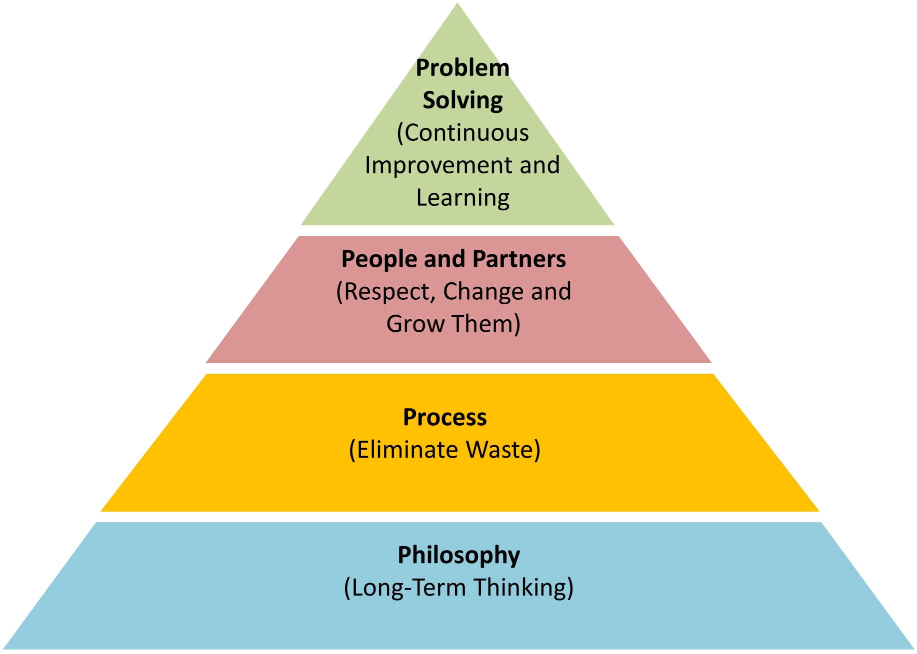


Figure 4-2: "4 P" Model of the Toyota Way (Liker 2004)

The global economic meltdown of 2008 was a serious test on the collaboration company's commitment toward lean and its long-term thinking philosophy. In the second half of 2007, the Edmonton housing market started cooling down. In 2008, the situation severely deteriorated. The collaboration company's sales dropped more than 60% from its 2006 level. Due to the significant decrease in the number of new house starts, the house construction market turned from a buyer's market to a seller's market in the middle of 2008. As shown in Figure 4-3, the framing labor price had fallen almost 40% in six months (the blue line represents the market price). At that time, GC had just started its wall panel prefabrication plant. Lack of experience and high fixed costs made the real costs of prefabrication much higher than the market price. The green line in the chart represents the actual labor costs of factory-based framing. GC had lost half of a million dollars on framing in the first eight months of 2008 and ran out of cash in September.

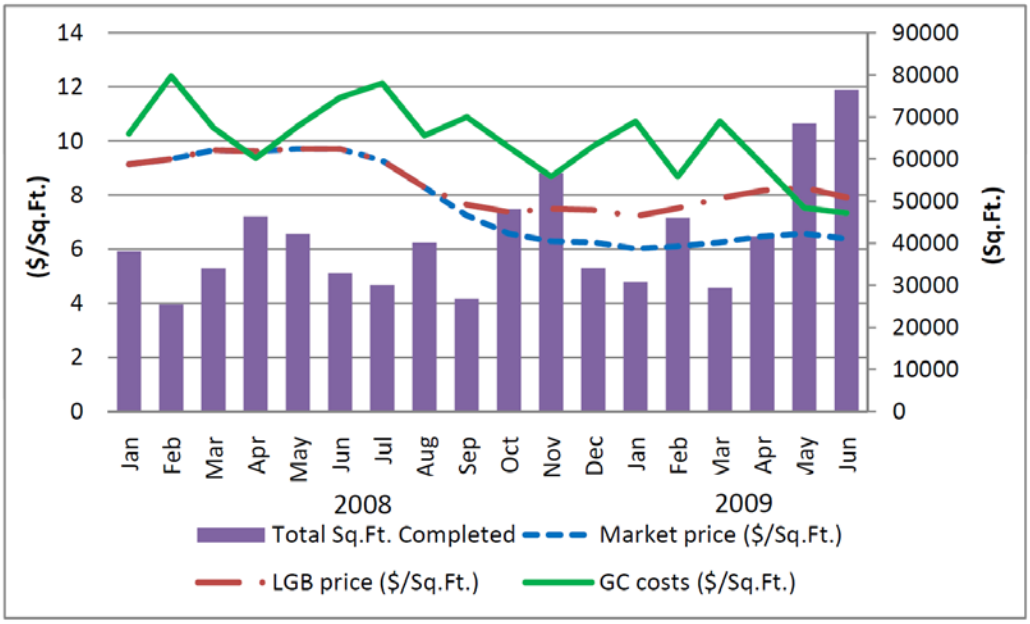


Figure 4-3: Great Canadian Prefabrication Costs vs. Price (Framing Labor)

The top management team of the collaboration company had to make choice: they could either make use of the low prices in the construction market to further reduce costs or invest more money into the prefab business. The first choice was good for the company's short-term financial goal – cutting prices to survive in the harsh housing market, but the failure of the prefabrication plant would be a heavy blow to the company's long-term strategy – industrialization and lean production. In contrast, the second choice supported the long-term goals but would reduce the company's already seriously narrowed profit margin.

After a series of debates and a thorough study on the benefits that prefabrication had and would provide to the company, the top management team decided to pay GC a $1.20/sq.ft. premium on top of the market price, which was the value of direct benefits that prefab framing brought to the company. The solid line in Figure 4-3 shows collaboration company's framing labor price to GC, and the premium started from September 2008 and was increased to $1.85/sq.ft. in March 2009. In addition, the collaboration company decided to inject $100,000 every month to GC to solve its cash flow difficulties. This decision was quite risky during the bottom of an economic recession, but it was an excellent example of the lean principle – "base your management decisions on a long-term philosophy, even at the expense of short-term financial goals." The collaboration company's efforts started to pay-off when the housing market started to rise sharply from the second quarter of 2009.

4.3 CONTINUOUS PROCESS FLOW AND FLOW RELIABILITY

In a lean production system, flow has a twofold meaning: process and operation. The application of lean thinking to construction has been centered on creating continuous process flow through improving flow reliability (Ballard 2001). Continuous process flow means the construction product – building – goes through the construction process without waiting. In residential construction, it is common practice that idle time, in which no construction activities occur on the site, accounts for more than half of the overall construction duration. A primary goal of the 18-month lean initiative of the collaboration company was to reduce the house delivery time from 10 months in early 2007 to 5 months by mid-2009.

The major cause of wasteful waiting time is the uncertainty in homebuilding process. Site managers cannot accurately predict when the site can be ready for the downstream tasks so that they have to book the subcontractors after the preceding tasks have been done. Thus, the lead time of the downstream task becomes waiting time. On the other hand, the subcontractors are not sure that they can start their work on the scheduled day and they have another job after they finish the first one. Then, overbooking becomes the only solution to minimize idle time of construction crews. Flow reliability is the prerequisite for continuous process flow and thus was the center tenet of future state VSM and kaizen plan development. Kaizen events in this area can be categorized into two groups. FIFO-lane-based flow and work restructure aimed at improving the process reliability, while standardized work and total quality control focused on reducing the variation of operation cycle time.

4.3.1 FIFO-Lane-Based Flow

The collaboration company's lean practice showed that FIFO-lane was an effective tool for shielding upstream variability to the downstream tasks, so at the beginning of the lean model implementation, it was used widely in the process to regulate almost every handover of subcontractors. However, along with the improvement in operation reliability and increased level of confidence of the subcontractors, FIFO-lanes became shorter and shorter, and eventually were replaced by continuous pull flow. Like the in-process supermarket in a lean manufacturing system, FIFO-lane is only useful when uncontrollable obstacles to continuous flow exist. Currently, there are only two FIFO-lanes in the entire construction process, one in Stage 1 and the other at the end of Stage 2 (see Figure 4-4). The one after "Backfill & Shallow Services" is to shield the uncertainty in the installation of the underground gas line and electrical meter. Those two tasks are performed by utility companies that are contracted by land developers. Although they have a standard work procedure (lead time is 5 workdays), in reality homebuilders have little control of when they come to the site. Therefore, an 8-workday window is left for those two tasks. The other FIFO-lane is placed at the end of Stage 2 to shield possible delays in framing and roofing.

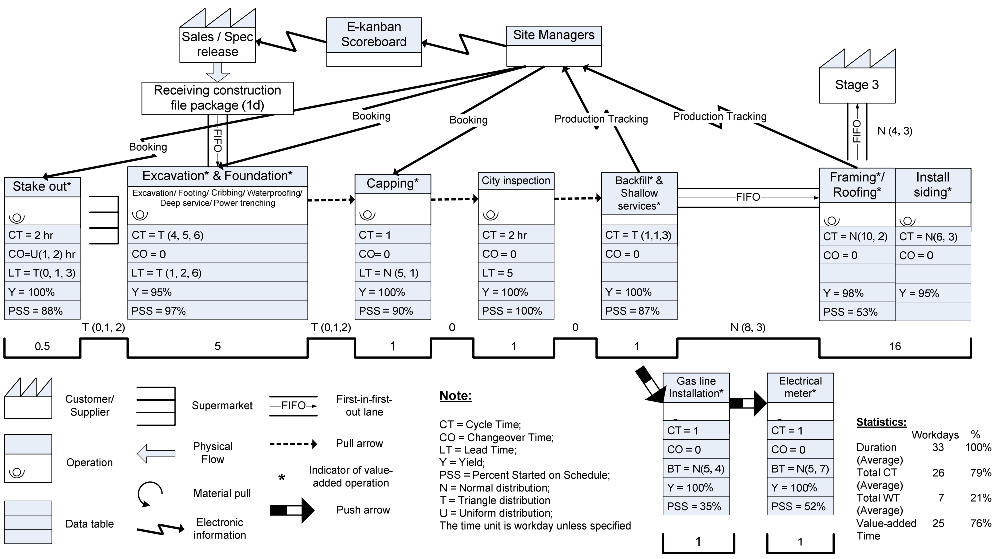
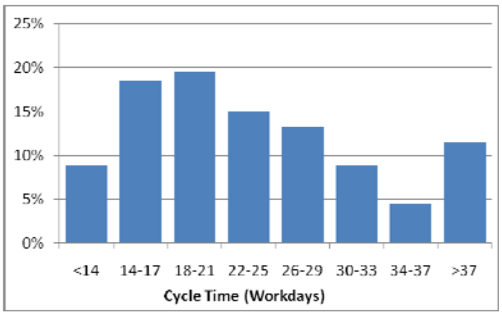


Figure 4-4: New Current State Map of Landmark Homes (Stage 1 & 2, 2009)

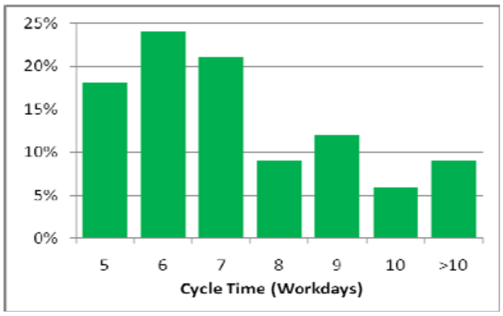
The elimination of FIFO-lane can be mainly attributed to operation reliability improvement, but the current buyer's market conditions also played an important role. Since the subcontractors did not operate to their full capacity, homebuilders could always get a skilled workforce on the scheduled date, and subcontractors worked hard to meet quality and time requirements in order to maintain good relationships with homebuilders. Whether the system illustrated in Figure 4-4 is sustainable in a seller's market like that in 2005 and 2006 is a topic for future study, but the establishment of super-subcontractors and prefabrication (detailed in Chapter 5) can effectively eliminate the root cause of the problem.

4.3.2 Work Restructure

Work restructuring and the emergence of super-subcontractors had a remarkable impact on the cycle time reduction and process reliability improvement. Currently 90% of construction work in the first two stages is performed by two super-subcontractors. The foundation contractor carries out all the underground work including excavation, footing, foundation walls, waterproofing, deep services, shallow services, power trenching and backfill, and the envelope contractor takes care of capping, framing, roofing and siding. As shown in Figure 4-5, process performance has been improved substantially. Chart A is based on the jobs whose foundations were built in May to July 2007, and the Chart B is calculated using data from May to July 2009. In 2007, less than 10% of jobs were completed within 14 workdays, and cycle time spanned in a wide range. In contrast, 2009's data are much shorter and close to the mean. More than 60% of foundations were completed in 5-7 workdays (from excavation to backfill) and 85% of jobs were completed in 9 workdays, which is the new time standard for foundation work.



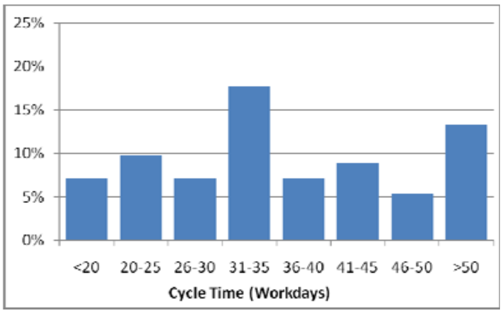
a. Cycle time distribution (May-July 2007)



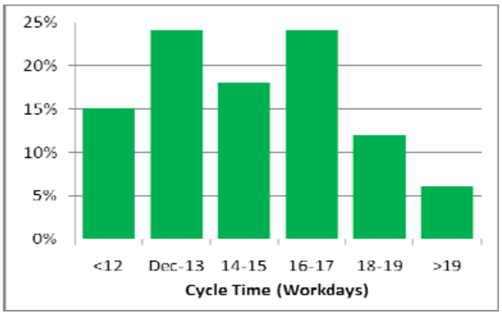
b. Cycle time distribution (May-July 2009)

Figure 4-5: Foundation Cycle Time Comparision (Excavation – Backfill)

Similar results can be found for Stage 2. Figure 4-6 shows the comparison between May to July 2007 and May to July 2009. The 2007 data scatter in a broad range from 20 to 50 workdays with no obvious pattern. In 2009, 66% of jobs were completed within 12 to 17 workdays and 94% of jobs within 20 workdays. Although there were still some challenges preventing the subcontractor from consistently achieving the goal of 16 workdays, which had been established two years ago in future state value stream mapping, the improvement was already significant.



a. Cycle time distribution
(May-July 2007)



b. Cycle time distribution
(May-July 2009)

Figure 4-6: Framing/Roofing/Siding Cycle Time Comparision

The idea of consolidating construction tasks into larger packages and contracting them to fewer multi-skill teams has been discussed by researchers for a long time. Ballard (2001) proposed to organize the following five system-based cross functional teams for the building cycle of single-family homes:

- Foundation
- Structure and skin
- Utility rough-in, interior walls & exterior wall ornamentation
- Utility and interior finishes
- Carpet, driveway and landscaping.

Sacks and Goldin (2007) used a similar concept for the process improvement in high-rise apartment building construction. Structuring the construction process by segments and designating a single team to take the responsibility of each segment have clear benefits due to "fewer interfaces and thus a more stable process with lower management overhead" (Sacks and Goldin 2007). However, in reality there is no cross functional team available on the market. Frequent fluctuation of the housing market makes it too risky for homebuilders to establish such teams in house. Moreover, construction is generally not the core business of production homebuilders, and they do not have qualified personnel to do so. The collaboration company's approach is to form long-term strategic relationships with a few selected subcontractors and help them become super-contractors. The foundation and framing/roofing/siding companies mentioned above are the outcome of this strategy. In the past two years, the collaboration company has worked closely with these two companies to provide lean training, management personnel, job projection, and steady workflow. Significant efforts were spent to integrate the work processes and improve the information transfer between companies. Meanwhile, the collaboration company continuously challenges them to enlarge their work scope and improve their performance. The homebuilding industry is currently so fragmented and specialized that most subcontractors are reluctant and do not have the capacity to become a cross functional team. Without a long-term strategy, serious push, and solid support from production homebuilders, a cross-functional team is simply impossible.

4.3.3 Standardized Work

Standardized work is regarded as the backbone of lean processes and the basis for continuous improvement and quality. It also reinforces employee empowerment and innovation in the work place by allowing people to control their work and improve upon standards. In manufacturing, standardized work normally consists of three elements: takt time, sequence of actions or sequence of processes, and quantity of in-station inventory. In construction, standardized work has a much broader meaning. Standardized work in the case-study company was conducted on two levels – process level and operation level, as shown in Table 4-1.

Table 4-1: Standardized Work in the Case-Study Company

Item	Developed by
Process Standardization	
Process Flowchart	LGB & Subcontractors
Site Managers' work procedure	LGB
Site Construction Management Manual	LGB
Standardized Construction Schedule	LGB
Operation Standardization	
Quality Standard	
Qualtiy checklist	LGB
Quality check procedure	LGB & Subcontractors
Standardized Work Procedure	Subcontractors

The future state flowchart described in Chapter 3 is an important part of the standardization of the construction process. Based on the flowchart, a work procedure was developed by the construction managers and site managers to provide a daily working guide to site managers and define the normal state of construction jobs (see Figure 4-7). Activities that subcontractors were expected to take were clearly defined for each day. It is critical to have a standardized stable process before any improvement can be implemented. If the process is shifting all the time and every one works in his/her own way, then any improvement will be just another variation that is occasionally used and mostly ignored. The standard work procedure (SWP) and site construction manual, shown in Figure 4-8, became the "bible" for site managers. Each one of them was trained to follow the procedure without constantly looking at it. Construction managers and management frequently checked whether the procedure was being followed. Both the procedure and manual were reviewed and revised regularly to reflect the current construction process.

The following procedure was developed in collaboration with site managers, construction managers and all related trades. There are major benefits for the plumbing, heating and electrical / smart wiring contractors who participate in this construction sequence. A controlled environment gives everyone an opportunity to work indoors all year-round. Benefits range from reduced man-hrs per job, safety, higher quality of workmanship, ability to retain workers due to more attractive work environment. As well, there is a reduced dependency on other trades and processes giving more predictability and control over start and completion of the work. Benefits realized by the builder include reduced cycle times, predictable sequence of events that can be measured and planned around, higher quality product and attracting higher quality trades.

Day	Site Manager		Main Contractor	Supporting Activities	Day
1	Receive complete file. Review the file using the File review Checklist. Visit site, inspect the work and review progress with contractors. Do a lot inspection noting any damage to CC or sidewalk, note dirt balance and neighboring construction activity. Submit lot form to the Production Coordinator.	**Book Excavator: Fax plot plan & basement plan to excavating contractor.** **Book Cribber, send them the Purchase Order & Plans** **Book Footing Material Package (if Required)** **Book Purchaser Orientation Meeting**	**Surveyor:** stake out the lot.	**Excavator:** "First Call" staking to mark existing underground services.	1
2	Visit site, inspect the work and review progress with contractors.	**Book Soil Test** **Book Sump Liner** **Book Sump Tee**	**Excavator:** Pre-Service the Lot & Start Excavation.		2
3	Visit site, inspect the work and review progress with contractors. Conduct the Purchasers Orientation meeting using the standard agenda and script. Review soil test results with the engineer and act on recommendations as required.		**Excavator:** Finish excavation. In the Summer the excavation will be completed. In the Winter the excavation will stop one foot from the bottom to allow frost coverage and the Excavator will finish first thing next morning	**Soil Engineer:** performs soil test and advises Site Manager of findings. **Area Manager:** Attend Purchaser Orientation meeting.	3
4	Visit site, inspect the work and review progress with contractors.		**Cribber:** installs footings & delivers forms and material package to site.	**Plumbing Contractor:** Install Sump Tee **Dampproof Contractor:** Install Sump Liner **Concrete Pump Truck:** required to place concrete. **Concrete Supplier:** delivers footing concrete.	4
5	Visit site, inspect the work and review progress with contractors.		**Cribber:** set wall forms.		5
6	Visit site, inspect the work and review progress with contractors. Check foundation with checklist prior to pouring. Check for CC damage	**Book Interior Gravel, Weeping Tile and Dampproofing** **Book Electrical Panel Installation** **Book Backfill & Shallow Services** **Book Pile Installation** **Book Framer to "Can" foundation**	**Cribber:** pour concrete walls.	**Concrete Supplier:** delivers wall concrete. **Concrete Pump Truck:** required to place concrete.	6

Figure 4-7: Standard Work Procedure for Site Managers (Landmark Homes 2007)

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Figure 4-8: Site Construction Manual –Page 1 (Landmark Homes 2007)

Another important tool in process standardization is the standardized schedule, which is a four-week schedule that mirrors the standardized flowchart. It shows in calendar format the specific construction schedule for a given job, as shown in Figure 4-9. Before a site manager sends a booking request to subcontractors, he/she generates a standardized schedule for the next four weeks based on the data in production tracking system (confirmed and projected task start and finish dates). This schedule is attached to the request. Since the lead time for most subcontractors is 2 weeks, the standard schedule provides subcontractors a big picture of the process before and after their tasks. It is proven that the subcontractors are more confident when they know that preceding tasks have been properly scheduled and more responsible when they see that the delay of their operations will have a serious impact on subsequent tasks.

April - May 2009

Job #: 09-010 Address: 1430-37 B Avenue NW Date: 20/4/09

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
19	20 Framing	21 Framing	22 Framing	23 Framing	24 Framing	25
26	27 City framing inspection	28 Roofing Mechanical insulation	29 Install fireplace	30 Basement and garage floor	Notes:	
Notes:					1 Siding	2
3	4 Siding **HVAC rough-in**	5 Siding Electrical rough-in	6 Siding Plumbing rough-in Electrical rough-in	7 Siding Plumbing rough-in	8 Siding Stuctural wiring rough-in	9
10	11 Install insulation and vapor barrier	12 City insulation inspection	13 Drywall boarding	14 Drywall boarding Frost wall & insulation	15 Drywall boarding Frost wall & insulation	16

Figure 4-9: Standardized Job Schedule (Landmark Homes 2009)

Reliability on operation level also plays an important role in waiting time reduction. When variation in the operation cycle time is high, a large time buffer, in the form of FIFO-lane, has to be used to achieve process reliability. There are basically four factors causing uncertainty in cycle time: bad weather, material supply problems, workers' productivity variation, and rework caused by defects. Weather is an uncontrollable factor and thus has to be shielded using in-process buffers. As discussed in the last section, there are two FIFO-lanes at the end of foundation and framing-roofing work packages to accommodate possible delay caused by weather. All tasks on the critical-path after roofing are performed in an indoor environment and weather is not an issue. Meanwhile, the collaboration company believes that it is homebuilder's responsibility to ensure that the site is 100% ready at 100% of time, including material supply, and this can be achieved by reinforcing long-term partnerships with material suppliers and standardizing site managers' work (ordering material in time).

Providing consistent performance in terms of productivity and quality is the responsibility of subcontractors, but the collaboration company did not simply set a goal for subcontractors but worked with them to improve their work consistency. Developing standardized work procedure for each construction task was a major area of this joint effort. The goal is to stabilize crews' productivity through standardizing their operation, including work sequence, time standard for each step, job design for each crew member, and operation tips. A detailed example of standardized work procedure will be introduced in the next chapter. The application of standardized work was very difficult at the beginning. Construction work is craft-based, and traditionally workers perform their jobs based on their experience without any standardization. It is widely perceived that a rigid standardized procedure is not applicable in construction where each product (house) has unique features. However, soon after the standardized work procedure, which had been developed based on the best practices, was published and used as training material. Some crews found that the procedure could help them improve their performance, making it more consistent. Gradually, the crews who had followed the standardized procedure became highly capable and stayed in the system and the crews who had not were weeded out.

A quality checklist is an effective tool for quality control, but it also has obvious shortcomings. First, it is conducted after the job has been done, so any problems found in a quality check will lead to rework. Second, the checklist shows only the quality check items, not the clear standard. In order to help the subcontractor clearly understand expectations and build quality into the product in the first place, the collaboration company worked with subcontractors to develop quality check standards for all the major tasks. Figure 4-10 is the Framing Check Standard. To make everything visual and easy to understand, pictures were used in every step to illustrate detailed quality requirements and checking measures. A clearly defined standard not only improved subcontractors' quality awareness, but also eliminated any disputes and misunderstandings in the quality check. Now, the quality of framing is so consistent that site managers only do spot checks every 5 jobs. This is a good example of reducing waste through building quality at the source. The elimination of the final framing check can save site managers time and reduce framing cycle time as well. The framing crew can go to the next job after the completion of the current job without waiting for the site manager to check its job.

Framing Check Standard (Landmark Group of Builders)

1.	**Basement and Basement Stairwell**	
1.1	Check position of teleposts. - Centered on beam. - No more than 3" of thread showing.	
1.2	Plumb posts	
1.3	Squash blocks above the beam and at point load.	

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Figure 4-10: Framing Check Standard

4.4 CONTINUOUS OPERATION FLOW AND PRODUCTION LEVELING

While process flow refers to the flow of a product going through the entire value stream, operation flow is the product's flow at a given point (work station) of the process. To minimize waste, both flows should be consistent without any interruption. In construction, a continuous operation flow is much more important for lean application. Unlike on a manufacturing assembly line where workers can go between multiple stations, construction crews are generally specialized to perform one task. Interruption in the operation flow means the crew needs to find a job from another homebuilder (value stream), which leads to a so-called temporary workforce structure – a major impediment to the application of lean production system to the construction industry.

In order to provide a continuous operation flow, production must be leveled. Unevenness in production level means that every work station (in the case of construction, every trade contractor) needs to have the capacity to accommodate the highest level of production. Overcapacity implies that work stations are idle from time to time waiting for new jobs coming down the line – non-continuous operation flow. Production leveling is considered by lean experts as a prerequisite of other lean tools. "In general, when you try to apply the TPS, the first thing you have to do is to even out or level the production," says Fujio Cho, the chairman of Toyota Motor Corporation. "Once the production level is more or less the same or constant for a month, you will be able to apply pull systems and balance the assembly line. But if production levels – the output – varies from day to day, there is no sense in trying to apply those other systems, because you simply cannot establish standardized work under such circumstances."

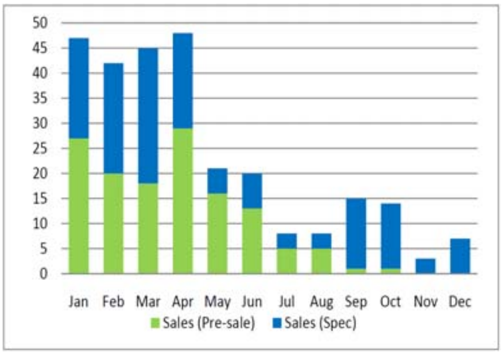
In lean manufacturing, the most widely used production leveling technique is Heijunka, which takes the total volume of orders in a period and levels them out so the assembly line can make the same amount and mix every day. The application of Heijunka depends on two key factors:

- Orders can be accumulated or demands can be accurately predicted. In Toyota, the production schedule is created 60 days in advance based on forecast, but each car in the schedule can be changed as long as the basic body type is the same. In fact, the production schedule is updated every week based on real orders. They call it "change to order" system.

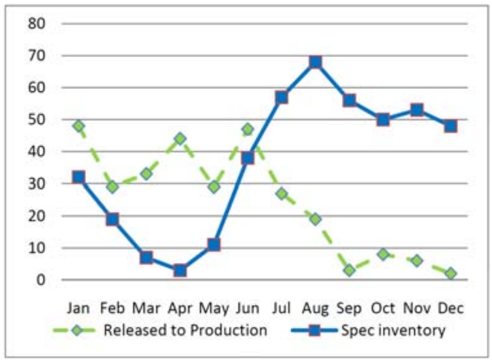
- The setup time for changeover must be reduced to near zero. The essence of Heijunka is to produce different types of products alternatively each day. It is amazing to learn that in a Toyota plant, a several-hundred-ton press can be changed over in minutes. A long changeover would mean that the plant has to build large batches of one product before changing over to another one.

The homebuilding process is basically one-piece flow with fixed travel time between job sites; the size and model difference of houses have only minor impact on cycle time. So the biggest obstacle that prevents even production flow is the unpredictability of customers' demand. In value stream mapping, the Stage 1 workgroup designed a supermarket-based pull system between the pacemaker task (excavation) and sales to create continuous flow. Since customers do not buy products predictably, the fluctuation in sales is virtually unavoidable. The supermarket functions like a reservoir. Although the input to the reservoir may not be even, the output can be even as long as the water level in the reservoir is under control. The upper and lower limits of the supermarket are decided based on outflow rate (the takt time of the house production system) and historical data analysis of sales variability. How to decide and maintain a consistent outflow rate is the key to level production flow while meeting the customer demands.

At the first, the workgroup suggested using a consistent outflow rate based on the sales forecast, but soon it was realized that a consistent takt time was only suitable when the market condition was stable, like that of 2005 (Yu et al. 2007). Starting in July 2007, the Alberta housing market cooled down due to high housing prices and uncertainty in the economy. As shown in Figure 4-11, the total sales in July and August 2007 were only 8 houses each month, and the spec house inventory escalated from 11 in May to near 68 by the end of August, two times the normal inventory level. A high level of inventory of spec houses means overproduction, a fundamental type of waste. It increases financial costs of houses and brings significant risk for homebuilding companies. In September, Landmark Homes changed its spec house release strategy to replenishing only half of the spec sales of the previous month, and the outflow rate from supermarket between sales and construction would be decided by the average volume of total released jobs in the previous 2 months. Due to a 30-45 days office cycle time, the jobs that entered the construction process were mostly sold (pre-sale houses) or released to production (spec houses) in the last two months. The new strategy was similar to Toyota's "change to order" system; takt time changes every four weeks, but within those four weeks, the production flow is leveled. The subcontractors, except the foundation contractor, knew their demand level at least three weeks ahead and thus could adjust their capacity accordingly. It takes several months for a house to go through the construction process, so the production system is virtually impossible to synchronize using one takt time. The continuous work flow for any given operation is basically ensured by a standardized process and 4-week capacity planning.



a. Sales Volume of 2007



b. Total Job Released to Production and Spec Inventory

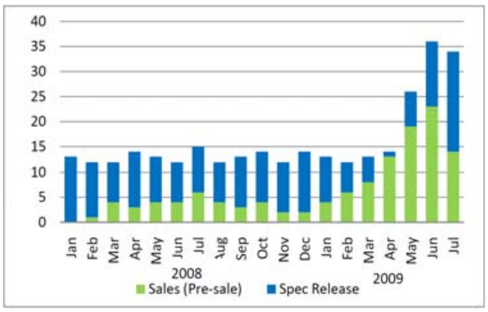
Figure 4-11: Production Flow (Landmark Homes, 2007)

A critical prerequisite of this pull system is the homebuilder's commitment to provide a minimum flow volume. September 2007 was the first month that Landmark Homes implemented the new production leveling strategy. Since 3 spec houses had been sold in August, 2 new spec houses were released in September. The total number of houses released to production in July and August were 27 and 19 houses, respectively. The number of jobs that entered into construction in September was 23, which meant a takt time of 1 day. However, extended low sales quickly led to an extremely long takt time. In November, the number of jobs released to construction was 6, which meant a takt time 3.5 days. For most operations, when takt time is longer than 1 day, continuous flow becomes impossible.

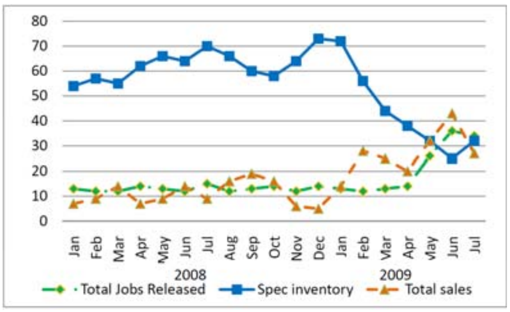
At the end of 2007 and the beginning of 2008, it was clear that the recession was coming and the housing market would be slow for the foreseeable future. A difficult decision had to be made by the collaboration company's management team – whether the company would continue its production leveling strategy and how to maintain the flow continuity of its subcontractors. At the annual management meeting, the following agreements were reached:

1) Spec houses' inventory level should be tightly controlled – no new spec houses would be released until the inventory level went back to a normal level, 30 spec houses in production. An exception to this rule was the spec houses necessary to maintain the minimum level of production flow.
2) Consolidate production flows of the three major subsidiary companies to provide consistent flow to major contractors.
3) A minimum flow level of 5 jobs per week must be maintained to prevent losing core production team (company employees and major subcontractors).

The year of 2008 was difficult for both homebuilders and subcontractors. Sales remained at a very low level. For example, sales of Landmark Homes (Edmonton), the flagship of the collaboration company, dropped more than 50% from that of 2007. For 7 months in 2008, the total monthly sales were less than 10 houses (see Figure 4-12). To maintain the minimum flow level of 5 jobs per week, Landmark Homes was required to provide at least 3 houses per week. Due to continuously releasing spec houses, the spec house inventory level reached 73 houses by the end of 2008.



a. Job Released to Production



b. Sales and Inventory

Figure 4-12: Production Flow (Landmark Homes, 2008-2009)

The collaboration company's persistence and long-term thinking paid-off when the housing market turned over in February 2009. In May, the inventory level of spec houses returned to a normal level and Landmark Homes started to release spec houses based on spec sales of the previous month. Although sales in early 2009 had increased significantly, most of the sales were spec houses and the number of pre-sales was lower than the minimum flow level. Therefore, the pace of construction (takt time at pace-maker task) did not change until May when the number of presales was higher than the minimum flow level, and the spec house inventory went back to normal.

Another important tool of production leveling is the job projection table, which provides subcontractors a clear picture of their future jobs and gives them 2-3 weeks to adjust their capacity. Figure 4-13 is the projection table for framing. Construction managers from the three subsidiary companies of the collaboration company and the production manager from super-subcontractor GC meet once a week to level the production using this projection table. The columns entitled "Starts" is updated by construction managers when the trigger task has been started. In the case of framing, the trigger task is excavation. According to the standard construction process of Landmark Homes, 3 weeks are needed from excavation to framing. For instance, job 08-037 started excavation on August 20th, 2009. The projected framing start date will be 3 weeks after, September 10th. After GC's production manager received the order, he checked the resource availability and put job 08-037 into the production schedule and then added it in the projection table as a scheduled job (in columns entitled as "Sch. Framing"). On the top of the table, we can see the overall number of scheduled jobs for each week. The table shown in Figure 4-13 was captured in the afternoon of August 21th, 2009. In the 4 weeks from the middle of July to the middle of August, the framing flow was leveled at 9-10 houses per week. Starting from the 3rd week of August, the flow level was increased to 11-12 houses per week. The number of scheduled houses in the 2nd week of September was 15, and bookings for the 3rd week had already reached 11 houses. Since the jobs that were booked in the current week (the last week of August) will also be started in the 3rd week of September, this number shall continuously go up to around 15. GC then has two weeks to increase its capacity to 15 units per week.

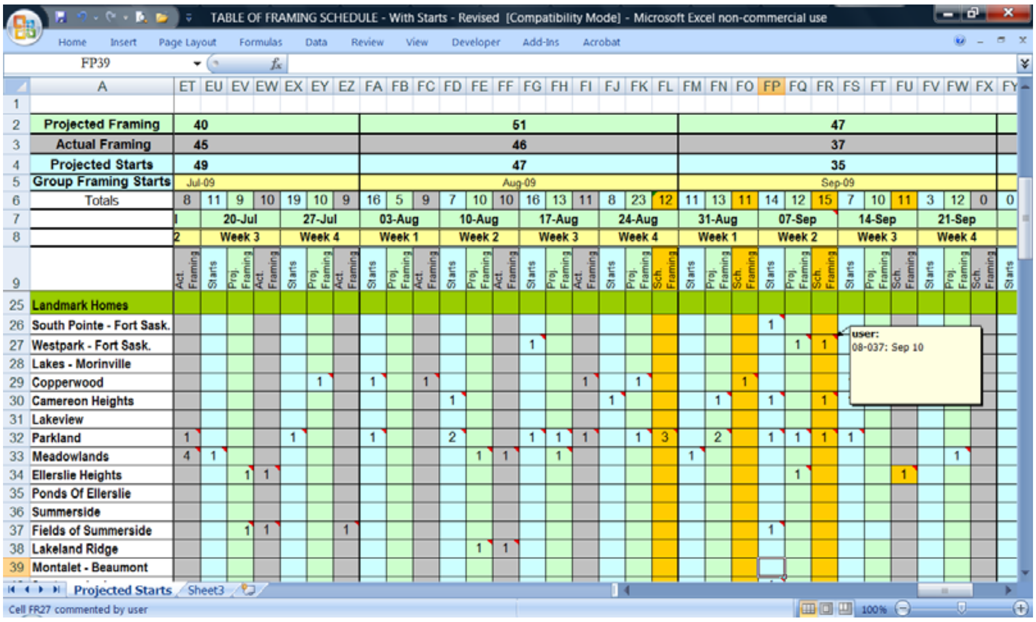


Figure 4-13: Framing Job Projection Table (LGB, August 21, 2009)

The practice of the collaboration company proved that production leveling and continuous operation flow are achievable in housing construction, even during significant market change. However, due to the unique characteristics of house construction, production leveling in the homebuilding process exhibits the following features:

- Production is leveled on the operation level, instead of the process level. There is no single takt time for the entire process, but for any given task the production flow remains stable for 3-4 weeks.
- The production is not only leveled at the beginning of the process, but also at multiple decoupling points throughout the process. Each decoupling point is a pace-maker for the tasks that are connected to it through pull flow (see Figure 4-14).
- A combined strategy of make-to-order and make-to-stock is used to overcome the fluctuation in sales. It is necessary to set a minimum flow level to maintain the stability of the core workforce.

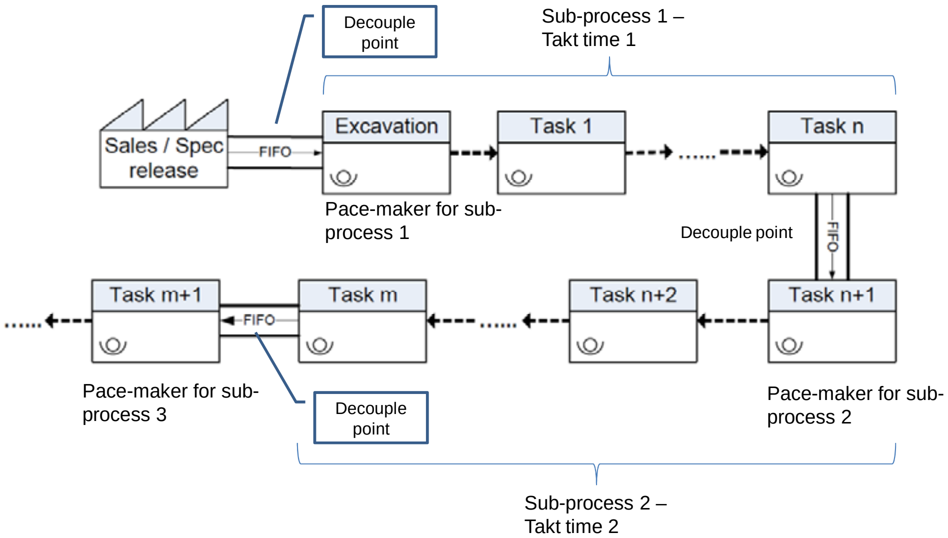


Figure 4-14: Illustrations of Multiple Point Production Leveling

4.5 LEAN IMPLEMENTATION RESULT

In the VSM sessions, each workgroup developed lean metrics for the target construction stage, and the management of the collaboration company set a goal of five-month delivery for lean implementation in the entire homebuilding process. After 18 months of lean application, Landmark Homes (Edmonton) remapped its homebuilding process in April 2009. Figure 4-15 is the new current state map for Stages 1 to 3. Compared to the current state map drawn in July 2007, the new current state shows significant improvements in terms of cycle time, process stability, waste elimination, and product quality.

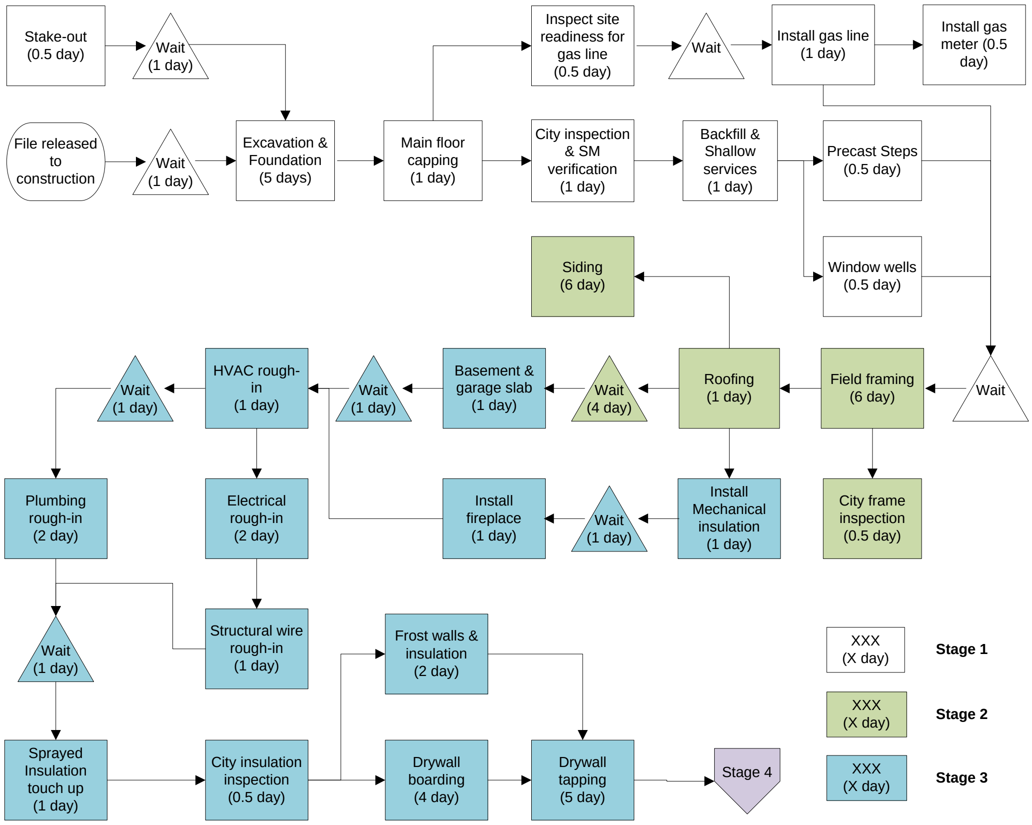


Figure 4-15: New Current State Flowchart (Stages 1 to 3, Landmark Homes)

4.5.1 Cycle Time

The first direct benefit of lean implementation is the reduction of cycle time. In March 2009, 35 houses were delivered to customers by Landmark Homes (Edmonton). The average construction cycle time of those houses was 161 days. Although it was still 11 days longer than the lean implementation goal of 150 days, compared to the construction cycle time of 25 houses delivered in July 2007, this represents a 48% improvement. Figure 4-16 shows the time series curve of construction cycle time and number of houses delivered in 25 months. There is a clear descending trend after June 2008, when jobs that entered production system after lean implementation reached possession. May 2009 was the first time that the average construction cycle time of possession houses was less than 150 days, achieving the lean implementation goal.

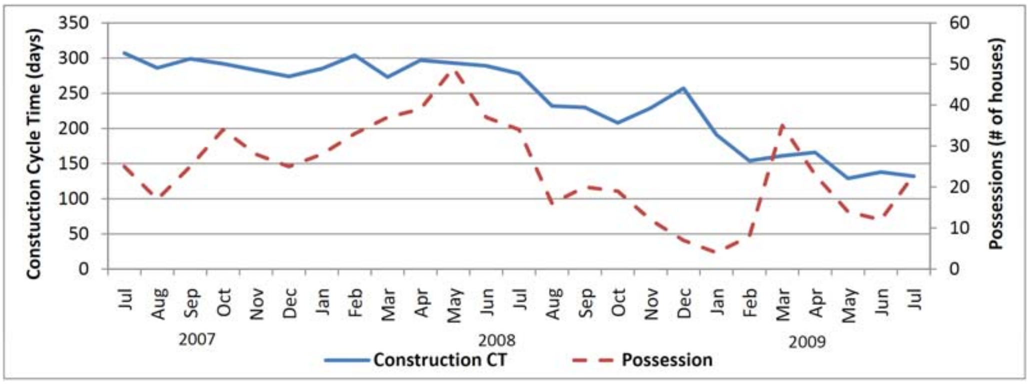


Figure 4-16: Construction Cycle Time and Possession (Landmark Homes)

Since houses generally take months from start of construction to possession, the total construction cycle time is a good indicator of overall lean improvement, but does not reflect the current cycle time situation. For example, the houses that were possessed in May 2009 were excavated in the previous November and December. Thus, stage cycle times are a better description of up-to-date lean implementation results. Table 4-2 summarizes the average stage cycle times of jobs that entered each stage in June 2009. Compared to the average cycle time of jobs that were completed in the first six month of 2007, significant improvements were seen in the cycle times of Stages 1 and 2, with some improvements in the cycle times of Stages 3 and 4. The cycle time of Stage 5, however, was five days longer than before. A study on waiting time helped explain why lean implementation had different impacts on each stage. Due to limited available data, Table 4-3 only shows the waiting time between construction tasks and does not include the waiting time during construction operation. It was common in 2006 and 2007 that a subcontractor started a construction activity, for example drywall taping, for one or two days and then stopped the work to go to other jobs, leaving the house idle for three days, and then came back to finish the job. That was a major reason why the cycle times of construction tasks were so variable at that time.

By comparing data in Tables 4-2 and 4-3, we can see that about 85% of cycle time reduction in Stage 1 comes from reducing waiting time between construction tasks. Leveled production provides a continuous workflow and predictable workload, which are the prerequisites of building a super-subcontractor.

Table 4-2: Construction Cycle Time Comparison (Landmark Homes)

		Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Average CT	Early 2007	75	31	54	42	26
	Jun-09	22	15	39	31	31
Reduction	Days	53	16	15	11	-5
	%	71%	52%	28%	26%	-19%

Table 4-3: Waiting Time between Construction Tasks (Landmark Homes)

		Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Value-Added Ratio
Waiting Time of A Typical Single-family house	Early 2007	46	1	25	11	6	53%
	Jun-09	2	0	1	3	10	82%
Reduction	Days	44	1	24	8	-4	
	%	96%	100%	96%	73%	-67%	

The improvement in the cycle time in Stage 2 was mainly the results of task cycle time reduction. Framing, roofing and siding are all long-cycle operations and can be overlapped. After a house was finished framing, the site managers checked the framing inside the house, while roofers worked on the roof and siding company delivered the material to the site. Therefore, there was no waiting time between tasks, but the cycle time of each task depended on the availability and skills of small trade crews and some idle time was hidden in the tasks. Factory-based construction and super subcontractors provide the possibility to standardize the construction process, to train crews, and to continuously improve their operation.

Stages 3 and 4 are both characterized by a large number of construction activities that do not have clear logical relationships to one another. The difference between the stages is that some major tasks in Stage 3 are long-duration tasks, such as rough-ins, drywall boarding and taping, and tasks in Stage 4 are mostly one-day jobs. Process reliability has been significantly improved after the implementation of a lean production system, and the waiting time between tasks has been almost eliminated. The one day and three days' waiting time in Stages 3 and 4 are mainly days when vacuum cleaning is taking in place. For one-day jobs, reducing task cycle time does not have an impact on overall cycle time since it is difficult to schedule jobs in terms of hours. Therefore, whether the task's cycle time is four hours or six hours or eight hours, it is counted as one day. The overall cycle time reduction of Stage 3 is less than the reduction in waiting time, because in the new standardized process there is basically no task overlap: one day with one trade crew on-site.

Stage 5 consists of a number of one-day tasks and some non-value-added activities, such as cleaning, inspections and repairs. In the old production system, the overall construction time was so long that at the end of the process, site managers and sales representatives normally pushed hard to finish the house and turn it over to the customer. On the other hand, since the house was already delivered late, customers generally moved into the house as long as it was completed. Quality problems were left to be addressed as guarantee issues. In contrast, the new process is standardized and a buffer of a few days is left between the completion of the house and key turnover date to shield possible delays and repairs of quality problems. Although the overall cycle time of Stage 5 is on average five days longer than that of two years ago, the collaboration company is able to provide tentative completion time when a customer signs the purchase agreement and the exact occupation date 45 days earlier. In fact, the collaboration company is the only homebuilder in the region that gives clear expectations on delivery time, which is extremely important for customers to make financial arrangements, to dispose of their current residence, and to prepare for occupation.

4.5.2 Process Variability

Increasing construction process reliability and predictability are the central tenets of lean construction. The implementation of LGB's lean production system not only remarkably reduced cycle time, but also reduced process variability. Table 4-4 shows a comparison of overall cycle time and its standard deviation for jobs started in February 2007 and February 2009. In two years, the house delivery time was improved by 55%, while the variability of the construction process reduced by 67%. A 19-day standard deviation allows the collaboration company to give its customers a forecast of their houses' completion dates at the time when they sign the purchase agreements with reasonable accuracy.

Table 4-4: Overall Cycle Time and Its Standard Deviation (Landmark Homes)

	# of Jobs Started	Average Total Cycle Time	Standard Deviation	Coefficient of Variation
Februray 2007	30	316	58	18%
Februray 2009	10	142	19	13%

The improvement of overall process reliability is built on efforts to increase operation consistency in every portion of the process. As shown in Table 4-5, substantial improvement on process reliability has been seen in all five stages. In a perfect lean production system, there should be no variation in stage cycle time. The production flow is leveled at the pace-maker task, and any possible delay is shielded by the FIFO lane at decoupling points. In reality, a production homebuilder usually has hundreds of houses in construction at any given time. Jobs are always running into unexpected or unavoidable events. As presented before, a carefully sized time buffer is used to shield those unforeseeable events, and those unavoidable events are dealt within a projection table. For instance, an in-fill land has no space around it to store the prefabricated roof, so the roof trusses have to be delivered after the house is erected, and the roof has to be framed on the top. This may lead to a two-day delay in framing. The expected delay will be reported by the framing subcontractor after its construction manager inspects the site, normally within one week after receiving the capping request. The projection table for the downstream tasks, for example dry-walling, will be revised and rebalanced based on the updated information. This can be done about 3-4 weeks before the actual start day of dry-walling. Although schedule adjustments mean variability, they can effectively reduce the size of the time buffer and keep the process stable and predictable.

Table 4-5: Standard Deviation of Stage Cycle Time (Landmark Homes)

		Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
Standard Deviation of CT	Early 2007	35	14	20	14	7
	Jun-09	3.7	5.2	6.8	3.1	4.0
Reduction	Days	31.3	8.8	13.2	10.9	3.0
	%	89%	63%	66%	78%	43%

It is important to find the optimal balance point of process reliability and overall cycle time reduction. While improvement in reliability increases the predictability of the process, and thus downstream subcontractors can be scheduled in advance to eliminate the waiting time between tasks, time buffers increase the overall cycle time of the process. Fundamentally, the balance point is decided by operation reliability. In lean implementation, standardized work and total quality control have reduced the variation of each construction operation to less than one day for long-duration tasks (task cycle time longer than two days) and zero for one-day tasks, so that FIFO lanes and projection tables can be used to develop a three-week production schedule and maintain PSS (Average Percent Started at Schedule) above 90%. In the second phase of the collaboration company's lean initiative, a goal has been set to reduce the standard deviation of stage cycle time to two days. Then, any variation can be completely shielded by using small time buffers between stages. The entire construction process then can be standardized on the process level, which means the production flow can be leveled once at the beginning of the process, and the house delivery date can be decided exactly at the time when customers sign the purchase agreement. This will bring tremendous advantages in cost reduction and improve customer satisfaction.

4.5.3 Quality and Customer Satisfaction

Jidoka (in-station quality) is one of two pillars of lean production. Building a culture of stopping to fix the problem and getting quality right the first time is an important lean principle. In the collaboration company's lean application, quality control systems have been developed in both the subcontracting and homebuilding companies. In Section 4.3 (Continuous Process Flow and Flow Reliability), the impact of standardized work and training on quality improvement has already been discussed. This section will focus on the result of the homebuilder's efforts.

Figures 4-17 and 4-18 are the quality tracking reports of houses that were occupied by customers in June 2008 and June 2009. In the report, "Ave # of Def" refers to the total number of defects that were identified in the construction process. "Ave # of Def Left" is the number of defects that subcontractors failed to repair within 48 hours. Three days before pre-occupation orientation, site managers checked the quality of the house, which is called "Qty Review." The defects found in the pre-occupation orientation are counted in the "Ave # of PreOcc Def," and defects found at and after possession are counted in the group of "Possession Def."

Quality Tracking Report

Possession Date From: 6/1/2008 12 Possession Date To: 6/30/2008 Run Report

Possession Jobs	Site Manager	Ave # of Def	Ave # of Def Left	Ave # of Qty Review Def	Ave # of PreOcc Def	Ave # of Possn Def
37	[redacted]	33.16	1.03	12.86	1.86	11.22
1	[redacted]	2.00	0	0	0	0
2	[redacted]	29.50	1.00	21.50	0	2.00
3	[redacted]	7.67	0	3.67	0	2.33
4	[redacted]	15.75	1.00	0.75	10.50	5.00
1	[redacted]	42.00	2.00	11.00	0	6.00
3	[redacted]	23.00	7.00	5.67	0	8.67
6	[redacted]	34.50	0	14.50	0	12.67
2	[redacted]	113.00	1.50	68.00	0	13.50
1	[redacted]	15.00	0	15.00	0	15.00
6	[redacted]	49.67	0.67	19.33	4.17	15.17
7	[redacted]	28.14	0.14	5.29	0.29	17.57
1	[redacted]	26.00	1.00	0	0	20.00

Figure 4-17: Quality Tracking Report (Landmark Homes, June 2008)

Quality Tracking Report

Possession Date From: 6/1/2009 12 Possession Date To: 6/30/2009 Run Report

Possession Jobs	Site Manager	Ave # of Def	Ave # of Def Left	Ave # of Qty Review Def	Ave # of PreOcc Def	Ave # of Possn Def
12	[redacted]	82.75	2.08	32.83	12.83	2.92
4	[redacted]	25.50	0.50	2.00	8.25	0.50
2	[redacted]	89.50	1.00	46.00	11.00	1.00
1	[redacted]	139.00	5.00	25.00	19.00	5.00
5	[redacted]	114.60	3.20	53.80	16.00	5.20

Figure 4-18: Quality Tracking Report (Landmark Homes, June 2009)

Comparing the two reports, it is interesting to find that in Figure 4-17 the numbers in the column of "Ave # of Def" varied substantially and were much less than those in Figure 4-18. This does not mean that the operation quality in 2008 was much higher than that in 2009, but that site managers did not follow standards to check construction quality. In fact, before October 2008 when the revised quality standard was issued, there was no clear instruction on when and how the defects should be recorded. Figure 4-19 shows an example of deficiency records for a job completed in June 2008. Based on the revised standards, there were two obvious problems in this quality detail report. First, there was no record of the deficiencies found during the construction process. Although the "Deficiency Type" of the first two items was assigned as construction, all records were inserted after possession. Second, the record was not specific. For instance, the second item in the report is "Paint touch up required" on "Cabinets." But it did not specify location and how many points. In the new standard, every point of paint touch-up needs to be specified in the report and counted as a defect. That means if five points on cabinets require painting touch-up, there should be five deficiency records and each should be counted in quality tracking reports separately.

Job	Address	Subdivision	Possession	Category	Deficiency	Insert Date	Completion Date	Deficiency Type
1-07-115	4055 Crowsnest Crescent	Lakeland Ridge	6/23/2008 12:00:00 AM	Cabinets	drawer at the left side of the sink to be fixed	6/24/2008 10:35:53 AM	7/4/2008 12:00:00 AM	Construction
1-07-115	4055 Crowsnest Crescent	Lakeland Ridge	6/23/2008 12:00:00 AM	Cabinets	Paint touch up required	6/24/2008 10:37:05 AM	7/4/2008 12:00:00 AM	Construction
1-07-115	4055 Crowsnest Crescent	Lakeland Ridge	6/23/2008 12:00:00 AM	Lighting	The glass of thr exterior light in the back yard to be replaced	6/24/2008 9:56:00 AM	7/1/2008 12:00:00 AM	Pre-Occ
1-07-115	4055 Crowsnest Crescent	Lakeland Ridge	6/23/2008 12:00:00 AM	Lighting	The light fixtures at both sides of the fireplace to be re-selectted by the customer(no more spare in the store of Park lighting)	6/24/2008 9:57:43 AM		Pre-Occ
1-07-115	4055 Crowsnest Crescent	Lakeland Ridge	6/23/2008 12:00:00	Windows/Doors	The chips in the exterior windows (from	6/24/2008 10:00:10 AM	8/8/2008 12:00:00	Pre-Occ

Figure 4-19: Example of Quality Deficiency Records (Landmark Homes)

Improved operation quality and tighter quality inspection standards resulted in higher quality of final products. The average number of deficiencies found in possessed homes has been significantly reduced from 11.2 in June 2008 to 2.9 in June 2009. As a combined effect of shorter cycle time and higher product quality, customers' satisfaction level increased in the past 12 months, as shown in Figure 4-20. From the chart, a clear correlation can be identified between the average number of deficiencies in possessed homes and the customers' satisfaction rating. Since Figure 4-20 is based on a 30-day move-in loyalty survey designed to capture feedback from home owners who possessed houses in the previous month, the AVID curve lags behind the quality curve by one month.

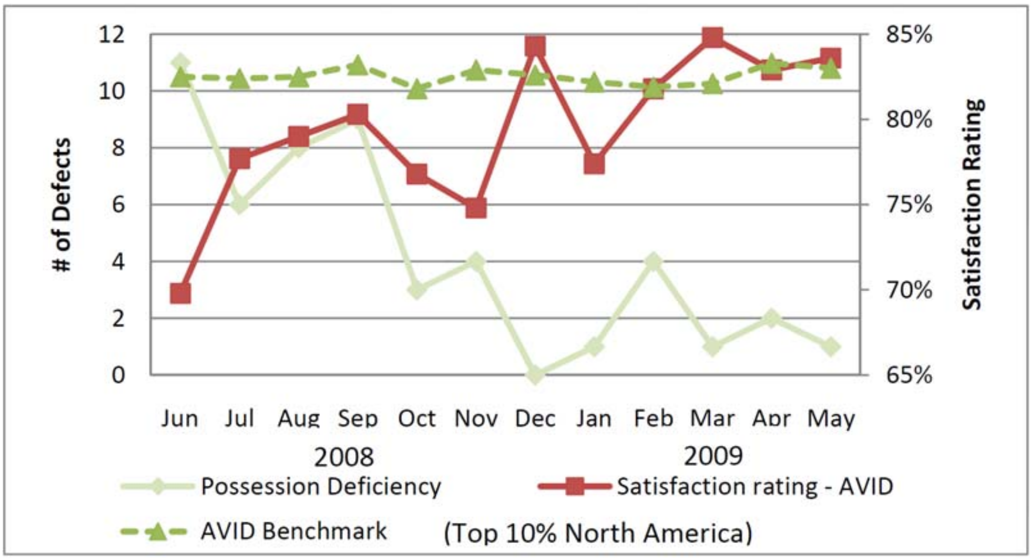


Figure 4-20: Quality and AVID Customer Satisfaction Survey (Landmark Homes)

AVID Ratings are a professional, third-party survey to assess homebuyers' satisfaction with homebuilders' service. As the biggest service provider in the customer loyalty management field, AVID Ratings Co. provides service for more than 400 builders in North America and conducts over 350,000 homebuyer surveys each year. Based on survey data, AVID publishes the average rating of the top 10% of homebuilders in North America. This allows its customers to benchmark their organization with industry leaders. Before February 2009, the ratings of Landmark Homes were lower than the industry benchmark, but now the company has entered the top 10% and consistently has ratings above 80%.

4.6 CONTINUOUS IMPROVEMENT

Phase I of the lean implementation in the collaboration company was 18 months and ended in February 2009. As discussed above, the lean implementation had achieved great success, and the management team of the collaboration company decided to commence Phase II immediately. In March and April, 2009 a series of VSM sessions were organized to map the new current state of the homebuilding process and formulate the future state map. The lean improvement goal for the next 18 months was to reduce the overall construction cycle time from 150 days (five-month delivery) to 90 days (three-month delivery). Table 4-6 summarizes the improvement objectives of each stage.

Table 4-6: Lean Improvement Objectives (Landmark Homes 2009)

		Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Total
Current State	Cycle Time	22	15	39	31	31	138
	Standard Deviation	3.7	5.2	6.8	3.1	4.0	
Lean Improvement Goal	Cycle Time	14	8	25	14	29	90
	Standard Deviation	2.0	2.0	2.0	2.0	2.0	

In order to achieve the lean objectives, the following seven issues were identified in the VSM sessions as key kaizen elements:

1) Reducing foundation cycle time so a house can be backfilled in 2½ workdays. Precast concrete foundation system is considered as a promising technique to achieve this goal.
2) Integrating more construction work to a factory-based production system to reduce site construction cycle. Possible moves include:
   - Use sprayed foam to replace fiberglass batt insulation and install insulation in the plant;
   - Install roof shingles on the ground;
   - Prefabricate shingled roof in the factory;
   - Develop a panelized roof system;
   - Pre-install electrical panels at the plant;
   - Standardize HVAC, electrical and plumbing design, so all openings can be pre-cut at the plant.
3) Increasing operation reliability so that time buffers between stages can be eliminated and short-duration tasks can be scheduled in hours. As shown in Figure 4-21, the key point of cycle time reduction in the finishing and final stages is to schedule more than one construction operation in one day. This requires 100% PSS and consistent operation performance.
4) Educating and helping subcontractors establish in-station quality control systems so they can take full responsibility of their work quality and protect surrounding works. Homebuilder's site managers will only do spot checks during construction, and all quality steps will be eliminated from the process.

5) Developing a super-subcontractor for electrical and structural wiring operations and encouraging the formation of large crews.
6) Establishing an in-house cleaning team. All the cleaning works will be performed on work days – with no separate days dedicated for vacuuming.
7) Cultivating a lean culture of stopping to fix the problem to continuously improve the working process.

Figure 4-21: Future State Flowchart (Three-Month Delivery)

In June 2009, the management of the collaboration company published its long-term view of the homebuilding process (Figure 4-22). The design originated from the practice of a Japanese industrialized housing producer (Barlow et al. 2003), but was modified to suit the market situation in North America. The process starts when a customer selects a basic model and makes decisions on the level of specification, exterior color and internal fit-outs (Figure, #1). This is an interactive process consisting of several sessions in a showhome and in the design center. The final product is visualized to the customer via design catalogues, material samples and 3D animation. Once the purchase contract is signed, all customer selections are compiled into a job file package and sent to drafting and estimating departments for drawings and purchase orders (PO) preparation (#2). Meanwhile, the construction division is informed to generate a job schedule and level the flow. Then the drawings, POs and job schedule are sent to the production division (#3) and subcontractors (#4) who are responsible for providing all the resources and workforces required for completing the assigned construction tasks on-site. The production division orders the job-specific materials (#5), such as roof trusses, windows, doors and stairs, and puts the job into a production schedule (#6). A three-week lead time and a two-day flexibility on erection date are required by the production division to ensure material availability and to level the production flow. Common materials, like lumber, OSB, joists, engineering beams, insulation and drywall, are controlled by the kanban system. Suppliers replenish the material inventory in the prefabrication shop based on production kanbans (#7). Building components, including precast concrete foundation panels, floor panels and wall panels, are delivered to the site. The delivery is synchronized with the crane and field erection crew (#8). All divisions and sub-contractors consistently adjust their capacity and resource allocation based on the company's forecast and strategic planning (#9).

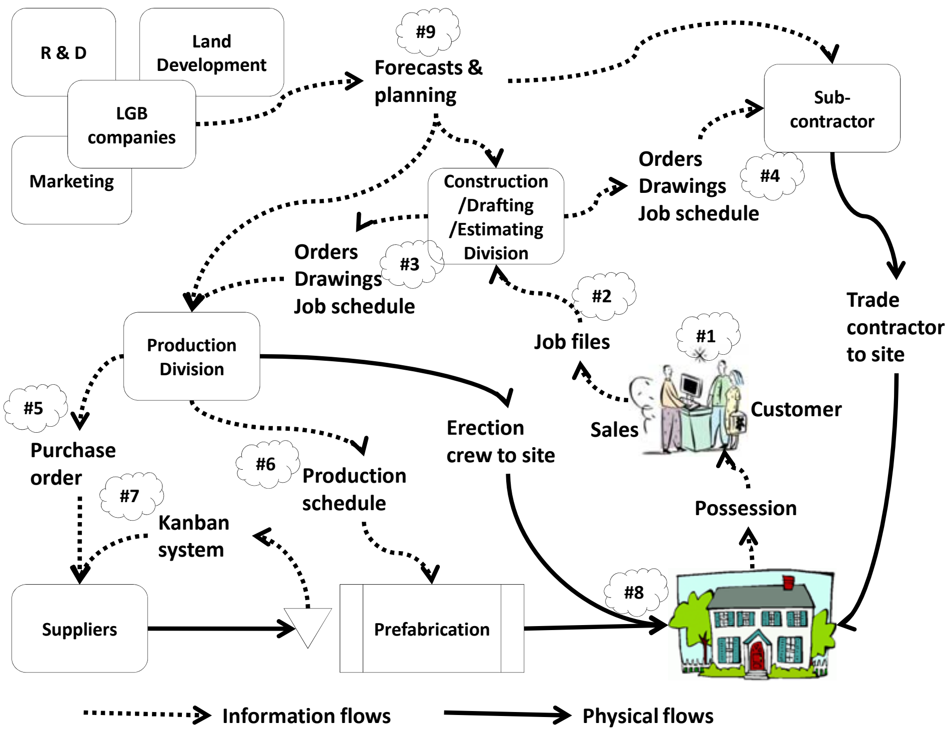


Figure 4-22: LGB's Homebuilding Process

A few strategic moves have already been in the planning stage, including:

1) cooperation with a leading precast company in the region to produce precast foundation panels;
2) the construction of an 85,000 sq.ft. facility to roof an automatic closed wall panel production system that has the capacity of producing panels for four houses per day, and
3) a research project with the University of Alberta using building information system (BIM) to link the entire homebuilding process, from house model development, to sales, to production, to site construction, to service.

CHAPTER 5 – PANELIZED CONSTRUCTION METHOD

5.1 PANELIZED CONSTRUCTION AND LEAN PRODUCTION

There are various types of uncertainty causing high variation in the construction production flow. Ballard and Howell (1998) summarized six high uncertainty areas in construction project delivery: (1) project objectives; (2) the means for achieving those objectives; (3) production rate; (4) availability of labour and materials; (5) delivery of drawings, specifications and other information; and (6) schedule (upstream task may not finish on schedule). In practice, these various types of uncertainty are interdependent. For example, uncertainty in labour availability is higher when the schedule is often delayed. The trade contractor cannot be sure whether there is a work available for a given time slot, and consequently overbooks its capacity to ensure continuous workflow. This may lead to more schedule delays and changes in the construction method, i.e. installation sequences, durations, costs, etc.

Since the uncertainty in the current construction process is virtually uncontrollable, the flexibility strategy, i.e. mobilizing resources to do whatever work that can be done, becomes the most common strategy in construction management. Some developed lean construction tools, represented by Last Planner System (Ballard 2000) and even flow production (Bashford et al. 2003), aim at improving schedule reliability by making quality assignments and using buffers to shield downstream operations from possible upstream delays. Shield production is an alternative strategy in conditions of work flow uncertainty (Ballard and Howell 1998b), but it does not eliminate the root cause of uncertainty. Obvious waste still widely exist in the process, although they are much less comparing to those in projects using the traditional management approach. The job has to wait until all prerequisites of the task, including information, materials, labour, equipment, upstream task, etc., are ready. In order to accommodate variability, the assignments have to be less than the estimated capacity of production units (it is called sizing in Last Planner).

Another approach to reducing construction uncertainty is to turn building into a product that can be manufactured in factory, where permanent workers are working in controlled environment and process management systems like lean production are applicable. For modular houses, 60-70% of their value is produced in factory. Most construction tasks, including structural and envelope works, wiring, plumbing, finishing and terminations (TV and telephone outlets), are performed in factory on a production line. Site assembly of units can be completed in one day, plus another 30 days for on-site finishing and connections to services (NAHB 1998). While modular construction has clear advantages in terms of construction time, quality and process stability, it has the following inherent shortcomings inhibiting its popularity:

- Relatively high cost. Due to high facility, transportation, lifting equipment and overhead costs, a modular home is generally 15-20% more expensive than its conventional counterpart. For example, the house sale price of Sekisui Heim, the largest modular manufacturer in the world, is about 16% higher than that of a similar wood frame house built on-site (Barlow et al. 2003).
- Limited customer selection. Standardization is the prerequisite for establishing economy of scale, which is one of the greatest advantages of factory production. Moreover, transportation restrictions constrain the configuration of house models.
- Large capital investment. Large initial investment in modular factories makes the entry threshold to modular construction high. In 1987, Toyota Homes spent $120 million to build one of its housing factories (Gann 1996).

Manufactured housing is a special type of modular housing, where homes are built under U.S. Manufactured Home Construction and Safety Standards (HUD-Code). In the mid-1990s, manufactured homes swept the low end of the U.S. housing market and reached a peak of approximately 20% of the market share (ratio of manufactured houses shipments to overall single-family home starts), but in the past decade this number has dropped substantially. In 2005, only 8% of new single-family house starts in the U.S. were manufactured housing. The industry needs a product/production system that allows a large variety of homes to be built in standard ways and standard components (Crowley 1998).

Compared to modular housing, the panelized homebuilding system, where the building is subdivided into basic planar elements that are prefabricated in factory and are then shipped directly to the construction site and assembled into the finished structure, provides high flexibility. Since the house is assembled with relatively small components, panelized homes can be built for any plan or architectural design with minimal additional costs.

Although the factory work generally represents only 15-30% of the value of a panelized house, it provides a completed building envelope. Therefore, the downstream construction activities can be carried in a controlled, indoor environment, and the impact of bad weather and poor site conditions are minimized. In addition, factory-based production allows direct application of lean production tools, such as takt time planning, standardized work, in-station-quality, and Heijunka box, to improve workflow reliability. The relatively fixed capacity of a factory also forces homebuilders to level their production flow, which significantly reduces buffer size while keeping the reliability of work flow.

In 2000, the Partnership for Advanced Technology in Housing (PATH) identified Advanced Panelized Systems as one of three high priority areas for roadmap development (NAHB 2000b). Since then, a series of research projects have been carried out in the areas of building panel design (NAHB 2002c) and standards development (Steven Winter Associates 2004). The objective of those research efforts is to develop adaptable, standardized, multiple-use panelized housing systems and create a more effective and efficient production, delivery, and site assembly process (NAHB 2002b). A few large mainstream homebuilders have also expressed strong interest in panelized construction. According to Sawyer's report (Sawyer 2006), Pulte Homes, the largest homebuilder in the U.S., has built a plant in Manassas, Virginia, to produce basement/foundation wall panels, structural floors and panelized interior and exterior walls. The production is on a house-by-house basis; each house in the line is allowed to vary from others as long as the design units, such as web depth and framing centers, meet Pulte's standard. Then all of the components for each house, complete with installed windows, are shipped to the site at the date designated by the construction schedule. Once on-site, the houses can be assembled from foundation to dried-in within one week.

Although more and more homebuilders, particularly production homebuilders, are recognizing that the old stick-by-stick approach might not be the most effective homebuilding method and that advanced technologies such as the panelized building system have exhibited clear advantages in terms of construction time and process controllability (PBSC 2009), the North American homebuilding industry is still dominated by on-site construction. Skilled tradesmen and general laborers sequentially fabricate and assemble materials and products on building lots. Panelized home producers are generally stand-alone practices, not integrated into the mainstream of the homebuilder industry. On the other hand, homebuilders are skeptical on basing the center of their construction process on an independent panel supplier and reluctant to pay premium for a technique that they are not familiar with. To some extent, their caution is right. Without fully integrating the panelized method to the homebuilding process and thereby improving the reliability of the entire construction process, the advantages of panelized construction are very limited. In other words, the high direct costs of panelized construction can only be justified when the implementation of a lean production system makes the process stable and reliable, reducing cycle time and costs.

In the lean production system of the collaboration company, panelized construction was an indispensible element, not only because it had the potential to significantly reduce field construction time of foundation and house envelope, but also because it led to a reliable process that would maintain the leveled and continuous production flow to downstream construction activities and establish a platform for further process integration. The collaboration company has already integrated insulation into prefabricated wall panels, and electrical and structural wiring, plumbing, drywall, drywall taping and priming will be conducted in the new prefabrication facility that is under construction and expected to be put into production in 2011. This chapter introduces the collaboration company's major efforts in prefabricated housing. Its initiatives consist of two subsystems: the Precast Concrete Foundation (PCF) system and Wood Frame Structural Panels (WFSP).

5.2 PRECAST CONCRETE FOUNDATION PANEL SYSTEM

The use of precast concrete in residential construction is not a new idea. Zielinska and Zielinski (1982) proposed a ribbed panel system for precast concrete homes, and Hurd (1986) introduced an insulated PCF system that is still used by some PCF manufacturers today. In the 1990s, a few precast concrete housing projects generated considerable attention and proved that precast concrete is viable and cost-effective for residential construction (Hurd 1994; Einea et al. 1994; Von Der Ahe et al. 1999).

Despite all of these initiatives, however, the homebuilding industry persists in its perception of precast concrete designs as costly, lacking in flexibility and restrictive to remodeling (Holmes et al. 2005). Currently, two major commercial PCF panel systems in North American residential construction market, Superior Walls® (Superior Wall of America Ltd. 2008) and Thermal-Krete® (Kistner Concrete Products Inc. 2007), contribute to just 2% of new home foundations in the U.S. The barriers that impede the PCF system from achieving a greater market share include the following:

- The technology is available only from a few PCF panel manufacturers; homebuilders can purchase their products only from a few franchises. As PCF panels are bulky and heavy, transportation is costly. The economical range for delivery radius of a PCF plant is about 200 km. Although a limited distribution of products may serve some individual manufacturers well, it tends to restrict the dissemination of the technology.
- The existing PCF systems target builders in temperate regions and are not easily installed in winter conditions (i.e. when the temperature falls below –10ºC). For homebuilders in northern regions such as Edmonton, where the winter season accounts for four months of the year, the present PCF designs are not adoptable.
- The cost of the current PCF systems is less favorable than conventional cast-in-place systems and is highly variable between regions and manufacturers.

In Canada, PCF panels have also interested some Canadian researchers and homebuilders. Hanna and Zeliniski (2002) proposed a conceptual PCF system in 2002. However, the regional differences and barriers previously mentioned have make homebuilders skeptical. To date, there are over 30 major precast concrete manufacturers in Canada. Their products include architectural panels, structural columns, beams and joists, hollow-core and solid slabs, and piles, yet no reported PCF system is produced and used in Canada for residential construction (CPCI 2009).

The PCF system research project was initiated by the University of Alberta and LGB in April 2005. After a feasibility study, two leading construction material suppliers and precast concrete producers, Lehigh Inland Cement Ltd. and Lafarge Canada Inc., joined the project at the end of 2005. In April 2006, the research was approved by NSERC as a Collaborative Research and Development (CRD) grants project. The goal of the project was to develop an easy-to-adopt PCF system that is cost-competitive, flexible and weather-independent. Two systems have been developed and experimented within the last three years: a ribbed panel system with exterior insulation and a sandwich panel system.

5.2.1 Ribbed Panel with Exterior Insulation (Yu et al. 2008b)

A typical foundation system in residential construction consists of footings, foundation walls and a basement slab. No matter what foundation system is adopted, it must meet the following functional performance requirements:

- Transfer the load of the building to the earth.
- Prevent differential settlement.
- Resist shear and bending stresses resulting from lateral soil pressure.
- Provide anchorage for the above-grade structure to resist wind or seismic forces.
- Provide a moisture-resistant barrier for the below-ground structure in accordance with the building code.

In the PCF design, some other issues need to be addressed as well. Residential construction is characterized by high variety, small-scale and a strictly controlled budget. Cost-effectiveness and flexibility are key for a PCF system to be successful. The greatest challenge in PCF design is, therefore, to identify the optimal design that not only satisfies design functions, but also achieves the minimum production and installation costs and provides maximum flexibility. Specifically, the design must meet the following requirements:

- The panel design should accommodate a variety of different house plans at no additional cost.
- The shape of the panel should be easy to cast and be efficient in material usage.
- Connections between panels and between panel and footing shall be simple and easy to install.
- The erection can be performed under tough site conditions, such as unlevel surface of footing, cold weather (-25ºC), lack of power supply, etc.
- PCF system must be cost-competitive with conventional cast-in-place (CIP) concrete foundation.

Ribbed Panel System Design

Precast concrete thin-wall ribbed panels are structurally efficient building elements, and have been used in industrial and commercial buildings for some time (Zielinki et al. 1983). Most existing PCF producers, including Superior Walls®, Thermal-Krete® and Pulte Homes™, use thin-wall ribbed structure for their wall panels. Based on similar consideration, the researchers proposed a PCF system that consists of ribbed wall panels, a hollow-core garage floor and precast driveway/sidewalk, as shown in Figure 5-1.

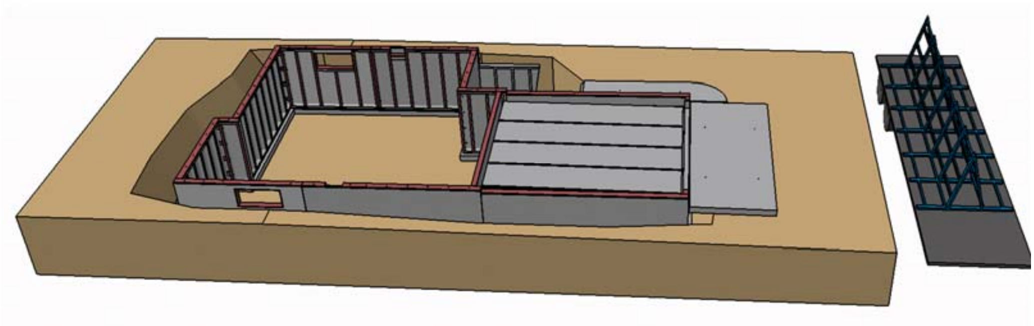


Figure 5-1: Ribbed Panel System for a Single-Family House

The engineering design of the exterior wall panels takes into account the combined effect of axial and lateral loads. In accordance with the Alberta Building Code (BTC and SCC 1997), the following load combination is used:

$$1.25D + 1.5L + 1.5H$$

where D = dead load; L = live load due to static or inertia forces arising from intended use and occupancy, snow, ice and rain; and H = lateral load due to earth and hydrostatic pressure. To simplify the analysis, the basement wall was considered as one-way T-shaped slabs, spanning from the footing to the main floor at the top. The bearing capacity of the PCF panels is calculated following the moment magnifier method of the Residential Structural Design Guide: 2000 edition (NAHB 2000c). As shown in Figure 5-2, a typical exterior wall panel consists of a 51 mm (2 in.) thick face shell, 76 mm (3 in.) thick top and bottom bond beams, and 126 mm (5 in.) deep studs spaced at 610 mm (24 in.) on centre. The studs are 76 mm (3 in.) wide, with a 25 mm (1 in.) thick treaded wood nailer attached to the inside edge, so that drywall or other finishing can be installed directly on the panel. In this design, a 200 mm (8 in.) thick wall panel has the bearing capacity of 105 kN/m (7200 lb/ft) factored axial load (uniform house weight); whereas maximum factored point loads can be up to 100 kN (22,000 lb). As the total factored axial load on foundation walls for light-frame houses typically falls below 44 kN/m (3000 lb/ft), the PCF panels can be used for all of the models without any additional structural design.

Insulation of 76 mm (3 in.) thick expanded polystyrene (EPS) board is attached outside the panel and establishes a total thermal resistance of 2.25 $m^2 \cdot °C/W$ (R value of 13). Additional insulation, as thick as 152 mm (6 in.), can be added inside, between the studs, to meet the homeowner's specific thermal performance requirements. In the design, the maximum length of the PCF wall panels is limited to 6.1 m (20 ft.), so that the maximum weight of a PCF wall panel is 3200 kg. All panels needed for a single-family house can be delivered by a flatbed trailer and be installed using a 30-ton crane.

A 52 mm (2 in.) thick sill plate is cast on the top of the upper bond beam for main floor connection. 32 mm (1¼ in.) holes are preformed through the top beam for wiring and plumbing. Wall panels are cast using 34,500 kPa (5000 psi) fiber-reinforced concrete and are fully engaged as 200 mm (8 in.) thick solid concrete wall, but with a 40% reduction in concrete. In addition, as the concrete is reinforced with fiber and has low water/cement ratio, cracking is effectively prevented, making panels inherently moisture resistant. Therefore, external water/damp proofing is not necessary for PCF panels.

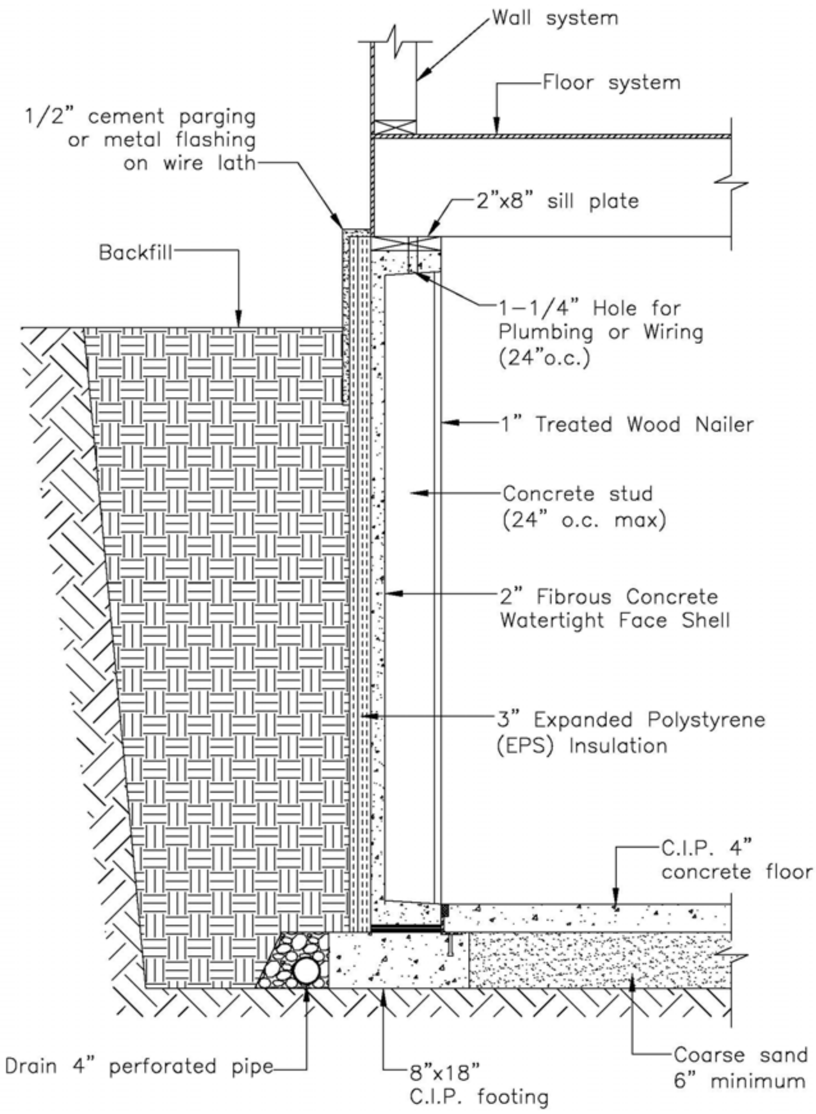


Figure 5-2: Typical Section of Basement Exterior Walls

Besides the 200 mm (8 in.) thick standard wall panels, the proposed PCF system also includes two 300 mm (12in) -thick panels to support both the garage slab and the above-grade garage walls. These panels have a similar structure to standard wall panels, but the depth of studs is 230 mm (9 in.). Considering the possible settlement of backfill, threaded inserts are imbedded in the panel to receive steel angles that provide a ledge for the precast driveway panel (Figure 5-3). The precast concrete brackets that support the sidewalk are also installed on garage basement wall panels.

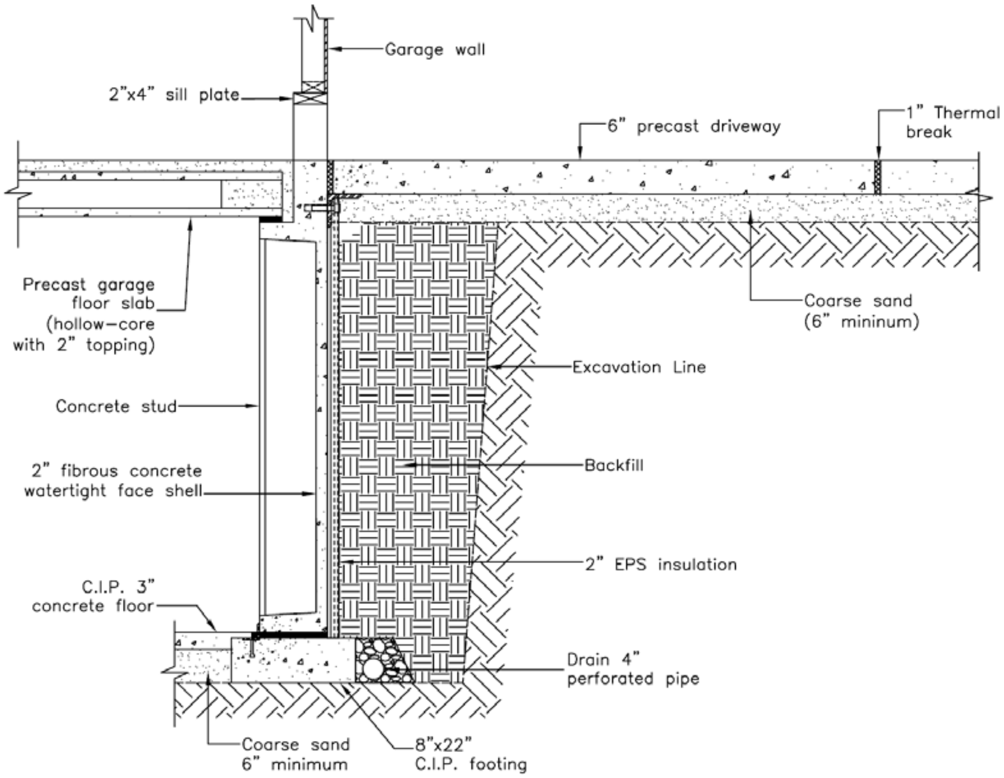


Figure 5-3: Section of Garage Foundation Panels

The garage floor spans about 6 m (20 ft.) and must be water-resistant. Prestressed hollow-cores with a 50 mm (2 in.) topping are a simple standard solution that provides advantages in deflection control, duration and speed of erection. Homebuilders can purchase 200 mm (8 in.) hollow-core from any precast concrete manufacturer, and CIP concrete coating can be poured later along with the basement slab. The other two elements of the PCF design – precast driveway and sidewalk – are optional, and are mainly for winter construction. They are flat panels reinforced with welded wire fabric at the bottom.

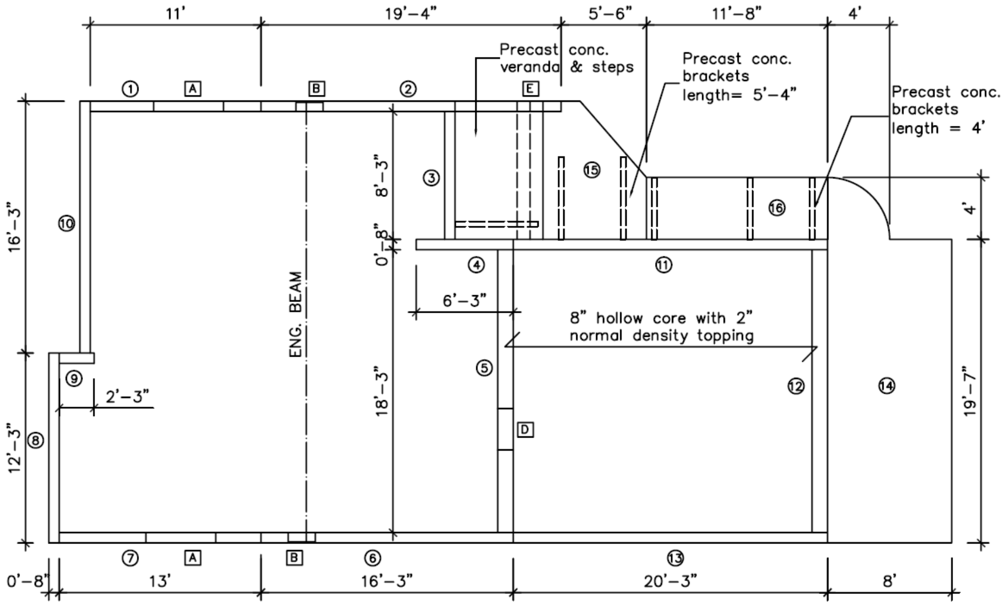
Innovative Features of the Design

The structural design of the proposed ribbed thin wall system is similar to existing PCF systems, but in order to meet the requirements in economics, flexibility and cold weather conditions, it has some unique features, such as a modularized rib design, external insulation, and simplified bolted connections.

The objective of the modularized rib design is to reduce the manufacturing cost through standardization. One of the reasons for the high production cost of present

PCF systems is the low volume and high variety of products. For example, Figure 5-4 shows a typical PCF system for a single-family house. There are 16 elements in the system, but 15 elements are one-of-a-kind. If the precast panel fabricator must customize moulds for every panel, it would be cost-prohibitive. In order to reduce costs of complex forms needed to cast varied cavities, the dimensional coordination concept was used at the design stage (Adams and Bradley 1945) to coordinate the sizes of PCF panels with the layout and design of houses. As a result, all PCF panels can be designed with consistent stud spacing. This means that the forms of panels can be assembled using one or two types of standard cavity moulds and regular side forms. It is difficult for commercial PCF manufacturers to use this method, but since the proposed PCF system is developed by the collaboration company, a homebuilder, the trial project was redesigned on a modular basis. The standard stud spacing is 610 mm (24 in.) and can be adjusted by 200 mm (8 in.) using different corner configurations. Thus, the overall dimension adjustment in the house plan is less than 100 mm (4 in.) for each side of the house. These few minor adjustments had no impact on the function of the house but significantly reduced the manufacturing cost.

The connection design was another focus of PCF system development. Connections bring continuity to the foundation walls, transferring loads from one unit to another, and resisting uneven settlement. They need to be designed for economy, high strength, durability, rapid erection and high tolerance. Standard configuration and hardware can reduce the variety of materials and thus simplify the construction. A typical PCF system for a single-family house, like the one shown in Figure 5-4, includes 14 wall panel connections in 7 different settings. In the PCF design, these connections were grouped into three categories. At 270° inside corners or 180° in-line connections, panels were directly bolted through holes preformed in the panels, as shown in Figure 5-5a and Figure 5-5c. At 90° outside corners, the main connection devices were steel angles with slots (Figure 5-5b). When two panels were erected to form a 90° corner, they were bolted via the connection angles (Figure 5-5d). A butt joint could be seen as the combination of a 90° outside corner and a 180° in-line connection. Two in-line panels were bolted directly and the perpendicular panel was connected with steel angles (Figure 5-5e). The standardized connection design effectively simplified the installation, whereby two sizes of connection angels and three sizes of bolts could meet all the requirements. The connection between the panels and footing consisted of steel angles anchored into footing and laminated fabric bearing pads underneath the panel, as shown in Figure 5-5f. After pouring the footing concrete, steel angles were installed based on the layout of the basement wall to provide horizontal support to the bottom of the panel. During panel erection, bearing pads were used to level the panels. This type of connection provided ample adjustment allowance for footing elevation variation and avoids fallible pre-embedding.



Panel Number	Description: Type		Thickness	Length
1	B.E.W.	A	8"	11'–0"
2	B.E.W.	B & E	8"	19'–4"
3	B.E.W.		8"	8'–3"
4	B.E.W.		8"	6'–3"
5	B.G.W.	D	12"	18'–3"
6	B.E.W.	B	8"	16'–3"
7	B.E.W.	A	8"	13'–0"
8	B.E.W.		8"	12'–3"
9	B.E.W.		8"	2'–3"
10	B.E.W.		8"	16'–3"
11	G.S.W		8"	20'–3"
12	G.F.W.		12"	18'–3"
13	G.S.W		8"	19'–6"
14	Driveway		6"	23'–7"
15	Walkway		4"	6'–10"
16	Walkway		4"	11'–8"

A = Window, B = Beam Pocket, E = Extension Wall
D = Door, B.E.W. = Basement Exterior Wall
G.S.W. = Garage Side Wal, G.F.W. = Garage Front Walll

Drawing Summary

9 8' height basement exterior wall (B.E.W.) panels
1 8' height basement garage wall (B.G.W.) panel
2 7'–8.5" height Garage Side Wall (G.S.W.) panels
1 7'–8.5" height Garage Front Wall (G.F.W.) panel
1 drivewall panel, width see architecture dwg., but no larger than 8'.
1 9' wide walkway panel
1 4' wide walkway panel

Total: 16 precast concrete panels

2 beam pockets, 6"(w) x 11–7/8" (h) x 21" (l)
2 windows, 54"(w) x 24" (h)
1 door (D), 32"(w) x 67" (h)

Figure 5-4: Plan of a PCF System for a Typical Single-Family House

In contrast to conventional practice and existing PCF systems, insulation of the proposed PCF system was installed outside the panels. This configuration was chosen based on the research result that insulation applied on the exterior of the basement foundation could achieve similar thermal performance to the interior one (Swinton et al. 1999). Furthermore, to attach insulation on a flat exterior surface was easier than to fit it into the cavities and around the studs and bond beams, and continuous uniform insulation can effectively avoid thermal bridges that are inevitable at the stud positions in present frost wall insulation systems. Research shows that even if the area of the thermal bridge accounts for 2% of the surface area, the overall loss of insulation efficiency can be up to 40%. In addition, the exterior insulation helps to decrease water leakage and moisture intrusion. On one hand, it serves as the first line of water defense, supplying a continuous means of managing water from the ground surface down to the gravel and drainpipe at the footing and providing a capillary break against moisture intrusion. On the other hand, it protects the concrete panels from the freeze-thaw cycle in extreme climates, which is one of the main causes of basement concrete cracking.

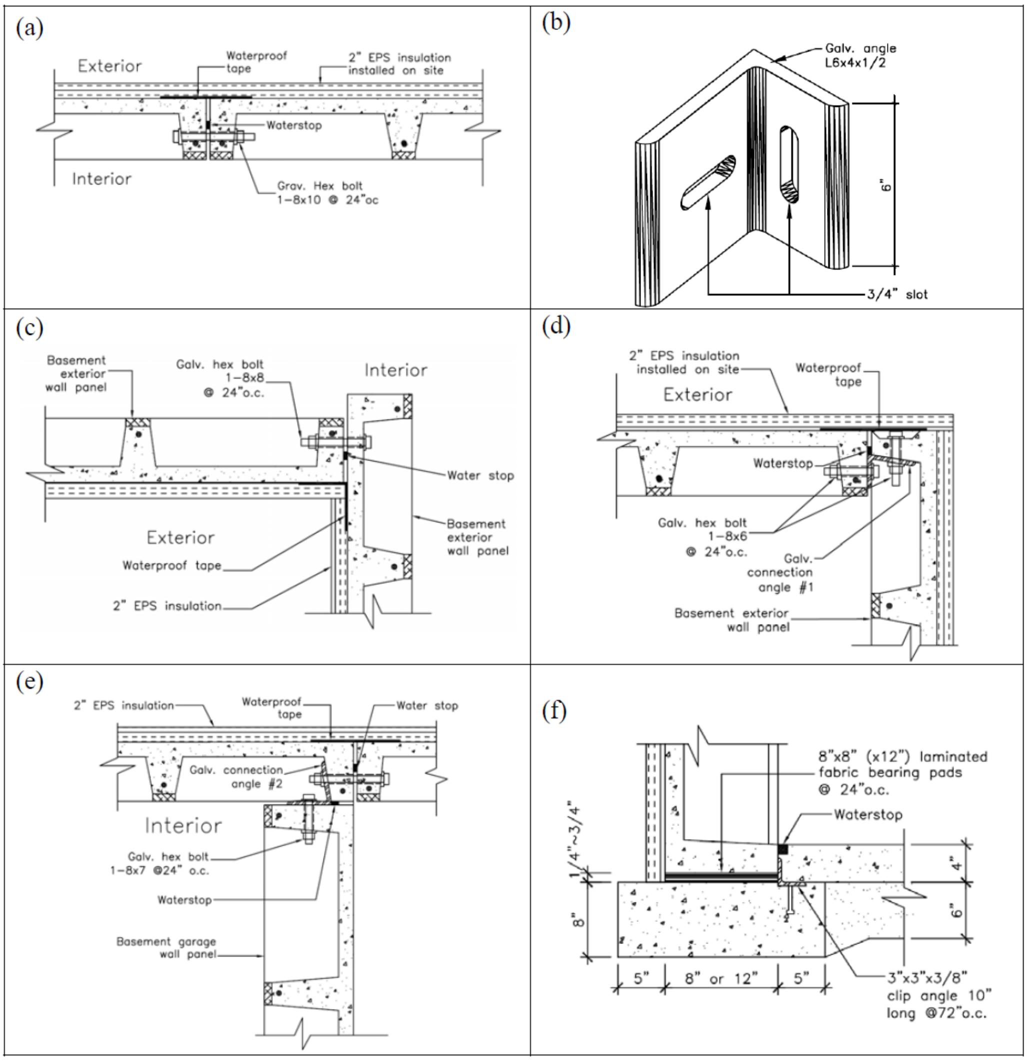


Figure 5-5: Details of Precast Concrete Foundation Wall Panel Connections

PCF System Application and Evaluation

After the system design had been approved by an experts panel, two trial projects were completed in January 2008 (Figure 5-6a and Figure 5-6b). Lafarge North America, a major local precast concrete manufacturer, was contracted to produce and erect the PCF panels. During the engineering design stage, the following changes were suggested by Lafarge's engineer to make the panel more producible and constructible:

- Changing the configuration of the 90º outside corner to the structure as shown in Figure 5-6d. As the end of the panel with irregular rib spacing becomes open, the panel was able to be cast using only the standard mould. Meanwhile, site installation is further simplified due to the elimination of connection angels.

- Customized bolts with a 3x3x3/8-inch steel plate head were used in corner connections, so that that the protrusion of the bolt on the external wall surface was reduced.
- Standard 8-inch panels were used underneath the garage, instead of 10-inch panels with bracket in system design. The cast-in-place garage floor is supported on all sides by rebar extended through a hole in panel ribs.
- Increasing the maximum length of a panel from 20 feet to 40 feet, thus eliminating all in-line joints. In addition, as the tolerance of precast concrete panel can be controlled in 1/8 inch, connections between panels were redesigned to zero-width joints with waterproof tape.

a. Erected Precast Concrete Foundation

b. Completed PCF Basement

c. Long PCF Panel Reducing Joints

d. Modified 90° Corner

Figure 5-6: PCF Trial Projects

The PCF system exhibited significant advantages over the traditional cast-in-place (CIP) concrete foundation system in cycle time reduction and process control. Despite harsh cold winter condition (below -20°C), the basements were erected in 4.5 hours and 2.5 hours, respectively, and capped in 4 workdays after excavation. Figure 5-7 shows the construction schedule of one of the trial projects. The PCF system also offers improved quality. Precast concrete panels were cast and cured in a factory environment, and manufacturers were able to produce consistent concrete mixes with strict quality control. Factors that lead to quality problems in CIP concrete foundation, such as temperature fluctuation, improper curing, poor craftsmanship and material quality, were minimized or eliminated with the use of precast concrete. Fiber enforcement, low cement-water ratio and exterior insulation further improved the performance of foundation walls by preventing the occurrence of cracking.

January 2008

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
Notes:		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18 Excavation	19
20	21 Footing	22 PCF Assembly Seal the joints	23 Capping	24 Spray Extrior insulation	25 Weeping tiles and rocks	26
27	28 City inspection Electrical panel installation	29 RWL Backfill	30	31	Notes:	

Figure 5-7: Construction Schedule for a PCF Trial Project

Another advantage of the PCF system is to save energy and reduce CO_2 emissions. Due to a long winter season, the energy consumption and CO_2 emissions are substantial for housing construction in Northern regions like Edmonton. For each foundation, a 29.3 kW (100,000 BTU/h) burner would run at least four days for concrete pouring and curing, with a total natural gas consumption of 260 m^3 or equivalent to four 45.4 kg (100 lb) propane bottles. Using the emission factors provided by Natural Resources Canada (Aube 2001), the CO_2 equivalent emission of 260 m^3 natural gas is 0.48 tonnes. As precast concrete panels were produced in a factory, the heating required for the concrete curing was no longer needed. In the winter of 2007/2008 (November 2007 – March 2008), Landmark Homes built 74 single-family house foundations, which meant 35.5 tonnes CO_2 equivalent emission would have been reduced if the proposed PCF system had been adopted. In addition, PCF basements were insulated in five days after excavation. In a conventional CIP basement, the frost wall is installed at least 2.5 months after excavation. Based on the experience of two trial projects, the energy consumption of winter heating was reduced by more than 20% when the basement was insulated.

While the two pilot projects were quite successful, the PCF system exposed some problems in the design and business model. Among the following four technical problems, two of them were related to the modification of system design, one was caused by defects in footing, and one involved material selection.

1) The engineered design on 90° corner failed at several corner connections. When the end surface of panels was not absolutely smooth and vertical, installers had to heavily fasten the bolts to achieve zero width joint. The 2-in-thick cantilever shell could not bear the bending moment and cracked (see Figure 5-8a).
2) A zero-width joint was not achievable in reality and irregular joints made the sealing difficult (see Figure 5-8b).
3) Due to the top surface of footing not being even, after levelling the PCF panels, the gap between PCF panel and footing varied so much that laminated bearing pads could not satisfy the requirement, and structural grouting had to be applied to fill the voids, as shown in Figure 5-8c and Figure 5-8d.
4) The protection of the above-ground portion of exterior insulation was hard to apply in winter and conflicted with siding, needing special architectural design.

The existence of technical problems was expected, and one of the purposes of the trial projects was to identify those problems so that the system could be improved. Management of the collaboration company decided to investigate other alternatives due to two considerations in terms of the business model. First, the complex shape (ribbed structure) and relatively large panel size means that PCF panels can only be produced in well-established precast factories with high initial investment on forms. Homebuilders that adopt the PCF system will highly depend on a precast concrete provider, for whom PCF is only a small portion of their product family. In fact, the panels for the two PCF trial projects were produced in Lafarge's factory in Winnipeg, Manitoba, as Lafarge's precast concrete factory in Edmonton had been overloaded to its capacity. The entire process took more than five months. Second, the cost of the PCF system was 15%-20% more than that of a traditional cast-in-place (CIP) basement. A detailed cost comparison will be introduced in Section 5.2.3.

a. Crack at a 90° Corner

b. Irregular Joints

c. Gap Between PCF Panel and Footing

d. Grouting Between PCF Panel and Footing

Figure 5-8: Technical Problems Exposed in PCF Trial Projects

5.2.2 Insulated Sandwich Panels

To overcome the problems exposed in ribbed structure panels, four alternatives, namely sandwich panel, structural insulated panel (SIP), internal insulated concrete forms, and steel/concrete composite wall system, were investigated. Composite sandwich panel and SIP are two major innovations recommended by PATH (Partnership of Advanced Technology for Housing, USA) for panelized construction. Over the past 5 years, considerable work has been devoted to understanding the failure mechanism for panels and connections. However, as the application area of these panels is an above-ground structure, these studies have been primarily focused on panels with eccentric axial or shear loadings. The PCF panel with internal insulated concrete forms has a similar shape and dimensions to the ribbed panel design. The challenge is to find a local supplier that can supply rigid insulation in the required size and shape and to design a production system. Cold-formed steel stud and concrete thin-shell composite wall is a hybrid system with light-weight and premade steel studs so that the panels can be easily produced at a small shop and installed using small cranes. In the past 5 years, this steel/concrete composite system has gradually gained popularity. In Edmonton, a plant has been opened by Building Products Inc., a major material provider of steel/concrete composite walls and floors, to produce cold-formed steel composite studs. Its wall system is used for above-ground structures, and the cost of a 8-in composite wall panel is 30% more than a conventional CIP concrete wall. After a literature review and feasibility study, the sandwich panel was selected as the most promising technology for further investigation due to the following reasons:

1) Sandwich panels have been produced and used by the construction industry for over 40 years. Most precast concrete producers have the ability and experience to produce sandwich panels, and the industry has a clear standard for panel design and production. Using sandwich panels complies with the lean principle – "use only reliable, thoroughly tested technology that serves people and processes."
2) Sandwich panels have all the desirable characteristics of the PCF system, such as reduced cycle time, superior energy performance, improved process reliability, and self-waterproof structure. Center insulation and a smooth surface on both the inside and outside of the panel provide a finished product requiring no further treatment. Thus, the high cost of a precast system is partially offset by eliminating exterior parging and interior frost walls.
3) Sandwich panels can be cast on a continuous working bed, as shown in Figure 5-9. No specialized form is needed and thus the initial investment for panel production and costs for panel customization are minimized.

Figure 5-9: Working Bed for Sandwich Panels

Sandwich Panel Foundation System Design

Sandwich panels are composed of two concrete wythes separated by a layer of insulation. From design perspective, there are, in general, three basic types of panels: fully-composite, semi-composite and non-composite panels. Composite panels are those in which two concrete wythes act together to resist applied loads. The ties or concrete ribs that are used to interconnect inner and outer wythes in fully-composite panels are so strong that there is no restrict relative movement between the wythes, i.e. two concrete wythes can be seen as a single unit, as shown in Figure 5-10a. Non-composite panels are those in which the structural wythe provides the total structural function of the panel and connectors do not transfer any longitudinal shear between concrete wythes. Depending on whether only one concrete wythe carries all the load or two wythes share the load, there are two kinds of non-composite panels, but in each case, the two wythes act independently, as shown in Figure 5-10c and Figure 5-10d. A sandwich panel is considered to be semi-composite if its connectors can transfer only a fraction of the longitudinal shear between two concrete wythes. In this case, the degree of wythe interaction depends greatly on the rigidity of the connector system, as illustrated in Figure 5-11.

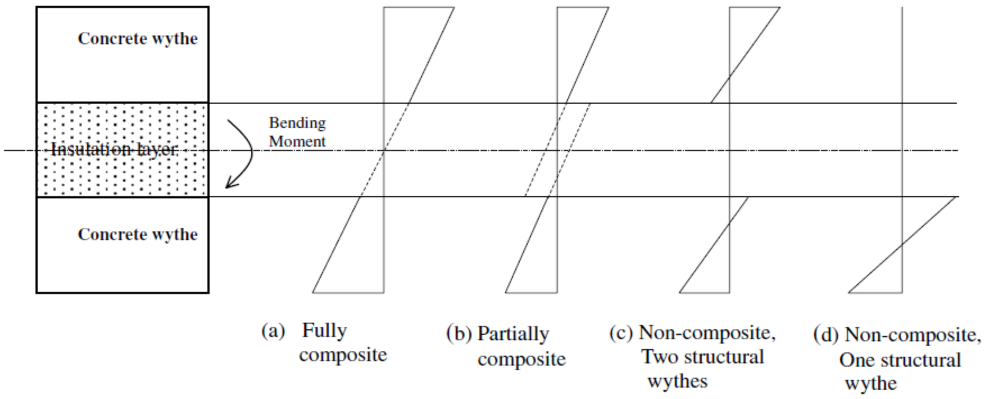


Figure 5-10: Strain Distribution Under Flexure (Benayoune et al 2008)

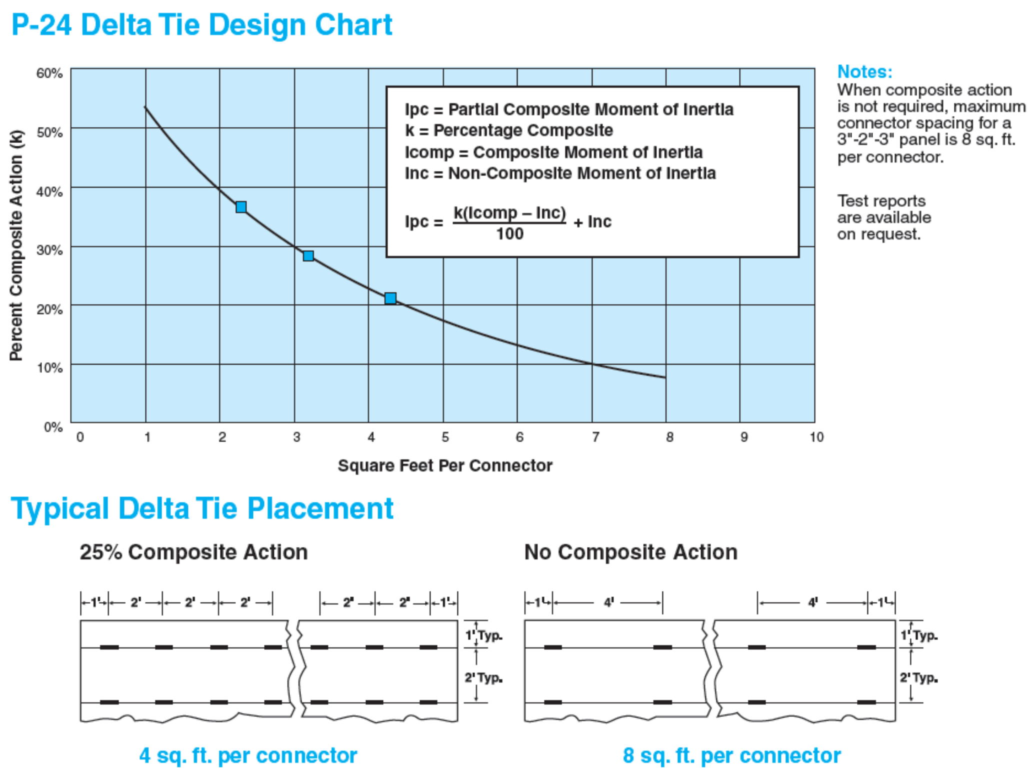


Figure 5-11: Interaction Percentage of Concrete Wythes (Dayton Superior 2008)

The design of non-composite and fully-composite sandwich panels is similar to that of typical precast/prestressed concrete member; while semi-composite panels exhibit some unique characteristics and behavior. The complex structure behavior, due to its material nonlinearity and lack of information on the effectiveness of shear transfer connectors, has forced researchers to relay on phenomena observation and limited testing backed by simple analytical studies (Benayoune et al. 2008). As different opinions exist among researchers and designers on degree of composite action and resulting panel performance, the Precast/Prestressed Concrete Institute (PCI) recommends analyzing and designing semi-composite panels "as composite or partially composite during stripping, shipping and erection, but as not-composite panels for in-place loads" (PCI 1997). The Canadian Prestressed Concrete Institute (CPCI) has provided principles and guidelines on sandwich panel desing and detailing, but does not have recommendation on a specific method for structrual behavior calculation (CPCI 1996).

Due to a lack of knowledge, the design of sandwich panels used in the collaboration company's precast foundation polit projects was conducted by precast manufacturers. Two designs were developed, one by a local small precaster and the other by a natione-wide precast concrete manufacturer. As a small private company, Canadian Concrete System Inc. (CCSI) services Northern Alberta and specializes in sandwich panels. It does not have an in-house engineer and special equipment in its plant. By contrast, ConForce is a major precast provider in Western Canada and the Northwestern United States. It has an experienced engineering design team, large production facility, sophisticated equipment and a wide range of precast products. The designs from the two companies had many common features. The thickness of the panel were both 8 feet, the same as conventional CIP foundation walls. They both consisted of two 2½" concrete wythes and a 3" center insulation providing R 15 insulating value. Adopting the same design as ribbed panels, clip angles (minimum 2 per panel or max 6 feet c/c) were used for panel base restraints. All panel base/footing and vertical joints were caulked with polyurethane sealant on both sides and covered by a waterproofing membrane on the outside surface. However, differences in engineering design capacity and production conditions of the two companies led to distinct designs in panel reinforcement and panel connection methods. Table 5-1 summaries the major differences between the two designs.

Table 5-1: Major Differences in Two Sandwich Panel Systems

Item	Design I (CCSI)	Desing II (ConForce)
Reinforcement	Vertical: 10 M @ 12” c/c Horizontal: 10 M @ 16” c/c Top and bottom: 2-10M	4-3/8” pre-stress cables each face (horizontal) with 6×6×6/6 WWM for crack control.
Panel Connection	Welding the weld plates embedded at the top edge of the panels.	Mitred corner connected by Simpson Strong-Tie plate strap on the top plate.
Panel joints	¼” joints	Zero joints with ¾” chamfer for sealing
Panel length	≤20 feet	≤ 40 feet

As shown in Figure 5-12, CCSI’s panel can be easily produced in a small precast facility or on-site without using any special equipment or technique. Compared to ribbed structure panels, sandwich panels use almost twice the amount of concrete and thus double the panel weight. In order to avoid the high cost of renting a big crane for installation, the maximum length of CCSI’s panels is less than 20 feet. Welding plates are cast-in at the top edge of panels for panel connection.

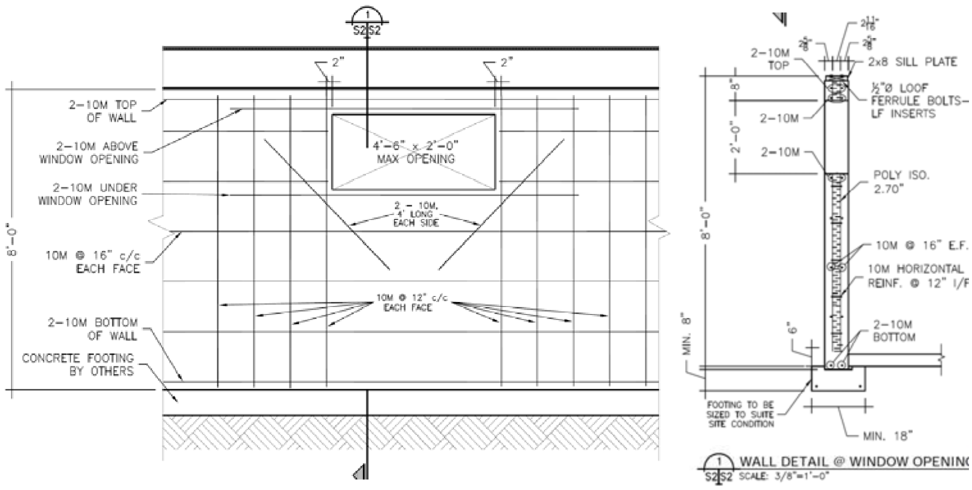


Figure 5-12: Sandwich Panel Design I (CCSI)

ConForce’s design involves sophisticated features used by large precast product providers, such as prestressed reinforcement, mitered corner connection, and small chamfer for sealing (see Figure 5-13). These features increased the performance/efficiency of the panel, but added difficulties for design and production as well. For instance, the use of the prestress technique can reduce the amount of reinforcement used in the panel, but it requires special equipment, and there is no standard method to calculate the effect of prestress in a composite panel. CPCI regards it as a "workable solution used successfully by experienced manufacturers."

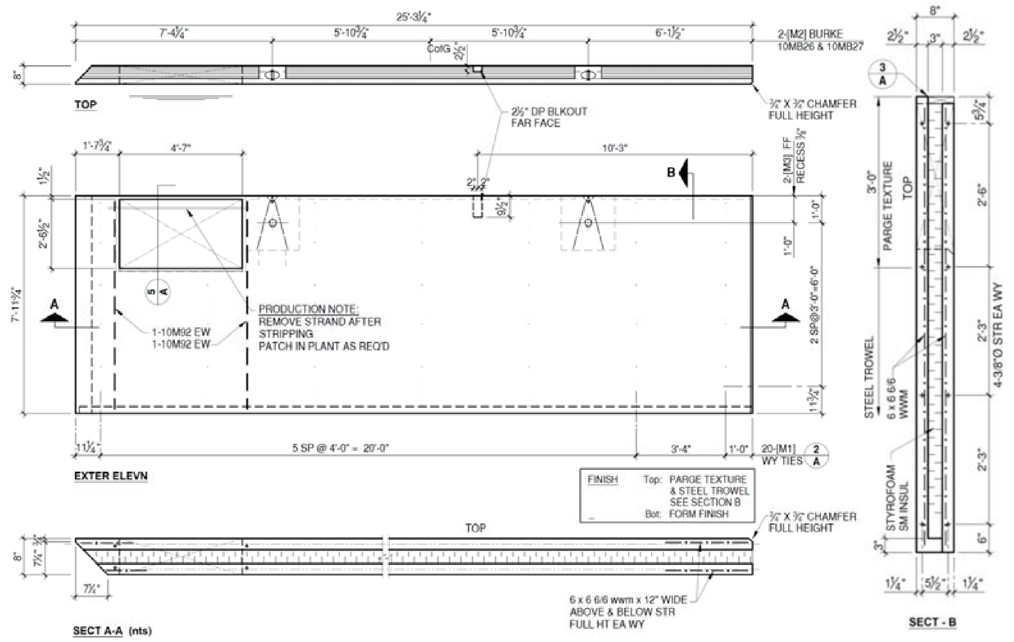


Figure 5-13: Sandwich Panel Design II (ConForce)

Sandwich Panel System Application and Evaluation

In the past year, four precast concrete foundations were built using sandwich panels and two others are in the planning stage. Although there were still some design and quality problems existing in the pilot projects, the sandwich panel foundations (Figure 5-14) showed excellent performance in terms of insulation value and ease of construction. Table 5-2 shows the comparison of heating costs between houses that used sandwich foundation panels and that used conventional CIP concrete walls. Houses 07-133 and 08-104 were both excavated in November 2008 and heated for the entire 2008-2009 winter season. The amount of propane used in winter heating of house 07-133, a pilot project of sandwich foundation panels, was 18% less than that of house 08-104 that had a conventional CIP basement. Better and early insulation also reduces the number of heating equipment needed to heat the house and the time of propane delivery. The total heating costs of house 07-133 were reduced by 23%. Similar savings was observed in house 07-233, which entered the construction process at almost the same time as house 08-035, in the middle of February 2009. Compared to house 08-035, house 07-233 used almost 30% less propane and saved a quarter of the total heating costs. Based on data from the U.S. Department of Energy, the CO_2 emission factor of propane is 63.1 kg/MMBtu (EIA 2007). Thus, for a complete winter heating season, a precast sandwich panel foundation can reduce CO_2 emissions by 1.82 tonne.

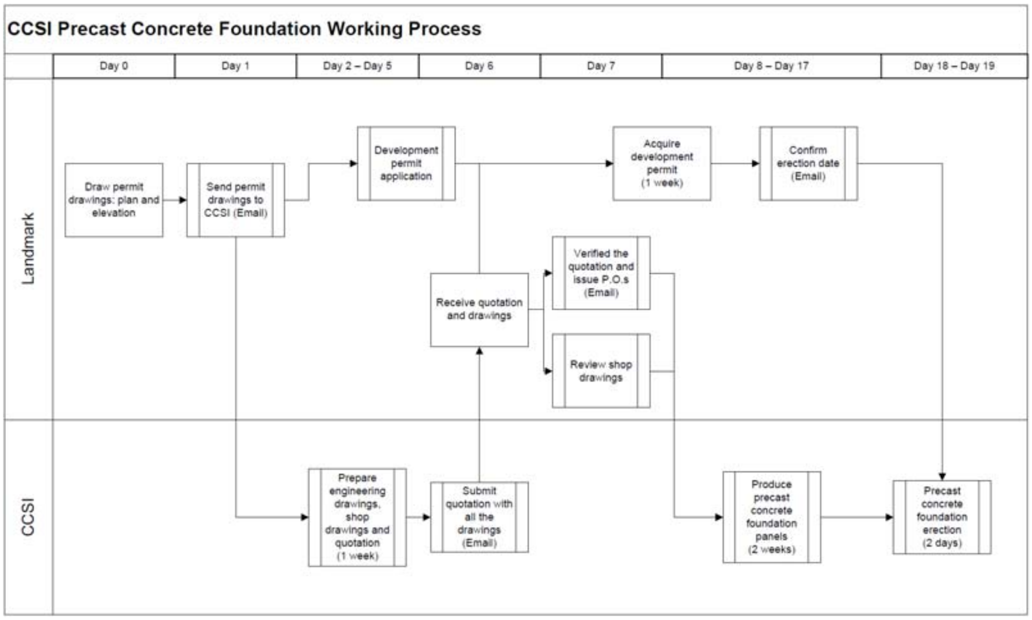
Table 5-2: Savings on Heating Costs of Sandwich Foundation Panel Projects

Job #	07-133	08-104	07-233	08-035
Size (Sq.Ft.)	1800	1904	1926	1903
Foundation type	Sandwich panel	8-in CIP	Sandwich panel	8-in CIP
Excavation Date	5-Nov-08	6-Nov-08	17-Feb-09	19-Feb-09
Total costs of winter heating	$4,725.10	$6,150.05	$2,452.50	$3,279.50
	77%	100%	75%	100%
Costs of heating equipment rental	$930.50	$1,461.50	$278.50	$594.50
Costs of propane	$3,194.60	$3,943.55	$1,484.00	$2,070.00
Propane usage (litre)	5716	6950	2740	3880
	82%	100%	71%	100%

Figure 5-14: Sandwich Panel Foundation (07-133)

After four pilot projects, most of the technical and coordination problems have been exposed and solved. Now the major obstacles that impede adaptation of sandwich foundation panels on a large scale are factors in costs and precast panel production. The discussion of cost factor will be detailed in the next section, and the dilemma in precast panel production is discussed here.

As shown in Figure 5-15, the standard working process of a typical precast foundation project takes four weeks, including one week lead time for engineering design, one week for development permit application, and two weeks for panel production. From a homebuilder's point of view, this process lengthens the office cycle time by about three weeks. In the current process, the production department compiles and submits the development permit application package as soon as it gets drawings from the drafting department, but under the precast concrete foundation process, it has to wait a week for foundation engineering drawings that need to be included in the development permit application package. Similarly, two weeks lead time for casting panels, including locating panels into production schedule and a minimum 5 days curing time, leads to about one week idle time between getting the development permit and sending files to construction. On the other hand, as panels need to stay on a precast bed for at least 24 hours to gain strength before they can be moved to a storage area, the turnover rate of a precast bed is 2 workdays. A typical basement of a single-family house needs 180-200 feet of sandwich panels. Thus, in order to meet the demand of Landmark Homes, which builds on average 400 houses per year, accounting about 40% of total sales of the collaboration company, at least 600 feet (182 meters) of precast bed has to be dedicated to precast panels. Small precast plants do not have the required facilities to meet the collaboration company's demands, while big precast providers are reluctant to commit their capacity to residential products like sandwich foundation panels, as they are used to working on large industrial, infrastructure, and commercial projects that have a bigger profit margin and need substantial engineering support. In the past two years, the collaboration company has struggled to find a partner in the precast industry that is able to provide a reliable production capacity to support its shifting from the conventional CIP concrete foundation to the precast sandwich panel system. The prices from major precast providers are so high that the collaboration company is unable to bear it as a standard cost item for all houses. Moreover, those major precast providers cannot dedicate their capacity or facility to a homebuilder due to concerns on whether it can provide them a leveled workload. The collaboration company has also contacted/worked with small local precasters, but they have neither the sufficient capacity to meet the demand nor the necessary capability to expend their capacity. Currently, the collaboration company is continuously working on this issue with potential partner companies.



Note: All days in the map are working days – the total duration of the process is 4 weeks.

Figure 5-15: Sandwich Panel Foundation Working Process

Costs Comparison

Cost reduction is the center of production management in today's highly competitive marketplace. Ohno believes that "all considerations and improvement ideas, when boiled down, must be tied to cost reduction" (Ohno 1988). However, this comparison must consider all the impacts of the improvement, not only direct costs. As shown in Table 5-3, the direct cost of a precast sandwich panel foundation system is approximately 30% higher than that of a CIP concrete foundation. For a typical single-family house basement, the direct cost increase is about $4,000 CAD. However, precast sandwich panels are insulated, self-waterproofing, and have a parge-like texture on the exterior finish. The factory-built method and excellent thermal performance of a sandwich panel can remarkably reduce winter costs. If all those factors are taken into consideration, the cost increase of switching from CIP concrete to precast foundation is less than 5%, about $800 CAD per job.

Table 5-3: Cost Comparison of Sandwich Panel and CIP Foundation Systems

House Model:	Pembrooke IB	Sq. Ft.	1800 ft2
Total Sq Ft Panels (8 in):	948.8 ft2	Total Sq Ft Panels (6 in):	456..5 ft2

Sandwith Panel Foundation System

8-in Sandwich Panels		Unit Price	Amount
Concrete (m3)	12.66	218	2760.52
Reinforcing (kg)	974.3	1.8	1753.72
Insulation (ft2)	888.6	1.2	1066.31
Connectors	474	2.5	1186.04
Misc. Mat'ls	LS		150.00
Production (m-hr)	80	20	1600.00
Yarding (m-hr)	10	20	200.00
			8716.59
6-in Solid Panels		**Unit Price**	**Amount**
Concrete (m3)	6.46	218	1408.10
Reinforcing (kg)	208.3	1.8	375.01
Misc. Mat'ls	LS		50.00
Production (m-hr)	20	20	400.00
Yarding (m-hr)	4	20	80.00
			2313.11
Beam		**Unit Price**	**Amount**
Concrete (m3)	2.00	218	434.94
Reinforcing (kg)	348.6	1.8	627.47
Production (m-hr)	20	20	400.00
Yarding (m-hr)	2	20	40.00
			1502.41
Installation			
Transportation (load)	2	250	500.00
Erection (m-hr)	64	25	1600.00
Crane (hour)	9	160	1440.00
Other equip	LS		100.00
Wood capping (ft)	183.1	1.0	183.09
Joint - vertical (ft)	96.0	3.0	288.00
Joint - horizontal(ft)	241.0	1.5	361.46
Waterproofing (ft)	216.5	1.5	324.73
			4797.28
Direct Costs			17329.39

Conventional Cast-In-Place Foundation

Foundation Walls	Amount
F/wall materials - lumber	159.00
F/wall materials - rebar	400.00
F/wall materials - concrete	6900.00
F/wall concrete pump	1325.00
F/wall cribbing labour	4520.00
	13304.00
Other Related Items	**Amount**
Parging	350.00
Spay and Patching	350.00
Basement steel stud frost walls	1033.00
Basement electrical rough-in	150.00
	1883.00
Winter Costs	
Item	Amount
2% non-chloride accelerator	600
Saving on winter heating	750
	1350
Total	16537.00

Summary

The sandwich panel foundation system has shown clear advantages over traditional CIP basements in terms of process reliability, quality, thermal performance and construction time. The direct costs of precast panels are about 30% higher than that of a traditional CIP foundation, but by using sandwich panels construction work such as waterproofing, basement frost wall and insulation, and parging can be eliminated. Moreover, pilot projects constructed during winter proved that using precast sandwich panels could reduce winter heating costs and associated CO_2 emissions. Through the completion of pilot projects, any problems in design and process have been exposed and solved. Now the major obstacle to the adoption of a precast concrete foundation is to develop a business model that can meet the requirements of both homebuilders and precast manufacturers.

5.3 PREFABRICATED WOOD FRAME PANELS

Prefabrication is one of the core elements of the collaboration company's lean efforts. Installed panels replaced conventional framing and completely changed the landscape of the company's construction management. For the first time that construction managers saw the promise that the construction process could be controlled in spite of unpredictable weather, site conditions, and crew availability. On the other hand, many operations management concepts/tools that have been used by the manufacturing industry for decades but never considered relevant to construction, such as process analysis, production leveling, work flow control, and capacity planning, became indispensible parts of day-to-day management.

Considering the acceptance of market and regulating authorities, the panels used by the collaboration company follow the same specifications and details as conventional site-built wood frame houses. The focus of implementing a panelized system was on improving operation efficiency and realizing the benefits. This is a notable challenge, as the factory-built method involves high fixed costs, such as facility rental and equipment costs involved in transportation and erection, and leads to less flexibility in responding to construction variation.

The collaboration company experienced earlier failed attempts in panelized construction. In early 2006, stimulated by a booming house market and shortage in skilled workforce, it established a plant to prefab wall and floor panels and roof sections. The same framing and management methods as in conventional house construction were used to build panels in the factory, and then those panels were shipped to the site and erected by in-house workers. The plant never met expectations – the cost of prefabrication was much higher than that of on-site framing, and site managers complained about the delivery time and quality of the panels. After one year of operation, the plant was closed and the primary reason for failure was identified as the lack of experience in managing the plant.

Despite the failure, the top management of the collaboration company did not give up its vision of industrialized housing and lean production. In November 2007, one month after the collaboration company redesigned its production process, a joint venture between the collaboration company and a local framing, roofing and siding company was established. After 6 months operation, the Great Canadian Renovation and Construction Corporate (GC) had formed a capacity of 20-25 houses per month and nearly broke even. Table 5-4 shows the plant's operating income and cost in the first 5 months of 2008, and Figure 5-16 illustrates the breakeven analysis. In order to further increase the productivity of the prefab operation, the author was invited to lead a lean initiative started in July 2008. After a 12 months effort, the output of the plant increased to 40 houses per month in mid-2009 (Figure 5-17). Although the output of the plant was mostly decided by market demands, improvement in production efficiency ensured that when the market demand increased the plant could meet demand under current resource limits, and that when the demand decreased the plant could maintain its unit costs at the same level.

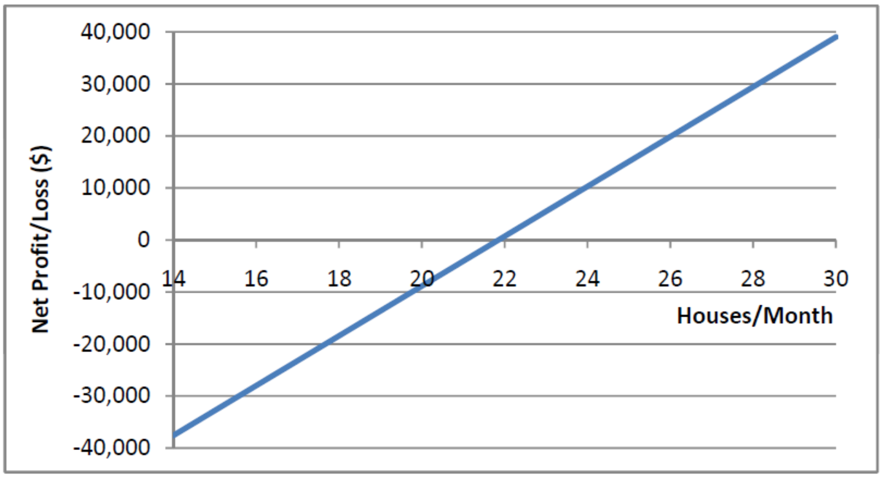


Figure 5-16: Relationship between Production Output (per Month) and Profit

Table 5-4: Revenue and Costs of Prefab Plant (January – May, 2008)

		Jan	Feb	Mar	Apr	May
Total Sales	# of Jobs	18	14	18	24	22
	Sq. Ft.	34,371	25,423	34,007	46,426	42,126
	Revenue	389,774	301,132	386,459	523,476	544,919
Job Character	Average Sq.Ft./Job	1,910	1,816	1,889	1,934	1,915
	Average Price/Job	21,654	21,509	21,470	21,812	24,769
	Average Price/Sq.Ft.	11.34	11.84	11.36	11.28	12.94
Sales Breakdown	Prefab Price/Sq.Ft.	9.35	9.88	9.54	9.38	9.65
	Lumber Price/Sq.Ft.	1.99	1.97	1.83	1.90	3.28
Cost Breakdown	Prefab Cost/Sq.Ft.	8.27	8.29	7.28	6.97	7.55
	Lumber Cost/Sq.Ft.	1.75	1.85	1.73	1.70	3.03
Contribution Margin Ratio	Prefab	12%	16%	24%	26%	22%
	Lumber	12%	6%	5%	10%	8%

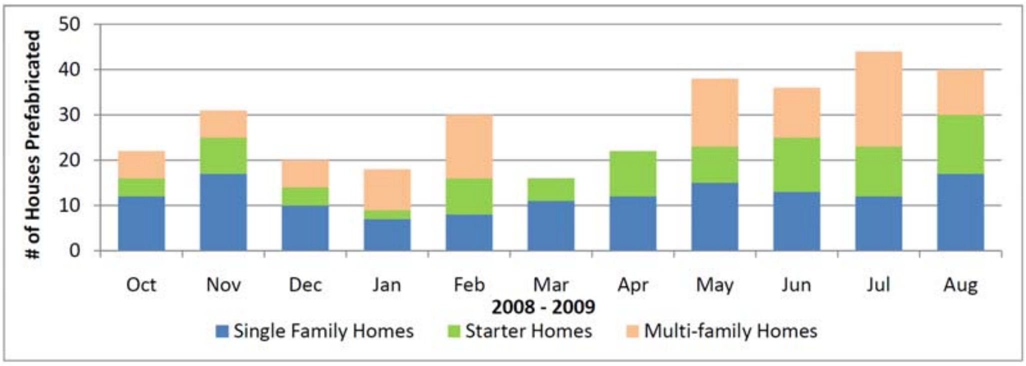


Figure 5-17: Monthly Output of Great Canadian Prefabrication

Figure 5-18 shows the average unit labor costs ($/Sq.Ft.) of three types of houses that the GC prefabrication plant has produced. By comparing Figure 5-17 and Figure 5-18, a clear correlation can be found between output and unit labor costs. In December 2008 and January 2009, the demand dropped significantly; less than 20 orders were received by GC each month. In addition, a fall in framing price added pressure for GC to control its costs. As a result, GC restructured its workforce and cut its workforce by 30%. Starting in February 2009, Edmonton housing market showed a clear sign of recovery, and GC was facing a new challenge to increase its production capacity to meet the coming demand. During those transitions, lean initiatives played a critical role in capacity planning, process optimization, and workforce restructuring. Although average unit costs fluctuated from month to month, an obvious down trend on prefabrication labor costs can be seen in Figure 5-18.

Figure 5-18: Average Labor Costs of GC Prefabrication

5.3.1 Starting the Lean Journey with 5S and Visual Management

Although starting a lean initiative requires complete commitment from top management, the biggest challenge and key success factor is to let the front-line workers see the necessity of change and motivate them to take initiatives. 5S (Sort, Set to order, Shine, Standardize and Sustain) has been recommended by many lean experts as the starting point of lean transformation (Productivity Press 2006), because compared with other lean tools, 5S, which focuses on cleaning and organizing the workplace, is easier to get worker's buy-in and produces immediate visible results. More importantly, effective cleaning and efforts to sustain a better-organized workplace involve many key lean principles and methods, such as standardized work and visual management. 5S can help people that have no lean production experiences to build teamwork, discipline, and a culture of continuous improvement, which are the cornerstones of lean implementation.

Frequently, cleaning is considered as a non-value-added step, and workers do it only because management tells them to do it, rather than realizing that the waste caused by a messy working environment are high. GC started its lean initiative by inviting an external lean consultant to the shop floor to take pictures and record the time that workers spend on looking for tools and materials and removing scraps in the way. Then the production team was called together to review the findings. After the lean consultant explained the basic concepts of 5S and 7 types of Wastes, pictures of shop floor, like Figure 5-19, were presented to the team and examples of workplace management of some world-class lean enterprises were introduced. At the end of the meeting, the lean consultant facilitated a brain-storming session to identify three top areas of waste and to develop a team action plan with possible solutions, completion deadline and person responsible. Top plant management also attended the meeting to show its commitment and support to the initiatives.

Figure 5-19: Saw Table at Floor Prefab Cell (Before 5S)

In one month, with the help of the external lean consultant, all production teams developed their own 5S action plans and started weekly 5S meetings. The working condition of the shop floor remarkably improved. Figure 5-20a shows the new lumber cutting station for floor prefabrication. Raw materials (dimensional lumbers) are stored on the rack behind the saw table and short leftovers are cut into blocks, which are stored under the table. A panel saw was also added to the station, so workers at floor prefabrication jigs do not have to go to the other side of the plant (wall production area) to cut OSB boards. The 5S efforts soon became a company-wide initiative, extending from shop floor to field construction and offices. Figure 5-20b shows a snapshot of the tool trailor of a field erection crew after 5S. "A place for everything and everything in its place."

a. Cutting Station for Floor Prefab Cell   b. Tool Trailor of a Field Erection Crew

Figure 5-20: Examples of 5S Results

One advantage of starting a lean journey with 5S is that people can see the results in a relatively short period of time, and then everyone is excited about the progress and improvement. 5S gets people enthusiastic about lean transformation. The next step is to smoothly transfer 5S initiatives, which focus on workplace cleaning and organization, to lean transformation that involves every aspect of the operation and needs a deep mindset and culture change. The lean expert and plant management had repeatedly asked one question in almost every 5S meeting, "The results are great, but how will we sustain what we have achieved and how will we use the same concepts on other aspects to eliminate waste?" Figure 5-21a shows an initiative of the floor prefabrication team to standardize the work of its material handler. It was quite simple and not written or formatted well, but it was the first standardization effort initiated by frontline workers. The team developed the to-do list in its weekly tool-box meeting, and then posted the document on the shop floor. The management immediately used it as an example to promote standardized work and visual management. Soon, standardization was not limited to cleaning activities, but extended to all aspects of production. By the end of 2009, all production processes and 80% of production tasks had been standardized, and a visual control system had been established. Details of standardization are introduced in Section 5.3.4.

Publicly recognizing results is an effective approach to challenge and motivate people to be part of a company's lean transformation. In the workers' lunch room, a lean achievement scoreboard, as shown in Figure 5-21b, was created to advertise the success stories and savings of the improvement. The scoreboard is updated bi-weekly and introduces the two improvement ideas with the highest savings. For the production team who initiated and implemented the idea, it is exciting to see its achievement being recognized by management and the picture of the team posted. The other production teams can see the progress of the company's lean efforts and get some inspirations from others' successful stories. In GC's lean journey, several reward systems have been implemented, but the lean achievement scoreboard remains the most powerful tool to encourage continuous improvement and to exchange improvement ideas.

a. To-do List of Material Handler b. Lean Achievement Scoreboard

Figure 5-21: Sustainable Efforts of 5S

5.3.2 Invest in People

A big challenge in lean transformation is that a lean production system needs people to have thinking capability and to thoroughly understand their work. A lean production system cannot be designed by lean experts and then implemented on the shop floor, because it is frontline workers who know the details of their process and have the technical knowledge to develop the improvement ideas. A few supervisors and experts cannot possibly deal with all the situations that arrise in everyday operation. It is critical to teach workers to see waste, to motivate them to pursue perfection and to coach them in the right problem solving skills. At Toyota, developing exceptional people is the top priority of managers and the most commonly used expression is, "We do not just build cars; we build people." (Liker and Meier 2007).

From the beginning, GC's top management had a clear vision that training was the critical success factor of lean transformation. Since all workers in the company were construction workers, they did not have manufacturing experience, never heard of lean production, and lived in a completely different culture than in a lean enterprise. The only way to change people's mindset and behavior is continuous training, but the training has to be pulled by workers, which means motivated employees initiating the resources and training they need to improve their working process. The interaction between management and workers can be described as a "catchball process," as shown in Figure 5-22. Management initiated the training by developing a *GC Lean Training Program for Production Employees* and providing general lean training for the entire workforce. Then the "ball" was thrown to the workers, who were organized into several lean improvement teams. They identified an area to improve and established their own action plan and improvement goal – then "threw" them back to management. Management and the lean expert then provided training on the lean techniques that the team needed to achieve its goal, and coached them during the course of improvement effort. Figure 5-23 shows two levels of lean training. Figure 5-23a is a 2-day initial lean training workshop, which taught everyone the concepts of lean production and tools to identify waste in their working process. Figure 5-23b is the lean expert coaching a lean improvement team on the floor on using lean techniques to develop improvement solution.

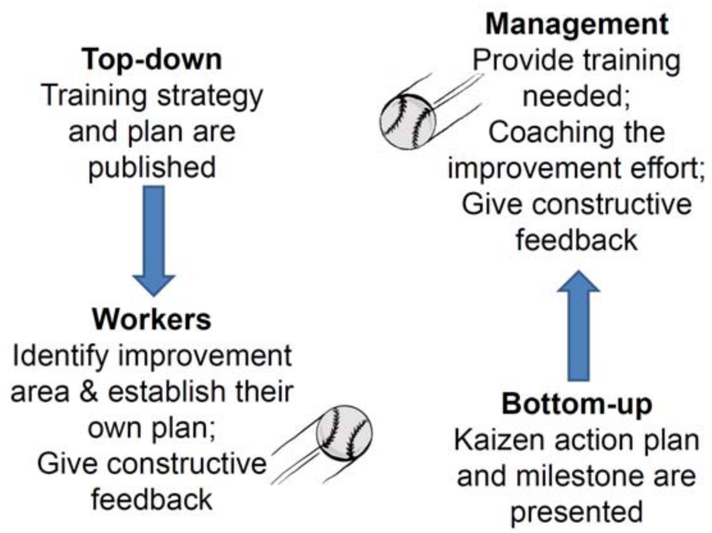


Figure 5-22: Catchball Process in Lean Training

a. Initial Lean Training Workshop b. Coaching on the Shop Floor

Figure 5-23: Lean Training Events

The catchball process has been used by GC for more than one year. Compared to conventional classroom training, GC's training program needs more time and a much larger investment, but all the efforts had a reward. It accomplishes three things:

- It ensures that management provides lean training that workers need at the time when workers need it.
- It ensures that the lean techniques learned in training are used by the workers.
- Most importantly, it establishes an environment where frontline workers take the ownership of the improvement process.

5.3.3 Standardization is the Foundation for Continuous Improvement

Standardization has long been regarded as being only applicable in mass production where workers repeat the same operation all the time, while in construction, every task is unique and workers have to select the best way to do their jobs based on their experiences. However, lean practice teaches us that some level of standardization is possible for any process, and the establishment of standardized processes and tasks is key to creating a lean production system. A process or task must be standardized and thus stabilized before it can be improved; if everyone does the job in his/her own way, then lean production is just one more variation that is occasionally used and mostly ignored (Imai 1996).

Standardization at GC started at the process level. As GC's process closely relates to the collaboration company's process and material suppliers' lead times, a half-day process mapping session was organized to achieve a workable consensus. Figure 5-24 shows the middle part of the prefab framing process for Landmark Homes. A standardized process allows every party to know the exact expectations and most likely results. For instance, by looking at the process map, a Landmark Homes' site manger knows that the house will be capped on the 5th workday after GC receives the capping request, and the framing will start on the 15th workday, so he should sending the capping request at the excavation day and ensure that the site is backfilled and precast steps are installed before the framing start day. Moreover, as the standard framing cycle time is 7 workdays, he is able to pre-book the downstream tasks, such as No-burn application (a fire retardant), plumbing and electrical rough-ins, accordingly.

A prerequisite of the standardized process is consistent performance of all parties involved in the process, so that tasks composing the process can be started and completed on time. First, the site must be ready and materials be delivered to the plant or the site on the designated day. Then, the wall panel production and floor prefabrication teams need to meet the production schedule. Meanwhile, field crews need to finish framing within the time standard and thus start another job on schedule.

In lean thinking, high production efficiency comes from relentlessly eliminating waste through analyzing the transportation method, rearranging material flow, improving tools and machining processes, and optimizing the inventory amount.

However, the most important method for maintaining high production efficiency and consistent operation performance is for everyone to follow the best practice to prevent the recurrence of defective products, operational mistakes and accidents. In the Toyota production system, this has been achieved by implementing a standard work sheet (Ohno 1988).

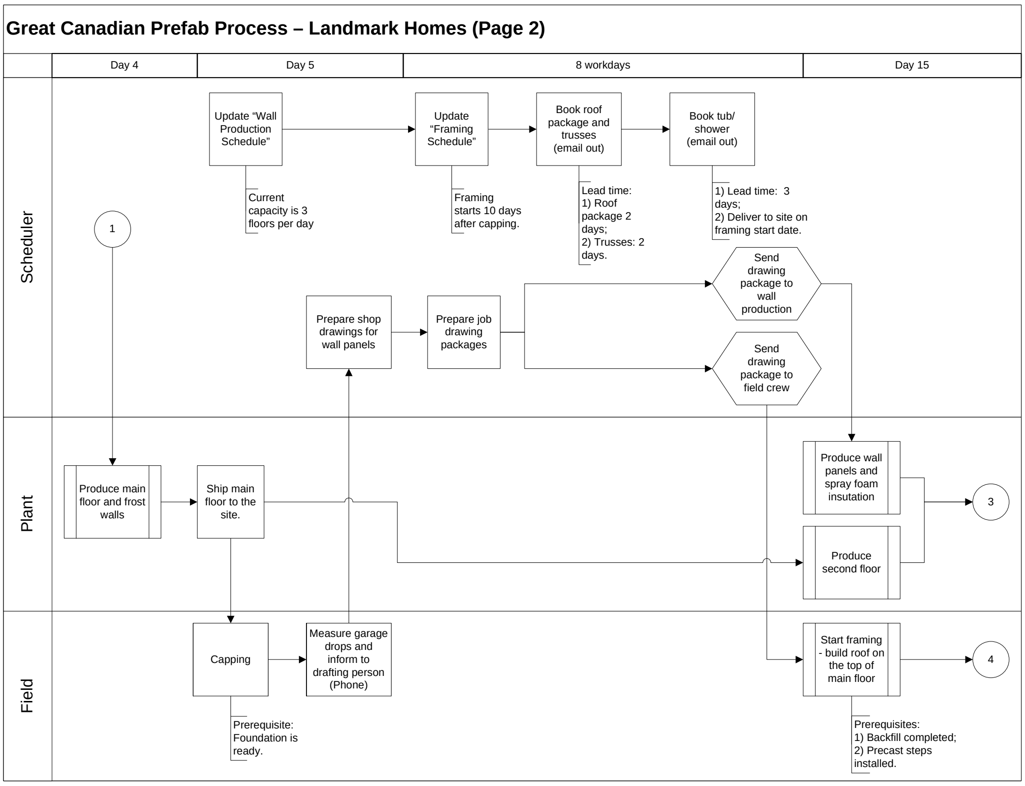


Figure 5-24: Standardized Working Process (Landmark Homes, Page 2 of 3)

However, construction is featured be customization. Although all the houses sold by the collaboration company are developed based on basic predesigned models, the number of varieties reaches hundreds when considering the combination of various options in plan and elevation. It is really rare to see two identical houses within a month. In addition, a house generally consists of 15-30 exterior panels and 40-45 interior panels, and all the panels are one-of-a-kind. The configuration of panels varies significantly and so does the time required to frame a panel. In order to accommodate high variability, GC separated the cycle time and standard work sequence, two basic elements in standard work procedure. Although the dimensions and configurations of different panels defer and so does the cycle time, the operations required to finish each panel at a given station are the same for the majority of panels. A standard work sheet that shows steps of workers' operations is posted at each station (see Figure 5-25a). All workers are trained to perform the operation in a standardized way before they are released to the job, and after the first few days, they should not have to refer to standard work sheet during their operation. However, a posted standardized work sheet provides a visual reference for management to ensure adherence to the standard. Deviations from the standard are usually caused by a problem, and the role of management is to recognize the deviation, uncover the root causes and ensure that they are corrected quickly, and reestablish the standardized work.

A cycle time standard is established at job level based on historical data and a time study. Table 5-5 is the time standard for exterior wall panel prefabrication. It shows the number of man-hours required to complete exterior walls for a given house model and working time needed in normal production conditions. All basic models of the three major customers of the plant are included in the table, and time standards of customized houses or jobs from other customers are estimated by job size and type.

Table 5-5: Cycle Time Standard for Exterior Wall Prefabrication

Landmark Homes (Edmonton)

Model	Sq.Ft.	Standard Man-hr	Standard Sq.Ft./hr	Work-Hr (10 Men)
Cambridge II	1900	70	27.1	7.0
Cambridge III	1860	70	26.6	7.0
Catalina II	1696	75	22.6	7.5
Lyons II	1985	80	24.8	8.0
Madrid I	2058	80	25.7	8.0
Pembrook I	1800	80	22.5	8.0
Pembrook II	1926	80	24.1	8.0
Others	1900	77	24.8	7.5
Ashdown I	2131	85	24.8	8.5
Glenabbey I	2337	95	24.8	9.5
Madison II	2073	85	24.8	8.5
Marseilles II	2137	85	24.8	8.5
Marseilles III	2131	85	24.8	8.5
Meadowbrook	2392	95	24.8	9.5
Montpellier I	2014	80	24.8	8.0
Rosewood II	1850	75	24.8	7.5
Rosewood III	1860	75	24.8	7.5
Sagewood I	1407	55	24.8	5.5
Southport I	1372	55	24.8	5.5
Southport II	1512	60	24.8	6.0
Springhill I	2131	85	24.8	8.5
Summerlea I	1958	80	24.8	8.0
Whitecourt	2355	95	24.8	9.5

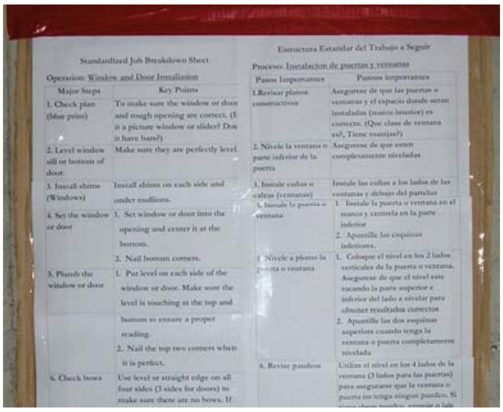
Summerhill Homes

Model	Sq.Ft.	Standard Man-hr	Standard Sq.Ft./hr	Work-Hr (10 Men)
Alexander	1451	65	22.3	6.5
Cartier	1534	55	27.9	5.5
Garneau	1348	45	30.0	4.5
Lougheed	1471	50	29.4	5.0
Others	1357	47	29.1	4.5
Carson	1358	45	29.1	4.5
Glenora	1184	40	29.1	4.0
Lacombe	1400	50	29.1	5.0
McLeod	1794	60	29.1	6.0
Pearson	1144	40	29.1	4.0
Riel	1056	35	29.1	3.5
Rundle	1357	45	29.1	4.5
Strathcona	1290	45	29.1	4.5

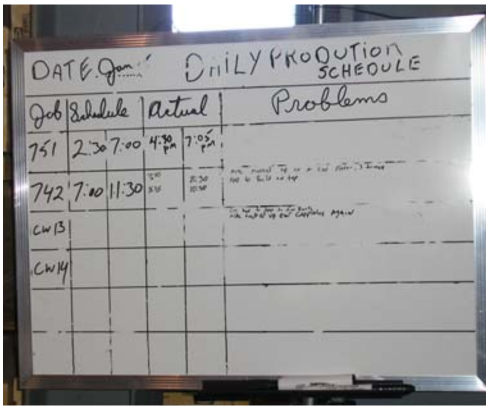
Best Communities (Duplex)

Model	Sq.Ft.	Standard Man-hr	Standard Sq.Ft./hr	Work-Hr (10 Men)
Apex II	2731	100	27.3	10.0
Brookside I	2408	100	24.1	10.0
Legardo	3048	75	40.6	7.5
Others	3000	98	30.7	10.0
Gala (per unit)	1234	40	30.7	4.0
Paramount	2877	95	30.7	9.5

The time standard is an important element in GC's production control. First, it is the basis for production scheduling. Every Friday, the scheduler will modify the production schedules, including wall and floor prefabrication, capping, field framing, spray foam insulation and crane schedules, for the next two weeks based on the current schedule situation, and schedule all the bookings received during the week into the second (for capping) and the third week (for framing and craning). The duration of each job in the schedule is calculated based on the cycle time standard, and any delay in the schedule means abnormal situation and the cause of the delay must be reported. Figure 5-25b shows the daily schedule board on the wall production line. The scheduled start and finish times are posted and problems that lead to deviation from schedule are recorded. Those problems then become targets of weekly lean improvement meeting. In addition, developing a schedule based on time standards allows the plant to proactively control the labor costs. Meeting the production schedule means the job is completed using the standard labor hours.



a. Standard Work Procedure for Window/Door Installation (Partial)



b. Daily Production Schedule

Figure 5-25: Standardized Work

CHAPTER 6 – CONCLUSIONS AND RECOMMENDATION FOR FUTURE RESEARCH

The goal of this research is to develop a lean production approach to guide production homebuilders' lean transformation. This study focused on two research questions: 1) How can a lean production system be integrated into the homebuilding process? 2) What are the challenges in lean implementation and how can those challenges be addressed? The research adopted case-study and action research method. As a researcher and a member of the core lean implementation team, the author carefully documented the lean transformation efforts of a production homebuilder and provides detailed insights into the lean production model design and lean model implementation. This chapter summarizes the results of the research and proposes conclusions and recommendations for future study.

6.1 RESEARCH SUMMARY

Homebuilding is a unique sector of the construction industry that is most analogous to automobile manufacturing. To better understand the current homebuilding process, the author conducted a comprehensive literature review to investigate the homebuilding process on the industrial level and a quantitative analysis on the practice of the collaboration company in order to map its current process. The comparative study between the automobile manufacturing and homebuilding industries reveals that homebuilders and automakers share clear similarities in supply chain management and production strategies, but peculiarities of construction lead to high process variability and impede the direct implementation of a lean production system. The homebuilding industry needs a comprehensive lean approach to guide individual company's efforts on improving the effectiveness and efficiency of the homebuilding practice through lean transformation.

In collaboration with a production homebuilder, a four-phase methodology was adopted to redesign the homebuilding process. 1) The Homebuilder and trade contractors work together to develop a process flowchart for the entire homebuilding process. 2) The current states of five construction stages are mapped by five workgroups using value stream mapping techniques and actual operational data collected through the production tracking system. 3) Based on lean principles, a future state map is created by each workgroup for each construction stage. 4) Five future state maps are compiled into a future process chart, which becomes the overarching goal of the company's lean implementation.

The implementation of the future state maps started with developing action plans. Each major improvement step was divided into a series of smaller increments with clear start and finish dates and a responsible person. Recurring meetings were set up for each workgroup to ensure that communication flow and consensus are achieved. As the collaboration company proceeded through implementation, a list of challenges was identified and key lean strategies for overcoming those challenges were developed.

1) Long-term commitment of top management was crucial for the success of lean implementation. True commitment means allocating sufficient time and resources for lean training and making management decisions to support long-term goals even with short-term expenses.
2) Waiting time caused by process uncertainty is the biggest waste in the current homebuilding practice. The key to eliminate or reduce waiting time is to increase construction operation consistency in every portion of the process and to establish a production process that can accommodate unexpected and unavoidable variations.
3) In construction, standardized work can be conducted on two levels – process level and operation level. A standardized process and standardized schedule should be developed based on current construction practice and modified along with lean implementation. They are the basis of process reliability improvement. Standard work procedures and quality checklist are two major elements of the joint efforts between the homebuilder and trade contractors to standardize construction operations. The application of standardized work on operations is difficult at the beginning but can significantly improve the performance consistency of trade contractors.
4) FIFO-lane and work restructuring are two important tools for process reliability improvement. The idea of a FIFO-lane is to decouple the homebuilding process at places where uncontrollable obstacles to continuous flow exist, thus shielding downstream tasks from upstream variability. In lean

implementation, the length and the number of FIFO lanes will be gradually reduced with operation reliability improvement. Work restructuring results in the emergence of super-subcontractors, which completely changes the workforce relationship and construction process organization, thus having a major influence on improvement of construction cycle time and process reliability.

5) Continuous operation flow and production leveling are the prerequisite of lean production. Production homebuilders must take the responsibility to provide minimum flow volume and keep the workload flow even for at least four weeks. One approach to achieve this is to establish a pull system (supermarket) between sales and construction and control the release pace of spec houses.
6) For a factory-based housing company, 5S is a good start point of its lean journey, because it is easy to get buy-in from workers and produce visible results in short time period. Besides that 5S gets people enthusiastic about lean transformation, and effective cleaning and efforts to sustain a better-organized workplace involve many key lean principles and methods. Therefore, 5S can help people that have no lean production experience, to build teamwork, discipline, and a culture of continuous improvement.
7) Prefabrication techniques, like panelized construction, clearly facilitate lean implementation. By moving most construction of the house envelope into a factory, the homebuilding process becomes stable and predictable. Meanwhile, for the prefabrication system to work well, the homebuilding process must be managed to flow as much as possible. This completely changes the production control strategies of the company and establishes the foundation for lean implementation.

In conclusion, the research found that a lean production system and lean implementation strategies can be effectively integrated in the homebuilding process. By implementing the lean production model, the collaboration company significantly improved its operation performance in terms of construction cycle time, process stability, and house quality, which resulted in higher customer satisfaction. Although the lean production model presented in this study may not be universal for the entire housing industry, the author believes that the approach of lean model development and key lean implementation strategies could be generalized for any market in North America. It is the researcher's conviction that lean production along with industrialized housing will dominate the homebuilding trends in the near future, as it has in manufacturing in the past two decades.

6.2 RESEARCH CONTRIBUTIONS

Most research in lean construction has been undertaken under a project view and focused on developing lean theories and tools that could be applied to either some particular construction activities or the process of project delivery. A few researchers, who took a system view and studied the housing industry, worked mainly on building a system model on the industry level (Bashford et al. 2005). This exploratory research employed an in-depth case study on lean transformation of a production homebuilder at the corporate level. The major contributions of this research include:

1) A comprehensive approach to developing the lean homebuilding model and to planning lean implementation has been presented in the study. This approach provides production homebuilders with a framework for redesigning their homebuilding process based on lean production principles. Companies that are interested in lean construction, but do not know how to start, may follow the course of the case study company.
2) The research shed light on the challenges faced by production homebuilders and prefabrication producers in their lean transformation and identified the strategies that could facilitate the implementation of a lean production system in the homebuilding industry. Findings from this research will contribute to a better understanding of the applicability of the lean production system in the housing industry and provide a guideline for lean implementation.
3) In the study, a list of lean concepts have been redefined and lean tools been innovatively applied to suit the context of residential construction. Other researchers and construction practitioners can either use those lean concepts and tools in their lean practice or be inspired by the ways demonstrated in the research.
4) Real operation data have been used in the research to assess the results of lean application. This study is anticipated to be a benchmark for future studies in

the academic field and for homebuilders that want to employ the lean production approach. They can refer to the observation and analysis in the study to assess the current practice and develop improvement goals.

6.3 LIMITATIONS

1) The scope of this research focused on the lean implementation of production homebuilders whose production volume and make-to-forecast strategy allow them to provide a continuous workload to its trade partners. Some lean techniques and strategies proposed in the dissertation may not apply to small and custom homebuilders.
2) The conclusion is based on the lean transformation of the collaboration company. Further validation of the proposed approach is left for future research in this area.
3) The 2nd phase of the lean transformation is still on-going in the collaboration company. The implementation results of the factory-based lean homebuilding model (see Figure 4-22) are not included in the study due to time constraints.

6.4 RECOMMENDATIONS FOR FUTURE STUDY

"The journey for lean is by no means over." The research undertaken in this dissertation demonstrates a successful approach for production homebuilders to developing a lean production model and overcoming the obstacles in lean implementation, but this approach is far from final and perfect. In fact, the collaboration company is now in the second phase of its lean journey and confronting difficulties in culture change. Based on the continuous improvement efforts of the case study companies and lean principles, several areas of future research can be recommended:

1) This study is largely based on the collaboration company's lean implementation practice in the past two years, but those initiatives were only the first phase of the company's lean journey. It is suggested that the researchers continue participating, observing, and analyzing the lean practice in the collaboration company with a focus on culture change and continual organization learning.

2) In the study, prefabrication was limited to wood-frame open wall and floor panels. A precast concrete foundation system, closed wall panels, and panelized roofs are still in the planning stage. Due to time constraints, the author's research on industrialized housing is not complete. More research is needed to develop those systems and integrate them into the lean homebuilding process. A high level of prefabrication can further reduce process variability, thus opening a new horizon for lean implementation.
3) The generality of the research results is suggested by the literature review on the current homebuilding process and by the fact that the collaboration company actually consists of a group of companies focusing on different submarkets. However, a natural progression of this study is to replicate the proposed approach in other production homebuilding companies. There is no universal lean production model – even Toyota is consistently adapting its production system to local conditions – but the approach and key strategies presented in the dissertation should be effective for other production homebuilders.

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