A Framework to Improve Modular Construction Manufacturing Production Line Performance

By

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ABSTRACT

This thesis describes the implementation of a production line assessment framework to help shift off-site modular construction manufacturing (MCM) from a conventional construction approach toward true manufacturing. The framework, which integrates Lean manufacturing construction and value stream mapping (VSM) with a structure called "Production Line Breakdown Structure" (PBS), is developed to help analyze the current production line performance, identify existing issues, assess the proposed solution, and visualize the future implementation for modular construction manufacturing production lines. Throughout the process, conventional construction methodology, Lean manufacturing philosophy, and commonly used visualization tools are utilized in conjunction with the framework to promote the efficient cooperation between modular construction manufacturing and innovative thinking. Research is developed in collaboration with an industry partner, Kent Homes. It is presented as a case study to illustrate how the proposed framework can be deployed to effectively improve modular construction manufacturing processes.

Preface

This thesis is an original work by Youyi Zhang. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "A Framework to Improve Modular Construction Manufacturing Production Line Performance", No. Pro00068806 , Jan 23rd 2017.

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Table of Contents

List of Tables

List of Figures

Chapter 1 Introduction

1.1 Research motivation

The concept of modular construction manufacturing (MCM) can be traced back to the automobile industry and the era of craft production. With Henry Ford's introduction of the Model A automobile in 1903, a century of evolution centered on fulfilling the market demand for auto manufacturing began. Ford's mass production reached a new height of production in the early 1920s, at which time the company was producing 2 million identical vehicles per year (Womack et al. 1990). Toyota Motor Company introduced and developed the practice of operating a continuous assembly line with innovative designs for complete and consistent interchangeable parts in mass production and carried on the legacy from Henry Ford by introducing Lean production to the world (Womack et al. 1990). Lean production offers a solution to the negative aspects of mass production, which include: (1) single product production line which is heavily controlled by market demand; (2) large capital investment on machines with little flexibility; and (3) tremendous amount of production waste (identified by Taiichi Ohno, the founder of the Toyota Production System) throughout the entire process. Today's construction manufacturing industry has inherited the application of Lean production for the purpose of minimizing any form of cost (time, man-power, material, etc.) without compromising, and possibly even with improvement to, product quality and customer service (Womack et al. 1990).

In Europe and North America, industrialized housing production began in 1914. At that time, inspired by Ford's mass production process, the goal for architects such as Corbusier, Gropius, Bemis, and Fuller was to "raise efficiency by rationalizing the process through the application of scientific methods" (Womack et al. 1990). Gann (1996) claims that the influence of this construction philosophy is insufficient to ensure success in the long run, as was the case for the Model T Ford[1]. Model T Ford was successful because of the ability of producing standardized product with huge amount of volume, yet failed due to the limitation of customization to meet the growing market needs. In Japan, however, although the original motivation of industrialized housing was solely to uncover the market for excess steel production in the 1950s, the successfully developed Lean production process was eventually adopted into the housing industry to fulfill customer demand. Their approach entails comprehensive control of the entire production system, including "balancing the use of standard components with flexibility in assembly" (Gann 1996). However, experience with and understanding of Lean production cannot provide a complete solution to the housing industry.

At present the construction manufacturing sector (particularly MCM) seeks to leverage the benefits of mass production and Lean production in an attempt to achieve similar production to successful companies like Toyota; the results, however, seem poor in North America, with the exception of a small proportion of construction manufacturers. Minor changes can be seen throughout the production line in modular housing manufacturing facilities compared with the conventional construction process (which is analogous to craft production in the automobile industry). Despite this marginal progress, though, both academia and industry have come to the realization that MCM has been following the "stick-built under a roof" method. Creating Lean culture in construction manufacturing is recognized as an ongoing challenge for the MCM and panelized construction manufacturing sectors. Workers who have been working in the same modular home plant for 30 or 40 years are still practicing the same procedures to complete their daily tasks. Yet human resources are recognized as one of the key factors in the success of Lean

[1] The rise and fall of the Ford Model T illustrates the strengths and weaknesses of mass production.

production. In Table 1-1, a summary comparison of mass production and Lean production in the automobile industry with current housing manufacturer performance is illustrated and supported by photographs. It is striking to observe how the level of industrialization has been delayed in the construction industry compared with other industries, notably that of auto manufacturing. There is no doubt that the unique characteristics of the construction industry play a key role in the path to its industrial evolution, as has been widely recognized (Koskela 1993; Gann 1996; Yu 2010; Nahmens 2012; Moghadam 2014). Despite the barriers that have been identified, including the one-of-a-kind nature of construction projects, fluctuation of market demand, degree of customization requirements, and complexity of the building components, the researchers cited above are in agreement that the integration of Lean production in the construction field is a feasible approach for the industrialization of construction capable of eliminating process waste and improving production flow.

Table 1-1: Comparison of today's MCM with classic mass production and Lean production

	Current MCM in North American (case study industry partner)	Classic mass production at GM Framingham & Ford production line in 1986 (Womack et al. 1990)	Classic Lean production at Toyota Takaoka in 1986 (Womack et al. 1990)
Inventory	 -One week's worth of inventory stored on site	-Next to each workstation were piles—in some cases multiple weeks' worth—of inventory.	-There was no room to store inventory beside the workstation. Material was delivered JIT.
Ergonomics	 -Heavy physical-demand work	-Ford discovered the need to reduce the amount of human effort by using a machine. -Yet, humans were treated as an interchangeable part of the assembly line.	-Few workers in the aisles of the production line. -Engagement of every worker on the production line ensured a Kaizen environment, which aided to maximize human contribution by encouraging workers to work smarter not harder.
New technologies and innovative processes		-Ford benefitted from advanced machine tools, developed "innovative designs that reduced the number of parts needed and made these parts easy to attach". -"The interchangeability, simplicity and ease of attachment" has been recognized as the greatest	-The Lean production philosophy placed the key role on a management level with respect to work process and overall production line flow. -Focused on improving the process efficiency by finishing the value adding activity more efficiently and

	-Similar construction process to stick-built construction	achievement during the mass production era.	eliminating as much non-value-added activities as possible.
Continuous assembly line	-A typical MCM plant contains (i) prefabrication section (wall, floor, and roof panel); (ii) boxing section, where all the panels are combined together; and (iii) main production line, including a number of workstations. -Some workstations are used as buffer zone due to various work cycle times along the line.	-Although a continuous assembly line was introduced by Ford where tasks were assigned to the workstation and workers were assigned to the specific task at the station, the unevenly distributed workloads were causing waste on the line. -Large buffer area constantly occupied with defective cars.	-Occupied small amount of space to promote effective communication and most efficient working areas. -Work tasks were better balanced on the line and workers were working at similar pace. -Defects are not only fixed on scene but also recorded for lesson learning.

Today's manufacturing process in construction, though it shares similarities with mass production, in some aspects may not even reach the level of mass production. Clearly, the industry initiates the changes and improvement process aiming for the degree of manufacturing at the Lean production level, and there are efforts being carried out to create an auto manufacturing-like environment for the construction industry (prefabrication, panelized, or modular home manufacturing). However, as Womack (1993) asserts, "the elimination of construction peculiarities is not any solution itself: it just brings construction to the same level as manufacturing". There may be struggles in the development of a successful Lean MCM, yet learning lessons from mass production and embracing success from Lean production are practical approaches toward MCM performance improvement.

1.2 Research objectives

This research focuses on the MCM production line process performance improvement. The goal of this thesis is to leverage the current construction manufacturing process toward other developed manufacturing industry practices with the aim of providing a path to enhance the existing modular off-site construction technology in order to achieve a highly competitive product which can be delivered to the market. The current MCM process seems to be constrained by the traditional construction methodology, and the limitations of these long-established practices have been recognized as barriers preventing the industry from moving forward. Within the context of these considerations, this research is built upon the following hypothesis:

The proposed ***Production Line Breakdown Structure (PBS)*** *for production line performance analysis with the integration of* ***Lean manufacturing concept*** *and* ***value stream mapping (VSM)*** *will help to promote a reliable, predictable, efficient, and innovate* ***manufacturing construction process.***

In order to verify the hypothesis, this research encompasses the following objectives:

- Design the production line breakdown structure (PBS) for modular off-site construction manufacturing to assist the production line analysis, diagnosis, and problem solving.
- Integrate the PBS with Lean production and adjusted VSM to create a framework for performance assessment.
- Implement the framework through commonly used improvement process (current-state study, issues identification, problem solving, implementation, and validation) for improvement recognition and lesson learning.

1.3 Thesis organization

This thesis is organized into five chapters. Chapter 2 (Literature Review) provides a general summary of the current condition of the MCM industry. The aim of this chapter is to investigate the gap between the construction industry and other manufacturing industries. Current usage of VSM in the construction field and its limitations when applied to MCM are also addressed. Related information about supportive tools, including 3D modelling, simulation, and team-based brainstorming, can also be found in this chapter.

Chapter 3 (Proposed Methodology & Case Study) introduces the proposed methodology. To achieve the research objective, a hierarchical structure, Production line Breakdown Structure

(PBS), is used as a production line performance assessment guideline. The assessment output drives the improvement process, which includes four fundamental steps: (1) study of current-state conditions, (2) identifying issues, (3) proposing changes, and (4) validating the proposed changes through implementation. With the integration of Lean manufacturing, proper data analysis, and MCM specialized value stream mapping, a complete production line performance improvement template is developed.

The proposed methodology is implemented in a case study with the industry partner. The proposed methodology is explained in detail in conjunction with the case study. The case study validates the effectiveness of the proposed production line improvement procedure, although there are limitations, and future work is needed in order to further develop the PBS described in this thesis.

Chapter 4 (Conclusion) concludes the discussion of the proposed framework and summarizes the final findings for current off-site modular construction industry practice. It highlights the critical academic and practical contributions of this research and recommends the direction of future research with a focus on the area of construction manufacturing.

Chapter 2 Literature Review

2.1 Lean production

Lean production (also known as world class manufacturing and new production system) has evolved from a conventional production philosophy. Lean focuses on the conversion of the product process to a new production philosophy introduced in the early 1990s with ideas and techniques concentrated on two important "root" concepts: Just in Time (JIT) and Total Quality Control (TQC). The ideas and techniques revealed from JIT and TQC are summarized in Koskela's Technical report (1992), entitled "*Application of the new production philosophy to construction*". These include total productive maintenance (TPM), employee involvement, continuous improvement, benchmarking, time-based competition, concurrent engineering, value based strategy (or management), visual management, and re-engineering. He also expresses the core idea of this new philosophy in a simple graph and differentiates it from the conventional philosophy, as shown in Figure 2-1.

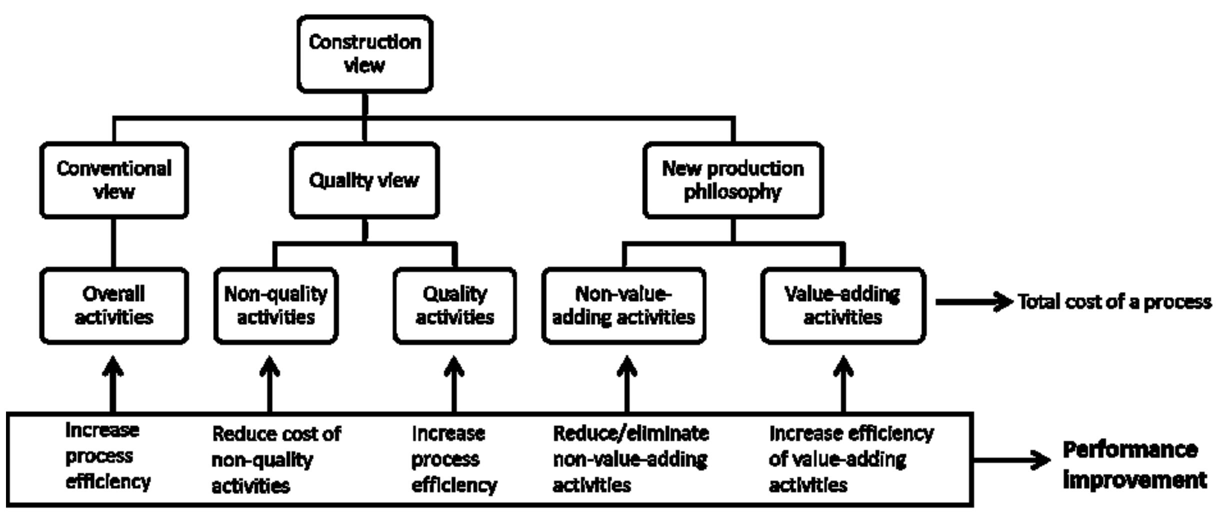


Figure 2-1: Performance improvement in conventional, quality, and new production philosophy approaches (modified from Koskela (1992a))

As shown, the successful identification of non-value-added activities and value-added activities ensures a practical performance improvement process in the factory, which is to reduce or eliminate the former and increase the efficiency of the latter. Another important point Koskela discusses is the difference between processing and flow in the context of the various aspects of production. Processing covers the conversion aspect of production, which is value-added activities, and flow covers aspects, such as inspecting, moving, and waiting, that do not contribute any value to the final product. A practical design procedure for a Lean production manufacturer is then translated into the following principles, according to Koskela:

1. Reduce the share of non-value-added activities.
2. Increase output value through systematic consideration of customer requirements.
3. Reduce variability.
4. Reduce the cycle time.
5. Simplify by minimizing the number of steps, parts, and linkages.
6. Increase output flexibility.
7. Increase process transparency.
8. Focus control on the complete process.
9. Build continuous improvement into the process.
10. Balance flow improvement with conversion improvement.
11. Benchmark.

To measure the effectiveness of these applications, Koskela cites Stalk's book, entitled "*Competing against time*" that cycle time, inventory turnover, value-added time as percent of total elapsed time, decision cycle time, lead time, and schedule performance are suggested as terms of use. In order to successfully implement the philosophy, the following four key factors are also mentioned: (1) management commitment; (2) focus on measurable and actionable improvement to maintain motivation and ensure the effectiveness of improvements; (3) involvement of every employee within the organization; and (4) learning continuously and consistently both internally (pilot projects) and externally (different tools and external information).

The above highly summarized content of Lean production from Koskela provides the fundamental knowledge of Lean production, which has gradually been adopted within the domain of off-site construction. Many of Koskela's ideas continue to be discussed and implemented in academia and industry.

2.2 Lean production in construction

2.2.1 Lean production as a general term in construction: Lean construction

The development of Lean production is based on three steps. It was originally a group of methodologies inherited from TPS—JIT, TQC, time-based competition, and concurrent engineering—which were used as the actual tools for implementation. These methodologies were later developed as second step, principles, targeted for flow design and improvement. When ideas begin to be widely implemented in the production industry, they eventually become the third step, concepts or a philosophy, to be utilized from a higher level aiming to assist any of the production consisting of flows and conversions (Koskela 1993). Given that the lack of efficiency in the construction industry is often criticized and considering that eliminating waste and improving efficiency are primary advantages of Lean production, naturally, the application of Lean in construction ought to be seen as essential. The construction industry diffuses Lean production from its highest level, as a philosophy, yet overlooks the development process to use Lean production as a fundamental tool at the first stage. This is one possible cause of the slow adaptation to this new philosophy, especially since it is a theory that needs to be clarified further with a holistic representation and a better definition of its existing concepts (Green & May 2005). Koskela (1993) explains his reason with respect to operation and process waste and the unique characteristics of construction as follows. The amount of waste in construction is a known factor in the industry, yet it has always been an aspect that left untouched. The root cause is that as "the flow aspects in the construction have been historically neglected", efforts to eliminate process waste are likely to conflict with conventional construction practice.

Koskela & Vrijhoef (2001) discuss the causes for deficient and implicit when defining theories and goals for modular construction industry, and suggest the following three: (1) the absence of radical, effective managerial innovation; (2) hindrance of top-down innovation from a theoretical perspective; and (3) hindrance of bottom-up innovation from a practical perspective. They note that although construction management is attempting to merge mass production and Lean production, which both lead to radical innovations and achieve significant productivity improvement for production, very limited improvement is seen in current construction practice due to the neglect of the underlying theory. From Koskela & Vrijhoef's point of view, the practical templates which worked for mass production and Lean production are not sufficient for today's construction industry, and one of their key arguments is that methods (including just-in-time and one-piece flow) "have been too far from the situation of construction to make direct diffusion possible" (2001). Yet, as the research is mainly focused on how theoretical developments are insufficient to assist the construction industry, few studies are available providing proof based on practical implementation to establish that methods from mass production and Lean production cannot effectively be applied to construction. In fact, those publications which do describe case studies of the implementation of Lean in construction have identified tangible improvement of the process (Salem et al. 2005; Moghadam 2014; Yu 2009; Meiling & Johnsson 2008).

A case study by Salem et al. (2005) implementing Last Planner System (LPS) on a field construction project provides a highly positive result. Another study illustrates the assessment of Lean construction implementation among seven different construction projects (Kim & Park 2006). Their results show that properly utilizing Lean tools will improve project performance. Their paper shows that personnel engagement and learning from past experience are vital to the success of Lean implementation. The authors point out that Lean construction focuses not only on pursuing the best performance for an individual activity, but also on viewing and managing the entire project as a system. Another important factor they mention is the difference between Lean and traditional construction's performance measurement metrics. Work Breakdown Structure (WBS)[2], Critical Path Method (CPM)[3], and earned value are some of the key metrics for traditional construction projects. But for Lean construction, percent plan complete (PPC), throughput (TH), cycle time (CT), work-in-process (WIP), and Takt time are the key metrics.

Alves et al. (2012) emphasize some key terms and suggestions about Lean construction practice, research, and education. They also identify three challenges in Lean production implementation in construction, as outlined below:

(1) Unclear defined guidance when applying Lean in construction (details will be discussed in the following paragraph).

(2) The translation of Lean construction from philosophy to real-life practice requires a stronger connection between academia and industry: Alves et al. make a strong argument that

[2] Work Breakdown Structure (WBS) is defined as a "deliverable oriented hierarchical decomposition of the work to be executed by the project team" by Project Management Body of Knowledge (PMBOK) (Guide 2001).

[3] Critical Path Method (CPM) is a project planning tool where activity sequence and duration can be visualized and the key activities can be identified.

practitioners simply do not have time to disseminate their knowledge and expertise to the academic community, yet practitioners are the contributors who are best positioned to provide novel insight and innovation based on practical experience.

(3) Sustainable engagement of personnel is vital for the success of Lean construction: many case studies emphasize that the engagement of people from all areas of an enterprise is key (Salem et al. 2005; Moghadam 2014; Yu 2010; Meiling & Johnsson 2008; Kim & Park 2006).

The unique characteristics of the construction industry have always contributed to the difficulty associated with implementing Lean. As the industrialization of construction becomes more widely known, other than the resulting relocation of the construction site from outdoor to indoor in order to mitigate the impact of weather, the actual benefits of modular home construction seem to be greatly inferior to those enjoyed by the auto industry when their production process evolved into a manufacturing process. Literature charges this to the lack of a holistic theory of Lean construction and the inability to apply the theory comprehensively at a level encompassing the entire enterprise (Koskela & Vrijhoef 2001; Green & May 2005; Jorgensen & Emmitt 2008; Asri et al. 2015). There is no doubt that this is one of the causes, yet the author of the thesis again asserts that the missing puzzle piece of carefully implementing Lean as a tool from a manufacturing point of view, drawing on how theory followed practice for auto manufacturing, is just as critical.

Jorgensen & Emmit (2008) summarize a number of missing links in the process of successfully transferring already well-developed Lean manufacturing principles in order to establish a truly Lean construction. One of their findings is that “impartial advice to practitioners based on empirical research finding, clear constructions, informed debate and constructive criticism” is lacking in today’s Lean construction. The construction industry is directly applying Lean construction as a philosophy from a holistic managerial level. As a consequence, limited information can be found in relation to practical studies about detailed solutions to improve, upgrade, and challenge the current, long-standing, common construction process based on the ample number of theoretical debates among academic researchers. Except for the ability to build floor, wall, and roof panels separately but simultaneously and then fit them together, (as some of the more innovation modular construction manufacturers have today), for most of the modular construction factory little change can be found in today's practice. The assembled module looks the same as if it were built on site, which means the way a craftsman would build a house in the past (stick-built on site) is the same way a modular manufacturer is building a house today; (refer to the images in Table 2-1 as an example).

Table 2-1: Off-site vs. on-site construction

Off-site (modular) construction	On-site (conventional) construction
	
Modular construction manufacturing	http://www.padavich.com/Residential.html

In order to encourage more practical solutions using Lean construction, a clear division of on-site and off-site Lean construction concepts is indispensable. The challenges associating with each of these paradigms can differ, especially in regard to the potential changes to the construction process and production line operation details. They do not necessarily need to share the same work sequence, type of materials, or operating tools, as working under a manufacturing environment provides more options of how to build the house. Therefore, not only is the development of Lean construction important, but how to utilize the Lean construction theory properly with respect to various personnel within the organization is vital in making Lean implementation practical. For instance, it is more appropriate for managerial staff to apply Lean as a comprehensive philosophy, whereas the approach to the operators on the line should begin with an introduction to Lean both as a tool and as a shaper of company culture.

2.2.2 Lean construction in off-site construction

Within the literature on applying Lean construction to both on-site and off-site construction are indicators of a shared theoretical background. There is no major distinction between these two construction methods when discussing the implementation of Lean production to today's construction industry. Industrialization, which in the context of construction is closely associated with off-site construction approaches, requires methods that differ fundamentally from those of conventional on-site construction. Koskela & Vrijhoef (2001), though, consider the amount of construction process waste generated by construction manufacturing in its current form to outweigh the limited benefits. A not well designed industrialized offsite construction could potentially create some process wastes that were not part of the conventional construction. Green & May (2005) point out that it is widely agreed upon that off-site manufacturing has strong potential in successfully applying Lean concepts to build a house by fitting the "Lego" parts together. But they also mention that problems with the incorporation of Lean to construction, including the deficient definitions of construction-related terms, make practical application of Lean in construction very inefficient. In the opinion of the author of the present study, Lean implementation for on-site and off-site construction should each include a separate set of enactments. Figure 2-2 illustrates the relationship between on-site and off-site construction in relation to Lean construction. The current literature mainly discusses Lean implementation within the Lean construction domain, and only limited conceptualizations and methodological studies of on-site and off-site construction individually (i.e., sections A, B, and C in the figure) can be found. As on-site construction (A) and off-site construction (C) each have their own specific characteristics, they also share some common processes, represented as section B. Treating these distinct paradigms as one and the same could slow the progress of shifting construction manufacturing fundamentally toward Lean due to the lack of clarity on pertinent concepts.

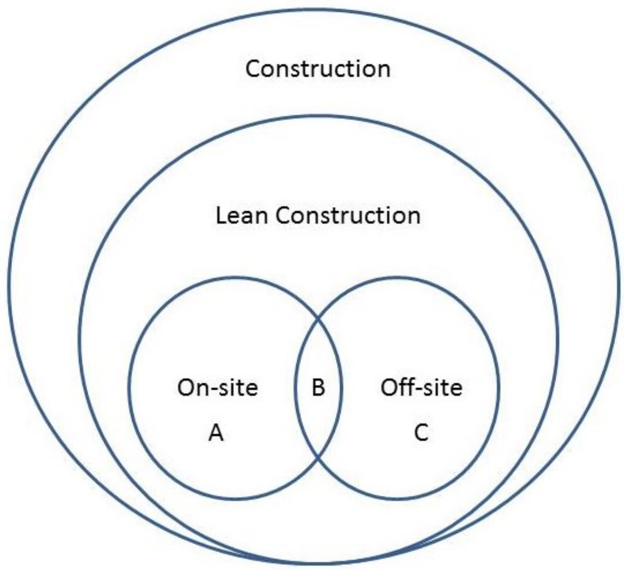


Figure 2-2: Relationship of on-site and off-site construction

A case study by Salem et al. (2005) offers little clarity as to whether various Lean construction techniques are suited only to on-site construction or if they are also applicable to off-site construction. As Kim & Park (2006) also note, features such as performance measurement, production process, and scheduling differ between Lean construction and traditional construction, and they thus question why scholars and practitioners have not differentiated between on-site construction and off-site construction in the context of Lean implementation. The author of the present study sees a need to provide clear guidelines for Lean implementation for on-site and off-site construction separately. Notably, Fernandez-Solis (2008) explores the differences between traditional manufacturing and building construction. He explains that mass product manufacturing is focused on the product and enabling its progression through process, whereas building construction under a manufacturing environment requires the effort on both the product and the process. He also summarizes 11 characteristics that define the essence of building construction and why it is difficult to translate building construction to manufacturing. His summary is developed based on 11 academic studies, and, although some of the points seem common in the construction industry, it has strong potential to be improved in the future by considering the off-site construction environment. For example, the inefficient operations, the overlapping activities that require long lead time, the continuous adaptation to on-site changes, and the "firefighter[4]" format of problem solving instead of effective learning characteristics of off-site construction ought to be addressed. As no clear conception of Lean in the context of on-site and off-site construction is given in the literature, and since the challenges of applying Lean in construction continue to be analyzed only in general terms, the complex nature of construction has become an excuse not to move the industry forward.

Poor performance measurement strategies, weak definitions of implemented methodologies, and limited prefabrication are recognized as barriers that affect the application of Lean in construction (Suresh et al. 2010). This is a valuable point, because the application of different methodologies to on-site and off-site construction will lead to different performance measurement strategies. As such, simply applying Lean the same way to both construction approaches is not sufficient. Researchers are focusing on studying Lean construction as an off-site construction format, yet little effort has been made to fully leverage the potential benefits of off-site compared to on-site construction. Also, since the process details of before-and-after

[4] Firefighter: problem solving: react to the problem after the impact of the issue has already been felt, with limited control of the problem beforehand.

implementation are rarely investigated, there is no measurement of whether the improvements achieved will be sufficient to offset the effort invested to industrialize the construction process. In addition, most of the literature in this area only mentions the benefits of off-site construction from a project management perspective in general terms, but little detail of the process improvement to be expected is demonstrate the effectiveness of the Lean concept when applied throughout the construction process. For example, Pasquire & Connolly (2002) use an integrated heating, ventilating, and air conditioning (HVAC) module as a case study to show how off-site manufacturing can benefit the construction process. The case study is a pre-assembly study where the modular construction process is not included. However, it does provide a good reference as to what can be expected for regular site construction when pre-assembly components are available to use. The data from their case study shows a significant improvement after the company introduces the use of complete prefab HVAC modules for on-site installation. In their paper, they also emphasize the importance of having effective performance measuring parameters and methods tailored to off-site manufacturing specifically. They suggest a measuring guideline encompassing three aspects: time cost, money cost, and quality improvement. Yet their focus is mainly on on-site work performance improvement, whereas off-site work should be the core area of study in this regard. The potential performance improvements, innovations, and technology upgrades should become the focus when shifting construction to manufacturing. Additionally, the performance data results given in their study do not speak to the overall savings in labour or money cost, which also critical metrics that ought to be considered. As a consequence, it is difficult to measure or assess whether the construction manufacturing domain is exploiting the benefits of a manufacturing environment to the full extent possible. Only focusing on the advantages of manufacturing with respect to performance of on-site assembly does not in a comprehensive assessment.

A number of publications have been proffered by experts with hands-on experience in modular construction manufacturing (Meiling & Johnsson 2008; Johnsson & Meiling 2009; Meiling et al. 2012; Meiling et al. 2014). These studies are highly practical and target the delivery of technical solutions for the production process through detailed case studies. Similar to the ideas of Liker & Lamb (2002), they not only focus on developing a vital cultural transition in the factory and high-level abstract Lean strategies, but also emphasize effective, practical utilization of Lean manufacturing tools. Meiling & Johnsson (2008) reference Hook's (2006) definitions that on-site construction is an object-oriented approach, and that off-site construction (i.e., prefabrication) should be treated as a process-oriented undertaking which can take advantage of having repetitive operations. These definitions help to emphasize what should be the key focus in Lean implementation: learning. Based on their case studies, they conclude that improving the communication among different parties, especially at the early stages of the construction cycle, can reduce the defect rate on the production line, and that tracing defects back to production and design is vital for continuous learning and improvements in the future.

Off-site and on-site construction can be divided into six steps, which provides important distinctions in moving toward studying these two construction methods as distinct paradigms of construction. The following diagram in Figure 2-3 presents the six steps in detail (Meiling & Johnsson 2008; Johnsson & Meiling 2009).

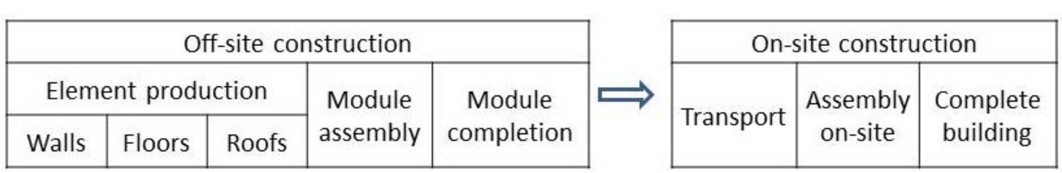


Figure 2-3: Six steps of construction procedures in industrialized housing

Each step should be focused on separately to ensure the effective implementation of Lean. In their case study, Johnsson & Meiling (2009) assess a complete project process for two companies, including the briefing process, the design process, the manufacturing process (off-site construction three-step process), and on-site assembly (on-site construction three-step process). The assessment focuses on the product defects, yet the entire assessment process is guided by the Lean concept. Based on their analysis, the predominance of a traditional on-site construction culture in the factory results in low worker involvement in process improvement as well as limited opportunities to learn from mistakes. Workers primarily focus on simply solving problems as they arise. More importantly, this behaviour hinders efforts to modify an existing and firmly entrenched building procedure with innovative long-term performance improvements based on the addressing of root causes. Johnsson & Meiling describe the case study companies in short as factories "moving onsite construction indoors and not adjusting to factory physics". They recommend that construction manufacturers avoid the practice of finding solutions solely to meet the external customer's demand, but to also avoid reactively looking for solutions for internal customers such as production line workers, design engineers, and plant managers (Johnsson & Meiling 2009).

Liker (2004) summarizes the following management principles which are used by Meiling et al. (2012) to help measure the successful application of Lean in off-site construction:

1. Making long-term decisions based on Lean construction philosophy.
2. Solving root causes through continuous improvement.
3. Using pull system[5] instead of push system[6] to reduce waste.

[5] Pull system: a Lean methodology to eliminate overproduction on the line by producing product when downstream requires.
[6] Push system: a system could lead to overproduction, a type of waste generation way of operation on the production line.

4. Balancing the workload on the production line.
5. Changing the "firefighter[7]" culture to a more proactive approach to problem solving.
6. Increasing the standardization of tasks and processes on the production line to assist in continuous improvement and employee empowerment.
7. Using visual control tools to reveal the hidden problems.
8. Ensuring the effective technology for use by internal personnel (right tools, proper equipment, efficient procedures, etc.).
9. Leadership development from bottom up.
10. Leadership development from top down.
11. Connecting with external partners and suppliers to promote collective improvement.
12. "Go and see for yourself to thoroughly understand the situation".
13. Conducting thorough consideration before making decisions and implementing the decisions quickly and effectively.
14. Learning from continuous improvement.

Their study finds that the ranking, given by management personnel and production personnel, of the perceived importance of these principles are inconsistent. Management rates the principles that are aligned with the philosophy aspect with higher scores, whereas production line personnel tend to rate the principles related with their daily operations with higher scores. Since all of the principles are equally critical in reality, ensuring the "buck effects"[8] while applying Lean principles is important.

Another study by Meiling et al. (2014) looks at how plan-do-check-act (PDCA) assists the company conducting the continuous improvement Lean strategy. PDCA is applied to two

[8] Given that all principles are equally critical, the actual performance is based on the principle that is implemented least successfully.

different off-site construction cases, one of which is carrying out window adjustments during the module completion procedure; the second case involves avoiding open connections during the module assembly operation. They discover that PDCA improves the window case more effectively than the second case, and summarize the reasons for success and failure as shown in Table 2-2.

Table 2-2: Differences between two cases while applying PDCA

Success for window case	Failure for connection issue
1. The activity is isolated from other processes.	1. The activity mainly operates on site.
2. It is a standardized work process with a stable assigned crew.	2. Less standardized work process is designed with larger and more complicated work crews.
3. It is a smaller scale project since the activity duration is small.	3. It is a challenge to accurately locate the root causes of the problem.
4. The root causes of the problem are successfully located by using Ishikawa diagram, therefore the improvement implementation is effective.	4. A comparatively large improvement project, which demands heavy resource input; therefore, people can be less engaged to pursue a permanent process.

Based on the findings above, they also provide a four-part solution to increase the effectiveness of applying PDCA in off-site construction. First, a comprehensively planned problem solving procedure is required. Second, proper utilization of the available visualization tool can provide a clear overview of the problem, which is critical to encourage the required changes. Third, a tangible improvement plan to make the project realistic and practical to the people involved needs to be provided; this is critical to gain commitment from frontline workers and will make the process measurable. Fourth, the culture of the frontline worker needs shift to challenge the current state with a positive attitude from the bottom up to ensure continuous improvement of the organization (Meiling et al. 2014).

The Modular Building Institute (2010) also underscores the need for effective performance measurements to boost the efficiency of as well as encourage innovation for off-site construction.

As they note, performance measurements will provide lessons learned from past failures and will help with assessing proposed improvements, and thereby support the effectiveness of long-term production line performance improvement.

Elnaas et al. (2014) discusses the factors that influence the house building industry to make decisions on whether to use off-site manufacturing instead of on-site construction. Cost is identified as one of the key challenges that concern the home builder. Despite opportunities to reduce the labour cost and improve productivity on site, the perception of many is that the extra resource requirements of off-site manufacturing will outweigh the disadvantages of on-site construction. The author believes that continuously improving the off-site construction process through innovative measures and process waste savings will lower the cost of the off-site construction process substantially. The challenge is to solve the current research limitations while also increasing awareness and understanding across the industry that merely transferring traditional construction processes to an indoor environment does not constitute a shift to true manufacturing.

2.3 Continuous improvement vs. innovative construction technology

Lean production has a long history of seeking a balance between continuous improvement and technological innovations. This has been a topic of concern since the early Lean production era when Ohno in 1982 stated that the co-existence of continuous improvement and innovation requires the establishment of an optimal sequence to ensure effective production line performance, as cited by Koskela (1992a). Yet, technological innovation seems to have been overlooked, if not missed entirely, in current efforts to improve the MCM process. Implementation of Lean production in construction has motivated substantial efforts in computer integrated construction (CIM) (Crowley 1998), integration of building information modelling

(BIM) with Lean production (Moghadam 2014), and process improvement focused on identification of non-value-added activities, though with limited efforts toward re-engineering the value-added activities for efficiency improvement. Yet in the scholarship re-engineering has been recognized as one of the primary techniques for early applications of Lean production in construction. Koskela (1992b) states that the term re-engineering refers to "the radical reconfiguration of processes and tasks, especially with respect to implementation of information technology", and he also refers to the statement by Hammer (1990) that re-engineering is a process that transcends the "outdated rules and fundamental assumptions" to achieve radical improvement not only for an individual activity but also for the entire process. In fact, re-engineering was originally identified as a result of the success of Ford's mass production. In Womack et al. (1990) argue that the advanced machine tools, the innovative interchangeability of the automobile components, and the new types of material from steel manufacturers resulted in massive benefits for Ford. Not only that, the legendary story of die-change[9] in the early Toyota Production System (TPS) also illustrates the necessity of evolutionary innovation along the path of production line improvement. Nonetheless, having a mindset of improving the flow by eliminating non-value-added activities and improving the value-added activities is not the biggest contributor to Toyota's success story. It is the emphasis on waste elimination and the focus on value-added lesson learning from Lean manufacturing that makes the achievements of mass production forgotten. Mass production use the concept of creating a smooth production line with resources assigned to each work station was also the foundation of the modern

[9] A die is a precisely shaped sheet metal, which requires considerable human effort—pounding—to fabricate over a long period of time. To replace a die usually requires a full day, causing delays on the rest of the line. Moreover, it requires a specialist to complete the task. Ohno, however, reduced this process astonishingly to three minutes and eliminated the need for die-change specialists by developing a new die-change technique to solve the root cause proactively instead of trying to apply extra effort to reactively address the problem as had been the practice among Western auto manufacturers.

manufacturing process which cannot be ignored. However, it is important to acknowledge the path that led to Toyota's current production system. The transformation from craft production to mass production, and then to today's Lean production, is inevitable, and mass production plays a key transitional role. As Crowley (1998) quotes from Drucker's *Theory of Business*, "just as one business theory becomes the mainstream, the world moves on to make it obsolete".

Some studies emphasize the importance of process improvement and overall production line system management over the development of innovation technology. Meiling's publications offer practical knowledge based on his experience, and clearly outline his thoughts on continuous improvement implementation in MCM. Meiling believes that creating a Lean culture and having a fully committed managerial staff plays a key role in the successful improvement of production line performance (Meiling et al. 2014). Based on his case studies, companies that have been adopting Lean construction principles in their factories are willing to consider new ideas for operational procedures; when a problem is identified, manufacturing-specific innovation of the procedure is applied. Creating a standardized window adjustment procedure, for instance, is not a highly skilled or advanced technological development, yet it is a continuous improvement measure that encourages all personnel to work toward a practical solution rather than the commonly known "firefighter" method of solving the problem. The importance of challenging the traditional engineering process is also mentioned by O'Connor et al. (2015). They provide a thorough study of the relationship between standardization and modularization and state that having a standardized modular plant leads to greater cost savings and higher quality products when compared to the stick-built process and a non-standardized modular plant.

An area that may be misunderstood is the technology related to automated machine development in the construction industry. The aforementioned innovative ideas do not encompass external support for the production process, but to the production process itself. Koskela (1992b) discusses the relationship between process improvement in construction and machinery automation. He mentions that technology itself (highly automated machinery design) will not achieve what Lean production has, but a good overall management procedure for the entire process will yield similar achievements to those of Lean production, and it is also applicable to Lean construction. He uses a chart to illustrate where automation stands on the path of process improvement implementation in the construction field, which demonstrates his idea clearly (see Figure 2-4).

The author of the present study believes the successes of innovative technology and continuous improvement, which involves the 11 principles previously mentioned in Section 2.1, are interdependent, and that the two should be advancing together on the process improvement path. Failing to consider the purpose of the new technology, a mistake which can prove costly and time consuming, may lead to failure when trying to fit the technology into an existing process. For example, the new technology could be over-qualified for what a given production line requires based on the performance of other activities. Furthermore, limited efforts toward creating and implementing the new technology can be a barrier to establishing a more balanced flow.

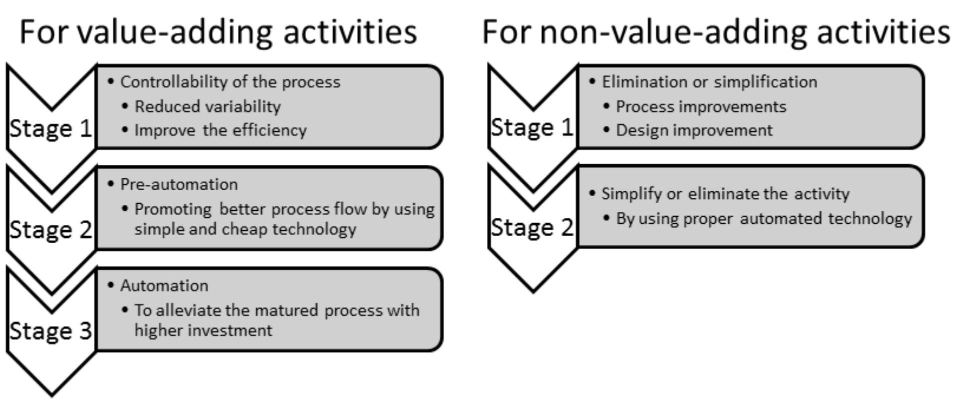


Figure 2-4: Relationship between process improvement and automation technology (modified from Koskela (1992b))

In Figure 2-5, Koskela illustrates the relationship between continuous improvement and innovative technology, which further proves the thesis's author's point of view (1992).

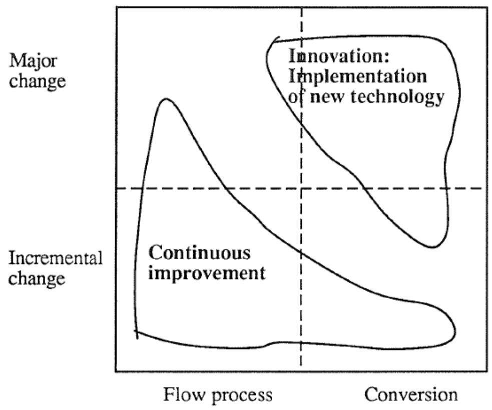


Figure 2-5: Continuous improvement and innovation: focus and aimed change (Koskela 1992a)

Nahmens & lkima, in one of their case studies, illustrate a process improvement by applying Lean construction technology (2012). They observe the process of hanging gypsum board by a modular house manufacturer and summarize their findings into five potential issues: (1) clutter and congested forklift path; (2) improper material staging; (3) quality issues related to unevenness of wall and ceiling wood frame; (4) poor supervision and management; and (5) leakage in the roof preventing proper staging of materials and positioning of modules. Their approach for the improvements based on the findings is strongly related to the flow improvement aspect of the production. Eliminating the non-value-added activities and improving the value-added activities are undoubtedly the key implementations from Lean construction. Therefore, the solutions are as follows from Nahmens & lKima: (1) improve material staging by reducing the moving distance; (2) pre-manage material delivery to avoid damage and traffic challenges; and (3) enhance design of workflow to improve the value added efficiency following the traditional work process. The results are noticeable as they report a 15% increase in efficiency improvement for value-added activities and a 63.6% process waste reduction. But, what does this 15% improvement mean to the overall production line? Are the findings from the old practices looks similar to some on-site construction processes? Will applying Lean production with an emphasis on the workflow aspect of production slow down the development of MCM? Lean production embraces the re-engineering aspect (process improvement) of mass production, but focuses on workflow improvement, which is ignored by mass production. Ensuring that the application of Lean production in construction not only focuses on the success of this philosophy but also on the success of other approach with common goals is critical especially considering that today's modular construction industry is still predominantly a stick-built-under-roof process—i.e., an updated version of craft production.

Fortunately, challenges to the conventional construction process are available. Shafai (2012) introduces an innovative manufacturing-based wall framing technique to increase the efficiency and quality of wooden wall panels. It is found to extend the benefits of what an automated framing machine can offer by reducing the degree of variation in the product. This innovative construction process is referred to as multi-wall panel system. In Shafai's study, combining a group of small wall panels to a standard-size single-wall panel, and fabricating them as one long "multi-wall" that will in turn be divided back in to individual panels later in the process, serves to shorten the wall framing process time by 40% by reducing the setup time for fabrication. The improvement not only applies Lean production principles from a workflow perspective to eliminate the non-value-added activities (the setup time for each small wall panel), but also breaks the outdated rule of framing wall panels one by one. Shafai challenges the traditional process and builds four or even five wall panels in one process. This example is also a low investment innovation, indicating that new techniques are not always expensive, (a common misconception which is seen as another challenge in MCM). Kim (1999) mentions that the rate of radical product innovation is high when there is a need to satisfy the market niche, even though it can be expensive. Perhaps this is what is needed in today's MCM industry.

2.4 Value Stream Mapping (VSM) application in off-site construction manufacturing

VSM is one of the methods to implement Lean at both the production process level and management level. A successfully mapped value stream will not only illustrate the material flow of the process but also the information flow, which supports the establishment of an effective value-added process (Rother & Shook 1999). Jones & Womack (2002) give VSM a comprehensive but highly summarized definition as "the simple process of directly observing the flows of information and materials as they occur, summarizing them visually, and then envisioning a future state with much better performance". The well-developed VSM modelling language and clearly defined scope of VSM application make this Lean tool practical to use within the general factory environment. Lian & Landeghem (2005) identify five key principles to consider when creating the VSM based on the study by Jones & Womack (1992): (1) identify the value based on customer demand; (2) identify the value stream and the waste portion of the value stream; (3) create flow; (4) promote a pull system on the line to minimize waste; and (5) maintain continuous improvement with respect to value, value stream, flow, and the pull system. In their paper, an integration system of simulation and a meta-level view of VSM, value stream mapping paradigm (VSMP), is developed to use as a validation tool and to create a dynamic VSM capable of visualizing the proposed changes on the production line. This is a valuable tool to support the company's decision making and to make Lean implementation visible and practical. Ben Fredj-Ben Alaya (2016) presents a case study of using VSM as a diagnostic and planning tool for Lean implementation in an auto parts manufacturing firm. She summarizes five reasons to apply VSM: (1) as a mapping and visualization tool; (2) as a tool that enhances effective communication; (3) as a diagnostic tool that uncovers the waste within a defined range of process flow; (4) as a strategic planning tool for improved performance in future process flow; and (5) as a change management tool—a tool to confront the challenge step by step from bottom up. Her study not only focuses on the qualitative side of VSM implementation, which relates to value stream metrics analysis, but also shows the detailed procedure of how to apply VSM as a diagnostic tool. The studied activities are clearly defined and the study procedures are as follows:

1. Diagnosis of the value stream.
    a. Information flow analysis to reveal the inefficiencies at different levels.
    b. Material flow analysis to reveal the inefficiencies on a more practical level.
2. Recommendations for current value stream based on Lean.
    a. Focus on following the Takt time production pace.
    b. Promote the Kanban system for inventory control.
    c. Ensure the FIFO (Fist-In-First-Out) production line flow.
    d. Use pull system for inventory control to ensure minimum delay on the receiving dock.
    e. Balance workload distribution throughout the production line to support the effectiveness of pull system and FIFO.
    f. Begin the load levelling from the assembly lines, and could steadily move this approach toward post-assembly line.
3. Putting the findings and solutions into action to ensure the effectiveness of the improvement process is vital for future operation.

Ben Fredj-Ben Alaya (2016) believes that by integrating the above study procedures with VSM, the manager can benefit in the following respects:

1. Not only can waste be identified, but a thorough analysis of root causes of the waste can also be carried out.
2. It provides access to observe both information flow and material flow, a systematic study.
3. Combining different Lean tools for comprehensive analysis avoids “cherry picking”.
4. By observing the entire value stream, the improvements can be maximized by focusing on the key issues instead of focusing on independent activities without considering the entire process as a system.
5. A step-by-step feasible improvement plan can be developed so that the implementation plan can be effective.
6. The promotion of communication skills both internally and externally, focusing on employee involvement from bottom up, will ease the implementation process.

Integrating VSM with Lean has also resulted in a positive experience for the aerospace industry (McManus & Millard 2002). However, as many of the case studies mentioned above are related to manufacturing sectors than other construction, VSM has been limited in its use in MCM due to the paper-and-pencil nature and other unique characteristics of the MCM process (Moghadam 2014), despite all of its benefits. It is widely agreed that VSM is a static tool and has this is a disadvantage when representing complex processes and uncertainties (Lian & Landeghem 2005), both of which are typical of construction. Simulation, which is more flexible in the handling of complex processes with a large range of variation, has become a popular tool to use for the manufacturing process in off-site construction (Moghadam 2014; Shafai 2012; Arashpour et al. 2016). Han et al. (2012) even combine the simulation process with a 3D visualization tool for modular building production assembly lines, although production line performance improvement procedures are not included in this study.

However, VSM has not yet been applied in a manner which effectively accommodates the MCM environment, this due to the immature application of Lean in off-site construction. Switching the mindset from building houses in the factory following the same procedure as constructing a building on site to building houses following manufacturing-oriented procedures will help with successfully implementing VSM in construction manufacturing.

2.5 Modular construction manufacturing (MCM)

Modular construction manufacturing (MCM) claims to be able to improve construction processes, capitalizing on the advantages of the process, high efficiency, and cost-effectiveness of manufacturing. Nevertheless, current MCM is criticized for limited innovations due to the fact that the techniques applied in are congruent to those in the conventional on-site construction process (Moghadam 2014). As Ohno (1988) developed the Toyota Production System (TPS), which built on the foundation of mass production to bring in a new era for today's most well-known manufacturing industry (automobile manufacturing), the Lean concept has been widely implemented in various sectors including the construction industry. The complexity of a given project in the construction industry often leads to the criticism that the industry has seen only limited implementation of Lean, prompting critics to conclude that Lean production may be less effective in construction manufacturing than it has been for the automobile industry. The present research thus develops a practical framework to integrate the characteristics of the construction process, the benefits of the manufacturing production line, and the specialization of Lean production principles in order to transform MCM into a highly efficient and cost-effective approach to constructing buildings.

Since MCM is the combination of both construction and manufacturing practices, Moghadam (2014) thoroughly studies the similarities and differences between them as well as their integration with Lean production. A summary of this study, focusing on the factors that influence the performance of MCM production line, which is the purpose of this research, is provided below:

1. For construction projects, the limitation of continually unique projects makes having a temporary resource management system for each project unavoidable. A manufacturing approach, where long-term equipment usage could be used to support optimal operation processes and stable permanent trade workers that ensure quality and timely delivery on the production line, seems impractical for conventional construction projects. Disruptive workflow and unpredictable schedule in the construction field are other disadvantages compared with the typical manufacturing process. To ensure the efficiency of the overall production line, in manufacturing the work sequence is typically stable and activities are assigned to the predefined workstations for best process control.
2. Adding the Lean concept to manufacturing successfully leverages the benefits of manufacturing operation; yet, when combining construction with manufacturing, only limited benefits to the actual operation are typically observed. Some key factors in Lean implementation include repetitive runs, stable workflow (constant Takt time), predefined workstations with designated activities and required resources, and standardized product design and work process for waste reduction and minimization of variation. However, these are not easily realized in construction, which by nature is highly variable and unpredictable. As such, a specific type of Lean implementation

needs to be designed for construction. In this respect, the Last Planner System (LPS) has been invented for construction scheduling, whereas Value Stream Mapping (VSM) is typically the scheduling tool of choice for manufacturing process control.

3. When transferring construction to the manufacturing environment, a new approach to Lean implementation is introduced for the MCM industry. For manufacturing production levelling, adding resource levelling helps to eliminate the disadvantage of having dissimilar product types. Designing sub-assemblies and documenting Standard Operating Procedures (SOPs) for both sub-assemblies and regular production line processes brings the potential to create a predictable production flow. A scheduling tool is also introduced where VSM, LPS, Critical Path Method (CPM), and Linear Scheduling Method (LSM) are integrated as a new Lean application in MCM.

Despite all of the above adjustments among manufacturing, construction, and their Lean applications, limited effort has been put forth to integrate construction into the manufacturing process prior to incorporating the Lean concept. The fact that efforts to modify conventional construction in order to adjust to the manufacturing environment have been limited has inhibited innovation in the MCM industry, and has also hindered the effective implementation of Lean production, which is a concept built on the foundation of manufacturing principles. Construction manufacturing embraces the characteristics specific to the construction industry, which in turn create barriers to the implementation of Lean tools; however, this research not only requires the adjustment of manufacturing to the construction process, but also the modification of construction to fit into manufacturing operation so that Lean can be leveraged. A root cause analysis in Figure 2-6 illustrates the aforementioned point.

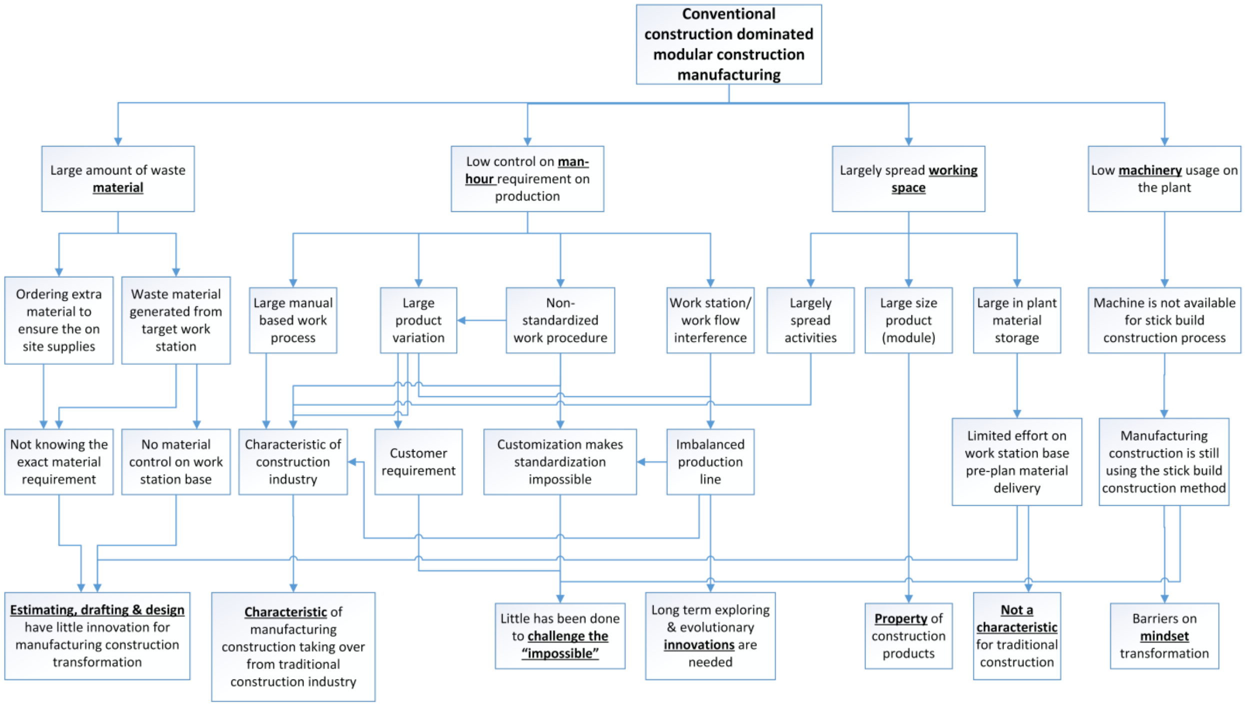


Figure 2-6: Root cause analysis for current modular construction manufacturing industry

Chapter 3 Proposed Methodology & Case Study

3.1 General background

3.1.1 General background of proposed methodology

The proposed methodology includes two core elements: (1) production line breakdown structure (PBS), which is a guideline designed to assist manufacturers in assessing the performance of a production line, and to break down the production line into different levels for targeted analysis; and (2) an extensive value stream mapping (VSM) application to support analyses at different levels of PBS. In order to apply VSM in off-site construction effectively, some of the input data or KPIs (key performance indicators) from VSM need to be adjusted for the construction context.

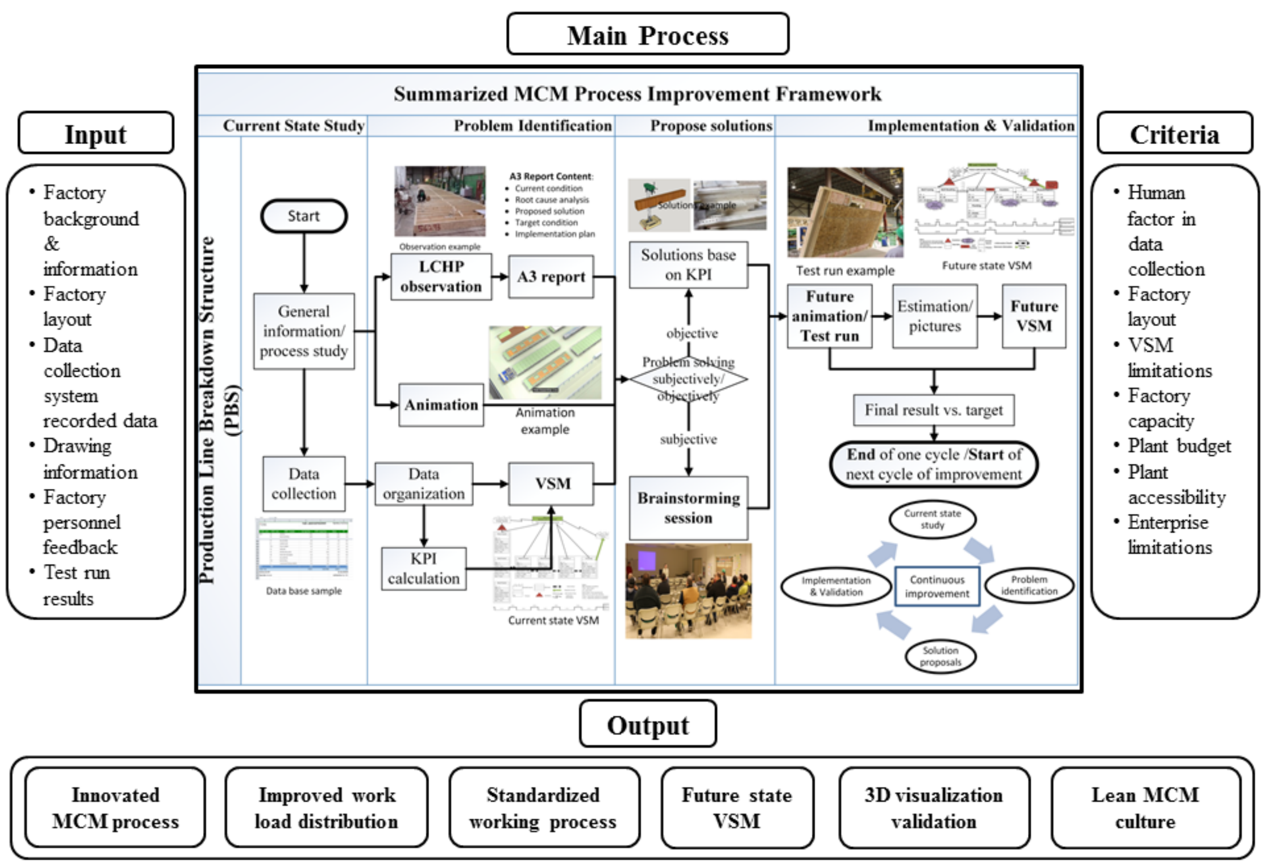


Figure 3-1: Research methodology for MCM production line performance improvement

Figure 3-1 illustrates the proposed methodology outlining how to use PBS-supported VSM to conduct a current-state assessment of modular house production line performance, troubleshooting the identified problems, and ultimately achieving improved performance of a production line validated with the future-state VSM. There are four pillars represented in this figure. The key pillar, "main process", requires input information including general factory information, collected data, and, most importantly, feedback from experienced personnel in the factory. The main process is also constrained by criteria such as company policy, budget availability, accuracy of the collected data, and the limitations of the applied Lean tools in the construction industry. In the main process, an MCM improvement framework is designed following four general steps. Each of these steps is guided by PBS so that the proper level of detailed study can be conducted along the improvement process. In addition to the PBS and VSM, data collection and organization, Low Cost High Payback (LCHP) observation (low hanging fruit observation), A3 report[10], and 3D visualization are used as the supportive tools. The outputs after the main process include improved MCM construction process, as well as future-state VSM for validation and as foundation of future continuous improvement.

The detailed explanation of PBS, VSM, and all the other supportive tools that are integrated into the framework for MCM production line performance improvements are illustrated in a case study. The complexities of this four-step methodology are best elucidated through real application. The case study will be introduced following the four-step improvement procedure: study of the current-state, problem identification, recommendation of future improvements, and validation of proposed improvements. For each step, key concepts and tools used (PBS, VSM, LCHP observation, 3D visualization, etc.) will be introduced, followed by real case application.

[10] A3 report indicates a report created using A3 paper. It is a tool used in Lean to help record the findings and potential improvement after the production line observation or performance assessment.

3.1.2 Case study of PBS & VSM integrated MCM process improvement framework

The case study in this research is carried out at Kent Homes, a modular house manufacturer based in Bouctouche, New Brunswick, Canada. The industry partner produces various types of modules, although only the "mini home" and "modular home" modules are studied in this case study. The mini home is built with a single module, and the modular home comprises two modules that are assembled together on site. The entire production line is studied, including the floor, wall, and roof sub-assembly line, erection line, and main production line. The case study process follows the improvement framework from Figure 3-1.

In Figure 3-2, a cross-functional flowchart is presented to illustrate the main process framework with details based on different PBS levels. The second row in the chart indicates the timeline for the factory to carry out the four-step process improvement journey. The first column indicates the PBS in five different levels. (The detailed definitions for each level of PBS will be introduced in the next section.) This cross-functional flowchart shows the level of detail required at each step of the improvement process and thereby provides a guideline for the factory to implement the production line performance assessment effectively. For example, the chart shows that at "Step 2: Problem identification" and "PBS level 4", raw data organization, LCHP observation, A3 report, and level 4 VSM are required in order to proceed to the next task on the flowchart.

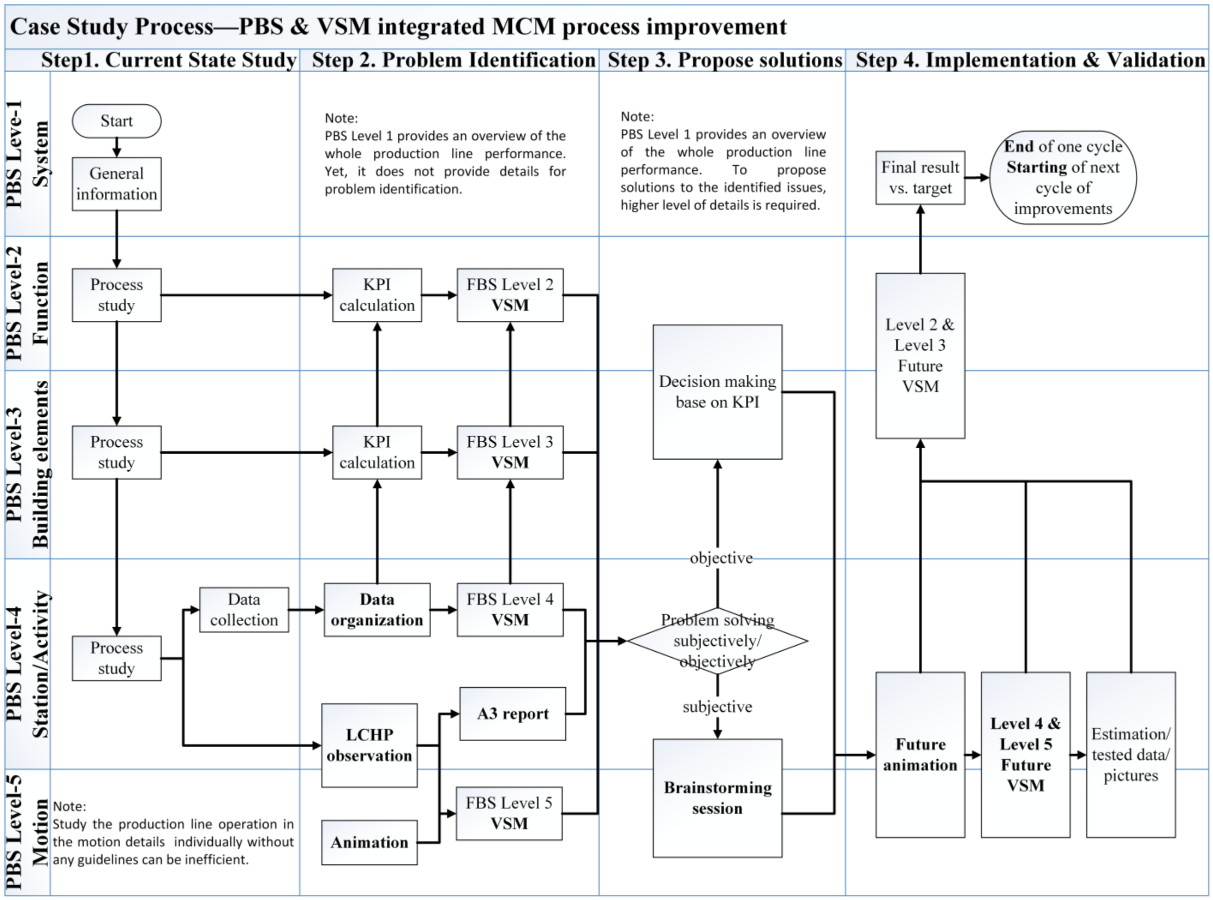


Figure 3-2: Cross-functional flowchart for MCM performance improvement process

This chapter will explain the proposed methodology in detail based on the provided framework in addition to the case study conducted by the author.

3.2 Improvement process step 1— study of current state

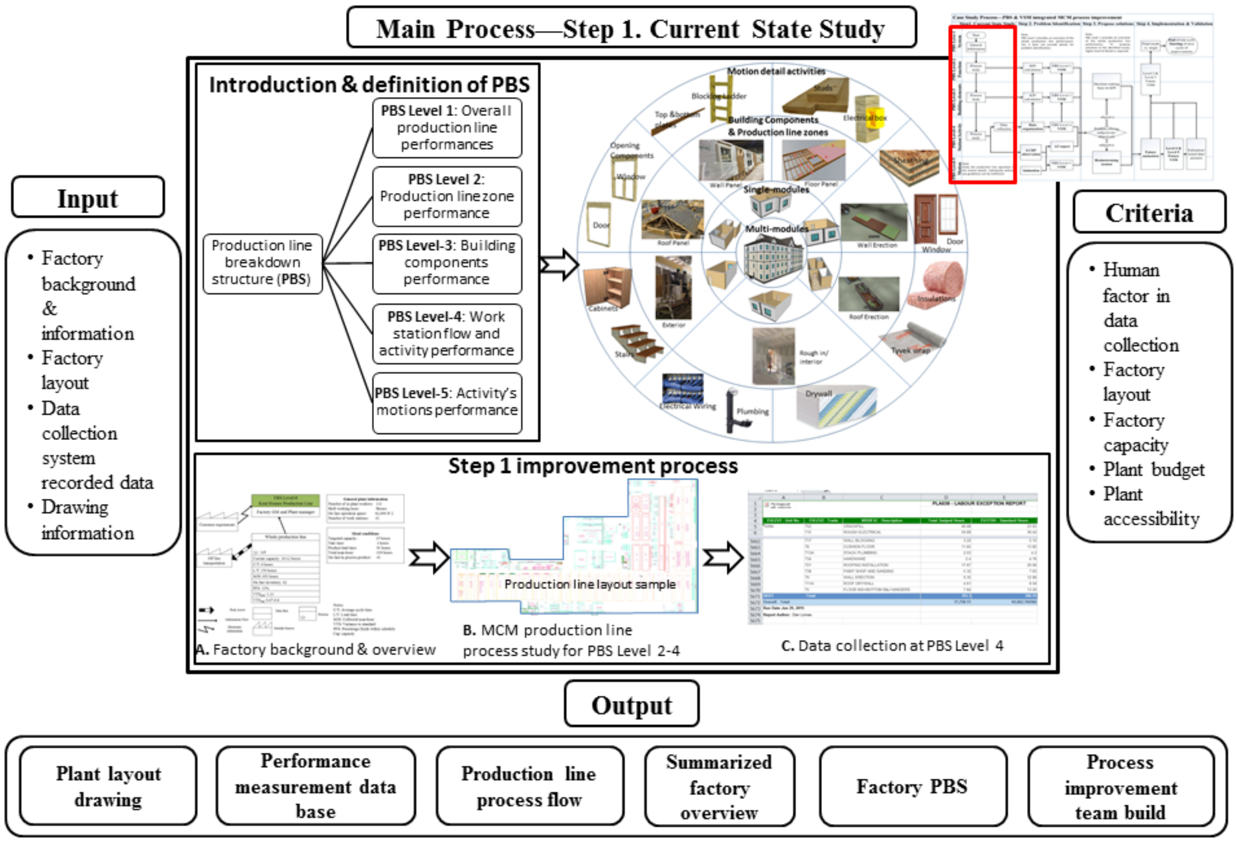


Figure 3-3: Research methodology Step 1—Procedures for study of current state

This chapter first introduces the concept of Production Line Breakdown Structure (PBS), followed by a definition for each level of the breakdown structure. The concept is applied to the current-state study of the case study factory. The production line process is introduced following the description of PBS, and the collected data is also explained.

3.2.1 Production line breakdown structure (PBS)

The Work Breakdown Structure (WBS) in conventional construction decomposes a project into deliverable-oriented components. Resources allocation and scheduling design for construction operation is based on these components, without any consideration of manufacturing operation characteristics such as production flow, workstations, or Takt time. To ensure an effective construction process that takes advantage of having a manufacturing operation, the creation of a new structure to decompose the project is needed so that the key features of manufacturing can be taken into consideration.

Production Line Breakdown Structure (PBS) breaks down a manufacturing plant into five different levels, where each level represents the production line with different degrees of detail. Out of five levels, the level that presents the condition of the single workstations with activities assigned within the workstations, level 4, is the critical level that could directly help to achieve an MCM process that improves on today's stick-built-dominated process. By clearly assigning resources using workstations as the base unit (a characteristic of manufacturing), PBS provides the factory with a reference point for production line performance assessment and a guideline to achieve process innovation by embracing the characteristic of manufacturing. Integrating the PBS for production line improvement provides a systematic approach so that not only is the local improvement enabled by studying each workstation independently, but also accesses are provided for managers to focus on the performance of production line flow among different workstations by studying the overall production line with different levels of detail.

For a conventional construction project, whether the project can be completed on time and within the projected budget are critical project evaluation components. Yet, following a master schedule and a final cost is not enough to deliver a full project performance evaluation from a manufacturing perspective. The necessity to achieve a continuous workflow on the production line and continuously improve its performance requires a new guideline for assessment. Following the different levels of PBS, a guideline is provided in this methodology so that proper data collection can be addressed. Key performance indicators (KPIs) that are specific for MCM are designed to assist the production line analysis. Each level of PBS is also assigned with specific parameters that serve different levels of personnel and different analysis purposes. This new guideline is also critical for implementing the adjusted VSM in this research to enable the visualization of current-state production line performance, decision making with regard to future improvements, as well as validation of the proposed improvements. In Figure 3-4, an MCM project construction breakdown structure is illustrated.

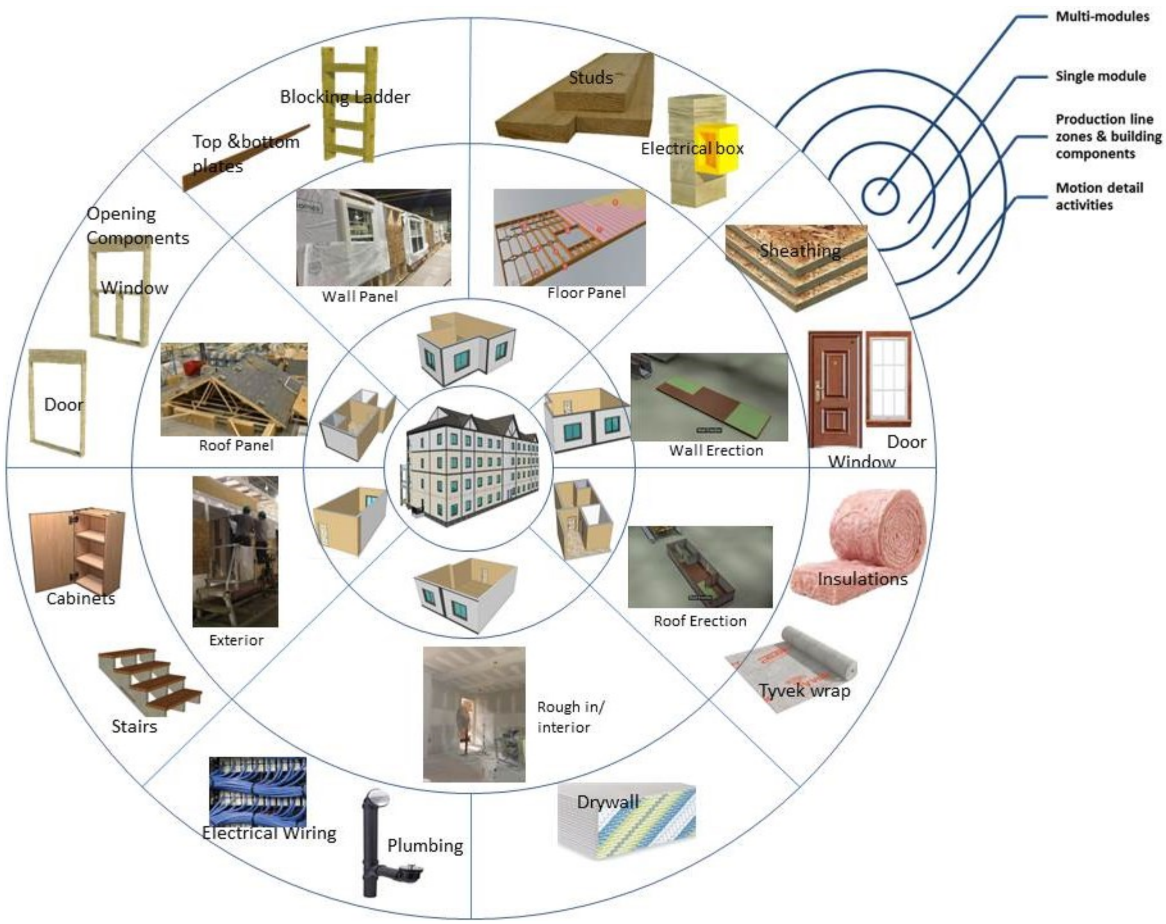


Figure 3-4: Breakdown structure of MCM project

From the circle's center extending to its outer boundaries, a complete construction project can be characterized from a full modular unit to as much detail as a single material component. Because all the activities involved in constructing a building component occur simultaneously and are interrelated, even though a specific sequence must still be followed on the production line, a systematic production line performance assessment method is needed not only for capturing detailed single activity performance, but also for visualizing construction operation in the factory from a true manufacturing perspective. This includes having activities and resources well defined within a workstation, balancing production flow between workstations, and establishing an environment of learning from experience rather than "firefighter" problem solving. PBS is a breakdown structure targeted to help modular manufacturers achieve the aforementioned goals. Adjusted based on Figure 3-4, a five-level production line breakdown structure, each level serving a different production analysis purpose, is presented in Figure 3-5. The five levels defined by PBS are: (1) production line performance; (2) production line zone performance; (3) building component performance; (4) workstation flow and activity performance; and (5) activity motion performance.

Compared to conventional construction WBS, which serves to plan the work schedule and cost estimation for the project, PBS creates opportunities to challenge the traditional construction method by integrating the benefits of manufacturing (i.e., innovative operational procedures, better inventory control, assigned workstations for predictable scheduling, quality control, Lean implementation). Additionally, being able to study the production line based on different types and levels of detail provides a guideline for effective and efficient implementation of Lean. For example, to improve the performance of production line flow based on Lean concept, connections between different workstations or work areas are critical, whereas only observing motions within one activity offers little. On the other hand, increasing a single activity working procedure by observing and eliminating Lean violations could have a positive impact on the overall production line performance. Therefore, knowing which activity takes priority over others or how the performance at a specific area of the production line impacts other areas is vital for making effective process improvement plans.

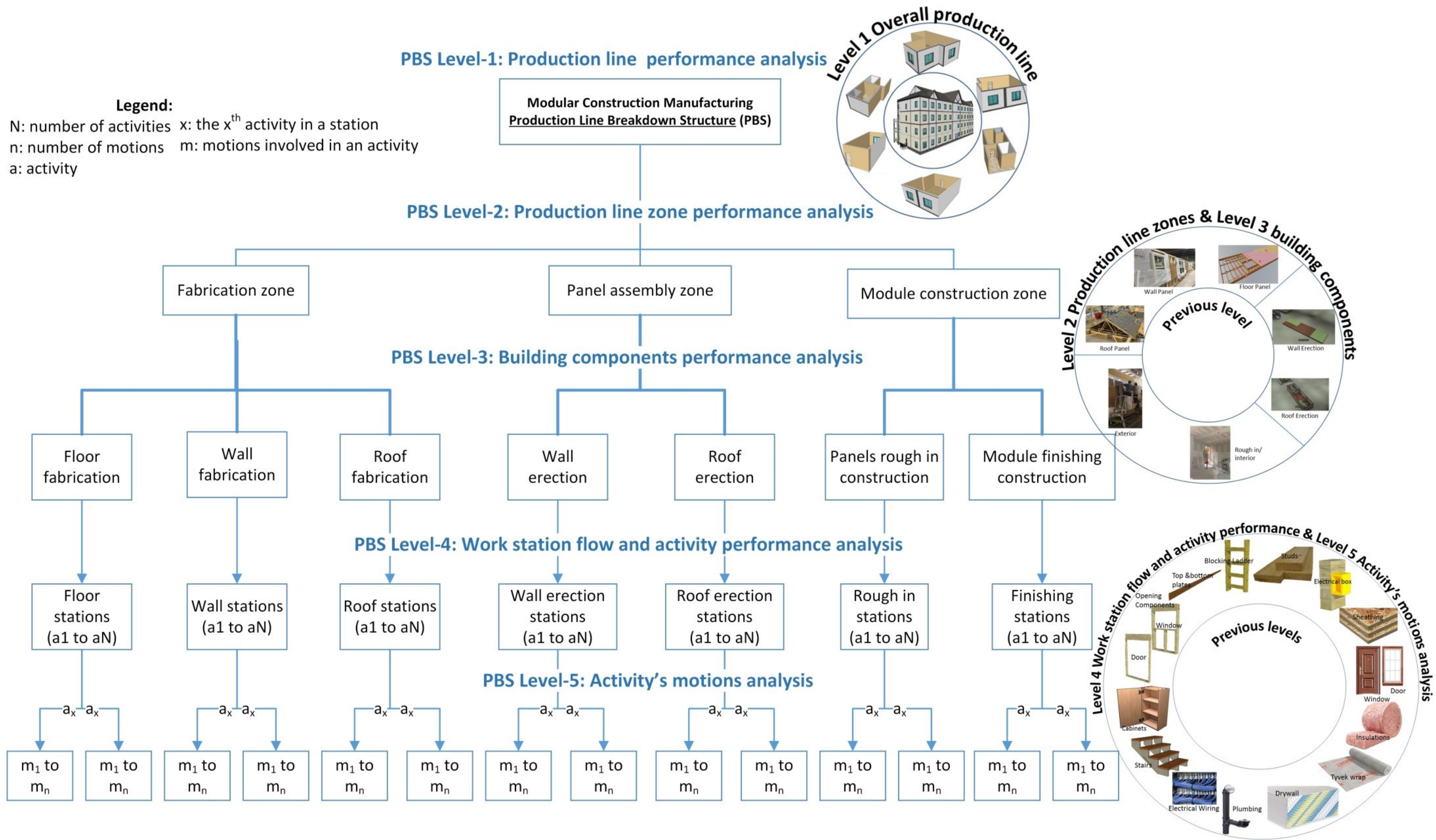


Figure 3-5: Modular construction manufacturing production line function breakdown structure

3.2.1.1 PBS level 1: Production line performance analysis

Level 1 is the macro level that encompasses the entire production line in the simplest way. Figure 3-6 illustrates the idea of breaking down a project into a single module, which is the final product of a modular manufacturer.

Figure 3-6: Modular building project breakdown to single modules

In this level, three types of information are collected to support the performance analysis: (1) general factory background information; (2) key performance indicators (KPIs) under the ideal condition; and (3) KPIs based on the current production line operation. The factory properties as well as the limitations for current production line design are the criteria for future improvement. These factory criteria combined with the market demand define the ideal condition of the plant, including the target Takt time and total lead time. The detailed parameters and their calculations will be illustrated in the case study.

3.2.1.2 PBS level 2: Production line construction zone performance analysis

Level 2 is the semi-macro level study where different zones of the production line can be identified. Figure 3-7 visually demonstrates the function of each production line zone. Zone one is the fabrication area where product value is pre-fabricated. Zone two is the assembly area where pre-fabricated products are assembled. Zone three is the value-added process through a single production line flow where the work procedure typically follows the conventional construction process but with parallel workstations so that different modules can be constructed simultaneously.

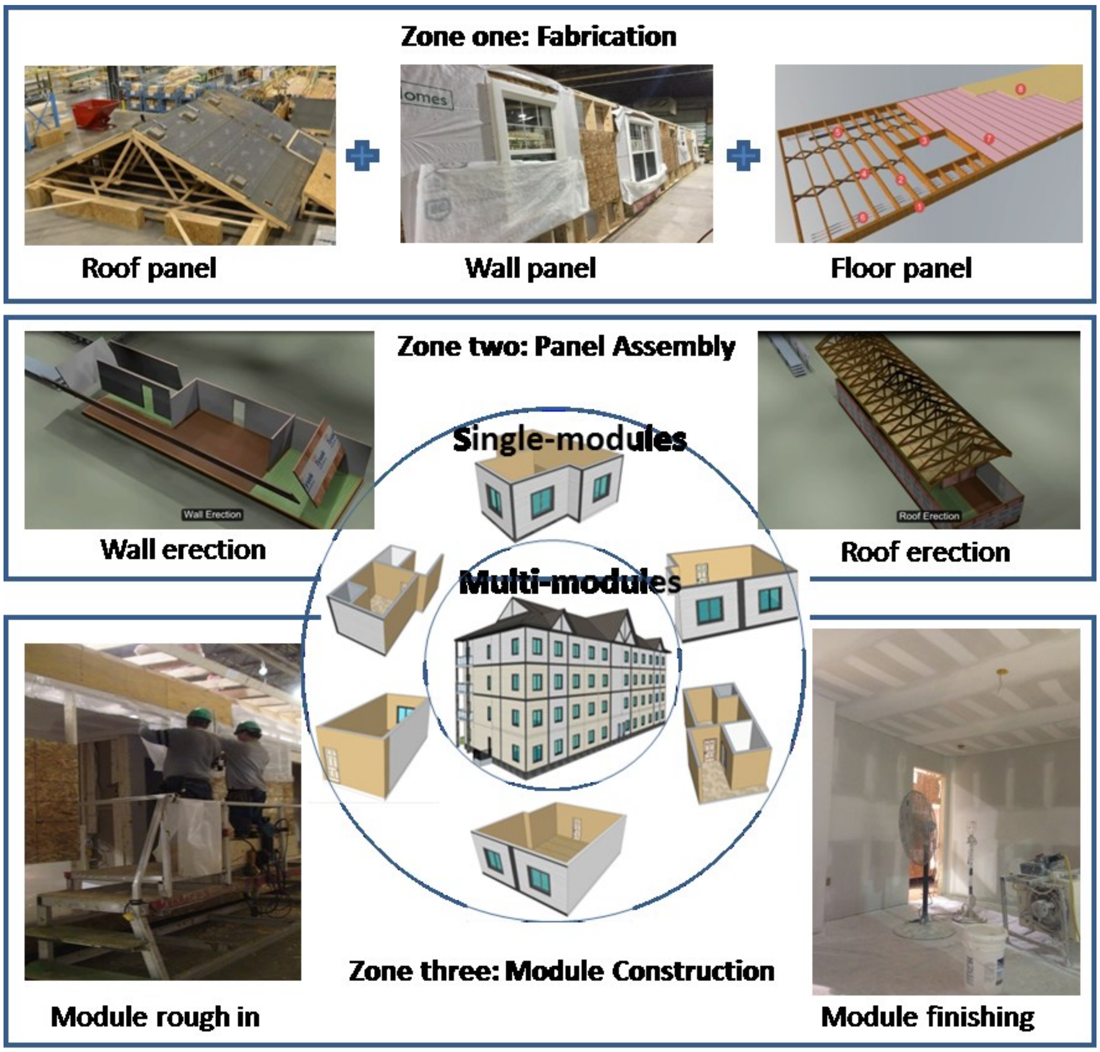


Figure 3-7: PBS level 2 and level 3 construction zone breakdown

For each production line zone, two performance indicators that differ from the previous level are the workload and workforce intensity. These indicators are used to represent the production line flow performance since the distribution of the workload and workforce are critical for production line flow balancing. The trades in a congested working area are likely to be interrupted by one another, thereby causing unexpected delays or work defects. Inventory control and working tools management are also challenges to consider. Similar to uneven workload allocation over a similar area, bottlenecks on the line are more likely to occur if one workstation is assigned more tasks than others. Although there are currently no absolute optimal target values for production line labour and workforce intensity designs for MCM, comparison of these parameters among all the existing zones (or among all the building element areas in level 3) provides the manager a reference point to even out the workload as well as a guide to adjust the construction process toward a manufacturing process rather than merely adjusting the production line to fit into a conventional construction process. In addition to the new parameters, station cycle time and total lead time are important measures of production line performance. The goal for MCM is to achieve a stable station cycle time, as well as a cycle time and lead time that mirror Takt time and ideal lead time, respectively. The detailed parameters and KPIs is further explained along with the case study illustration later in this chapter.

3.2.1.3 PBS level 3: Production line building components performance analysis

Similar to level 2, PBS level 3 is also defined as a semi-macro production line breakdown. It is a further breakdown based on the different building components in which detailed activity information is provided. Although each module can be customized with different details, from the type of framing material to type of cabinets to be installed, all modules include the following seven construction elements: (1) floor fabrication, (2) wall fabrication, (3) roof fabrication, (4) floor and wall assembly, (5) volumetric assembly, (6) panel connection assembly (module rough-in), and (7) volumetric module finishing (similar to traditional construction procedures). Figure 3-7 illustrates these elements by zone. To measure the performance of each section of building elements, the same data parameters and performance indicators as level 2 are used in the study of level 3. (The detailed information about the data calculation and analysis procedure are explained along with the case study in step 2 of the proposed improvement framework.)

The pre-calculated parameters and indicators for level 2 and level 3 not only provide access to overall production line flow analysis, but also provide enough detail to identify the central problem area on the line. Also, the ability to consider a production line for building a module by means of the seven elements both individually and systematically rather than constructing a single module will promote the idea that modular construction does not have to follow all the conventional construction rules, since the manufacturing process allows new work sequences that could potentially improve work efficiency.

3.2.1.4 PBS level 4: Production line workstation & activity performance analysis

Level 4 is identified as a micro-level study for the production line performance which breaks down a building component into different elements (activities) that are assigned to different workstations. As shown in Figure 3-8, workstation flow and the activities for floor panel and wall panel fabrication lines are illustrated by including the potential value-added options for the final products.

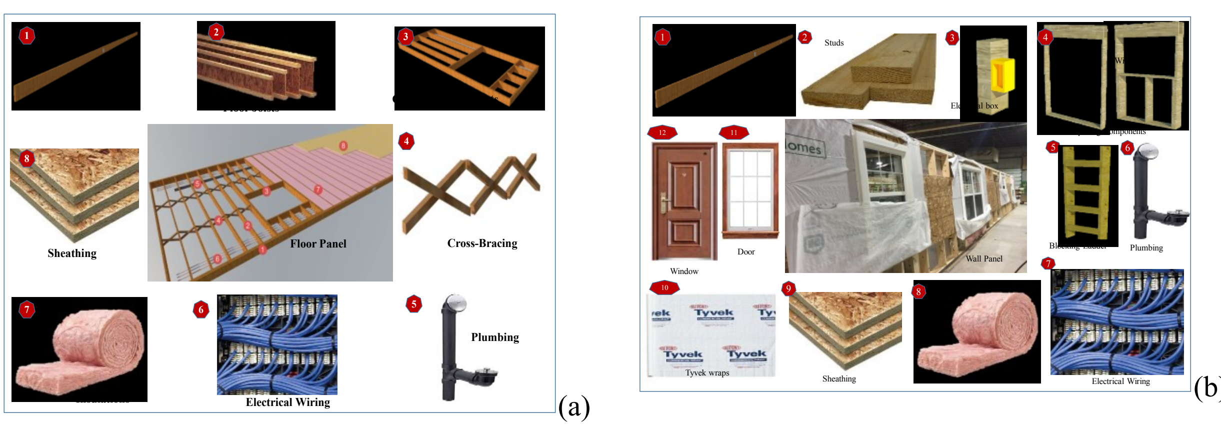


Figure 3-8: Floor assembly (a) and wall assembly (b)

At this level, bottlenecks, barriers, limitations, and process improvement areas are being exposed at the activity level; in other words, the exact activities (plumbing, insulation, window and door openings, etc.) can be observed in detail in order to implement any changes for current practice. According to the previous level of analysis, level 4 analysis can proceed with the focus only on the problematic area that increases the production line assessment efficiency and effectiveness. In addition, although level 4 breaks down the production line into different workstations and sections with analyses in an isolated area only, the integration analysis that combines with the output of level 3, which oversees the entire production line, will ensure a comprehensive analysis result for workstations and the performance of their activities' rather than a standalone and possibly misleading result.

The collection of raw data, including activity duration and man-hours, is currently processed in this level of detail for most MCM plants. It is crucial to realize that very limited efforts have been put into collection of data on workstation duration, which is one of the key factors in measuring and improving manufacturing performance. Although the work duration of activities is essential for more detailed analysis, for the purpose of identifying the production line flow bottlenecks, barriers, and the influence of activities on the workstations, activities should be broken down based on workstations for further assessment rather than having a conventional construction work breakdown structure (WBS) and assigning the workstations to the activities. As a consequence, the underlying goal of traditional manufacturing, which is a constant workstation cycle time that is as close as possible to the plant Takt time throughout the production line, becomes unfeasible for MCM due to the size of the product, complexity of the process, construction process standards, etc. PBS emphasizes the importance of establishing a cycle time per workstation and provides opportunity to challenge the stick-built construction practice by breaking down the activities in a different way.

This level is also where the on-site low hanging fruit observation, VSM, and Lean production application begin for any detailed analysis. The case study in this research uses the collected activity man-hours and man-power for all the VSM input database calculations, including the workstation cycle time calculation. However, for a high level of confidence data calculation in the future, data can be collected from further breakdown levels, activity motion details, or a more accurate recording method on the basis of workstations. The scope of this research is only to explain the importance of assigning work and labour to workstations rather than activities to precede effective production line analysis; thus a look at the detailed method of data collection is outside the scope of this research.

3.2.1.5 PBS level 5: Production line activity motion analysis

PBS level 5 is the detail-level analysis in this framework, which focuses on motion analysis. The objective is to help visualize the value-added motion of the workers for each activity and measure the efficiency of the current working procedure. This level of PBS provides detailed information needed for the manager to conduct Lean production analysis on the line for local performance improvement (work efficiency for individual activities). The previous level locates the key activities that require improvement and analysis with the consideration of overall production line flow, and the specific activity is selected to precede further study. By selecting the appropriate activity, the proposed improvement can be more results-driven.

The reason for selecting a target activity to improve is to ensure a positive impact on overall production line flow. Although, based on conventional construction, improving the performance for activities using the critical path method (CMP) can reduce the delivery time, the manufacturing production line performance will not improve based solely on critical path performance, but based also on a comprehensive upstream and downstream production flow adjustment. Therefore, knowing the overall production line performance, understanding the key issues at each workstation, and realizing the upstream and downstream impact when adjusting one single activity or motion are all critical to the success of the implementation. In other words, conducting level 5 analysis without a comprehensive understanding of the other PBS levels is insufficient.

During the analysis, once the current-state VSM is plotted, the most critical step is to identify the violations of Lean principles, which include a low percentage of value-added motions; high labour demand and non-value-added motions. In Figure 3-9, a group of captured motions for floor framing is shown as an example. The detailed analysis for the example can be found in the case study of this research, refer to section 3.3.1.5.

(a) Joists manually delivered | **(b) Joists manually set in place** | **(c) Joists floor panel**

Figure 3-9: Current-state motion capture at floor framing station

3.2.2 Case study of industry partner production line process

The industry partner's production line process is studied and introduced in this section following the proposed framework. The PBS for levels 1, 2, and 3 of the factory production line are demonstrated in Figure 3-10 based on the plant layout.

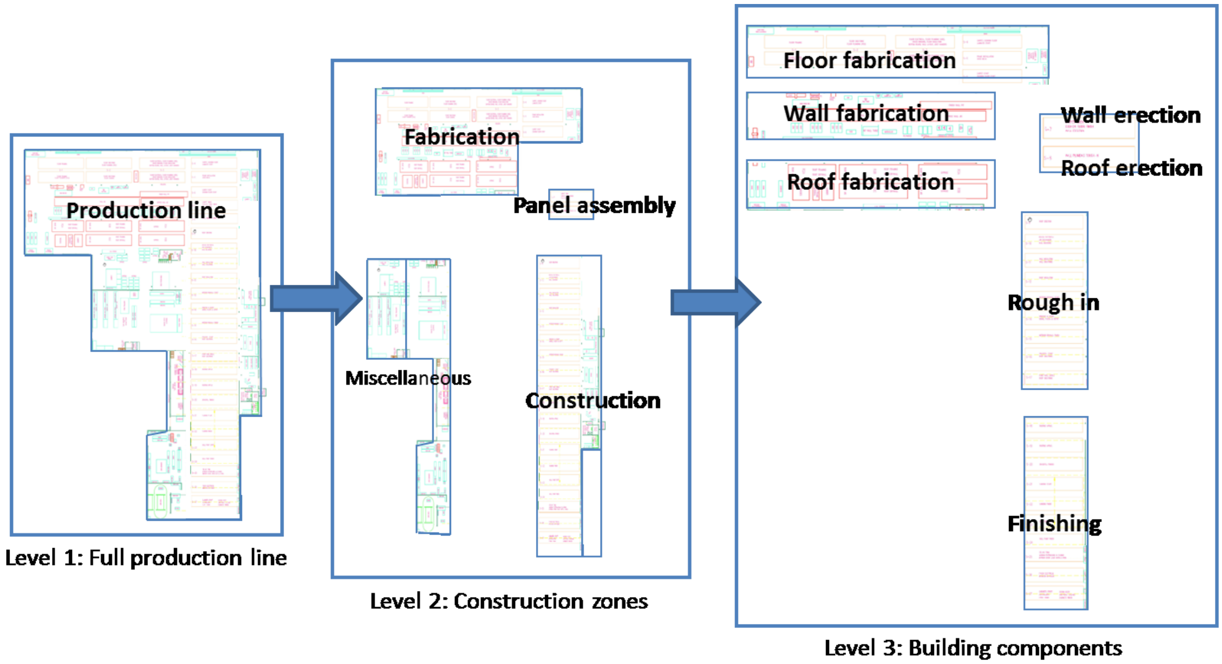


Figure 3-10: Initial current-state production line study for PBS levels 1, 2, & 3

The detailed breakdown for level 4, which includes the breaking down of both workstations and activities, is summarized in the tables and figures below. Level 4 is categorized following level 3—building component breakdown, which contains floor fabrication (Table 3-1), wall fabrication (Table 3-2), roof fabrication (Table 3-3), wall erection (Table 3-4), roof erection (Table 3-4), panel connection assembly and rough-in (Table 3-5), and finally the volumetric module finishing section (Table 3-6). Wall erection and roof erection constitute the volumetric assembly section of the production line and are each assigned one buffer station to reduce the impact of a push system on the production line.

Table 3-1: PBS station and activity breakdown information for floor fabrication line

FBS L3-Station	FBS L4-Activity	Activity Code
Ff-1 Floor framing	A1. Component	T1
	A2. Framing the floor panel	T3
	A3. First half of PEX plumbing if needed	T4
Ff-2 Floor sheathing	A1. Finish the PEX plumbing	T4
	A2. First half floor wiring if needed	T15A
	A3. First half of HVAC if needed	T16
	A4. Sheathing	T3A
	A5. Subfloor and sanding if needed	N/A[11]
Ff-3 Value-added	A1. Finish floor wiring	T15A
	A2. Plumbing [ABS]	T4A
	A3. Finish HVAC	T16
	A4. Install the insulation/under sheathing	T5
	A5. Wall layout	T28C
	A6. Wood beams	T28D
Ff-4, 5 Floor finishing	A1. Possible flooring: Vinyl	T6
	A2. Possible flooring: Laminate	T6B
	A3. Possible flooring: Carpet	T28
	A4. Flooring protection	N/A

[11] N/A: These activities are recognized as one single activity by the industry partner's production line manager, yet the activity code is not assigned in the factory's data collection system and the data was therefore not available for this activity. The assumption in the thesis is that the time duration for flooring protection is included in other flooring activities.

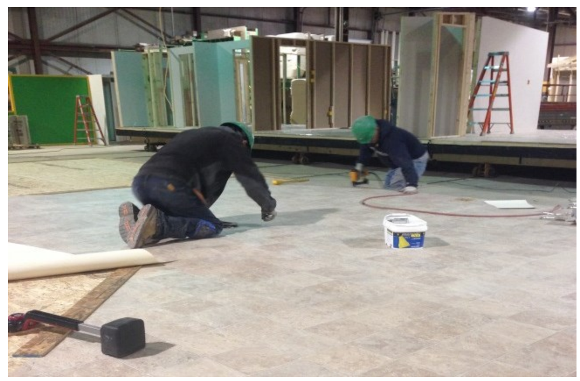
Ff-1 Floor framing	Ff-2 Floor sheathing
	
Ff-3 Value-added	Ff-4, 5 Floor finishing
	

Figure 3-11: Floor production line sample photographs

There are five workstations for the floor fabrication production line, as presented in Table 3-1 and Figure 3-11. The work sequencing generally follows the given order in the table, with some activities occurring simultaneously. The activity code is given by the data collection system. Stations 1, 2, and 3 each have an adjacent workstation which forms a buffer floor panel fabrication line. This extra line creates the flexibility to adjust the production line flow by eliminating blocked units or delays on the line. However, it is important to recognize that although there appear to be two production lines for floor fabrication, without two working crews to support the activities on the station the extra line does not double the productivity. Actually, as a consequence of having no fixed production flow, extra man-hours will contribute to product transportation, which is considered a non-value-added activity for the production line.

There are also two side workstations that share the same area to feed the main wall fabrication line with sub-assembly components: the pre-assembly top plate and bottom plate station and the interior wall framing table. Since the data for these two activities is collected and combined with activity A1 and A2, respectively, it is then excluded from Table 3-2.

Table 3-2: FBS station and activity breakdown information for wall fabrication line

FBS L3-Station	FBS L4-Activity	Activity Code
Wf-1 Wall framing	A1. Wall component/blocking	T10
	A2. Wall framing	T7
Wf-2 Wall panel	A1. Drywall	T19

Wf-1 Wall framing
Wf-2 Wall panel

Figure 3-12: Wall production line sample photographs

As shown below, in Table 3-3 and Figure 3-13, roof fabrication production line flow consists of three workstations, and, similar to the floor production line, there is an extra parallel line serving as a buffer zone with one crew member working on both lines.

Table 3-3: FBS station and activity breakdown information for roof fabrication line

FBS L3-Station	FBS L4-Activity	Activity Code
Rf-1 Roof framing	A1. Roof component	T11C
	A2. Framing the roof panel	T11
	A3. First half of drywall if needed	T11A

Rf-2 Roof interior	A1. Finish drywall A2. Roof crack fill A3. Roof sanding	T11A T52 T52A
Rf-3 Roof finishing	A1. Roof paint A2. Roof finish A3. Roof HVAC if needed	T38B T14 T16

Rf-1 Roof framing | Rf-2 Roof interior | Rf-3 Roof finishing

Figure 3-13: Roof production line sample photographs

The wall erection and roof erection sections constitute the volumetric assembly section of the production line (refer to Table 3-4 and Figure 3-14). These two stations are assigned one buffer station each to reduce the impact of a push system on the production line.

Table 3-4: FBS station and activity breakdown information for panel assembly function area

FBS L3-Station	FBS L4-Activity	Activity Code
FW-1 Wall erection	A1. Wall erection (wall installed on the roof panel)	T9
Rb-2 Roof erection	A1. Roof erection (roof installed on the half box)	T12

FW-1 Wall erection | Rb-2 Roof erection

Figure 3-14: Erection section sample photographs

As can be seen below, in Table 3-5 and Figure 3-15, there are 15 activities spanning the seven workstations of the panel connection assembly area, which is called the "rough-in section" by the plant. These activities can spread over multiple workstations, and there is usually one working crew assigned to these activities.

Table 3-5: FBS station and activity breakdown information for panel connection assembly

FBS L3-Station	FBS L4-Activity	Activity Code
Pc-1	A1. Tub/wall plumbing	T13
Pc-2	A1. Stack plumbing	T13A
	A2. Electrical	T15
	A3. Wall blocking	T17
Pc-3	A1. Hot water tank	T13C
	A2. Electrical panel	T15C
	A3. Electrical	T15
	A4. Finish HVAC	T16
Pc-4	A1. Electrical	T15
	A2. Wall insulation	T17A
	A2. Wall drywall	T19A
	A3. Wall Sheathing	T8
	A4. Window & Doors	T22
Pc-5,6,7	A1. Crack fill	T52
	A2. Sanding	T52A
	A3. Paint walls	T38B
	A4. Siding, Soffit, Fascia	T23
	A5. Roof insulation	T20A

(a) Plumbing rough-in (b) Insulation (c) Sheathing

(d) Electrical rough-in (e) Closing the wall after wiring, plumbing, and blocking

Figure 3-15: Rough-in section sample photographs

The work sequence generally follows the given order in the table, with some activities occurring simultaneously. Most activities in this section involve the connection work among different panels, such as the electrical wiring connection between floor panel and wall panels, and the sheathing board connection between wall panels and roof panel. The performance of these activities and workforce requirements are relevant to the amount of value that has been added to the fabricated panels prior to assembly. As a result of prefabricating the floor, wall, and roof panel in the factory instead of using the conventional construction process where panels are built volumetrically one after another, special work procedures at these production line sections can be identified and specific activities can potentially be improved by implementing Lean construction and innovative operational procedures.

Activities introduced in Table 3-6 and Figure 3-16 occur further down the production line process for final module value adding. Little information at this section is closely related to the panel assembly process. For the purpose of this research, limited study has been carried out at this section since it is not the priority improvement area. However, the performance at this section can be indirectly influenced by the improvements from upstream activities due to the product quality improvement, reduction of working space and duration requirements, and improved labour resource allocation.

Table 3-6: FBS station and activity breakdown information for traditional construction finishing

FBS L3-Station	FBS L4-Activity	Activity Code
C-1	A1. Siding, soffit, fascia	T23
	A2. Roof sheathing	T20
	A3. Interior casing	T26
	A4. Chair rail/Batten assembly	T35
	A4. Window & trim assembly	T31
	A5. Baseboards	T37
	A6. Ceiling Molding	T25
C-2	A1. Roofing	T21
	A2. Cabinets & countertops	T30
	A3. Interior Door/hardware	T34
	A4. Shelving	T29
C-3	A1. Final Finish	T46
	A2. Wrapping/pre offline	T44-D
C-4	A1. Wall touch up	T39E
	A2. Cleaning units/mini blind	T45
C-5	A1. Finish electrical	T42
	A2. Finish plumbing	T41

(a) Interior rough-in (b) Exterior finishing (c) Interior finishing

(d) Interior final finishing (e) Final product delivery

Figure 3-16: Module finishing section sample photographs

PBS level 5 is the targeted activity detailed motion study. A preliminary problem identification of the line is prerequisite for any level 5 analysis. Therefore, no activity motion study information is provided in the current-state study.

3.2.3 Data collection and input database for PBS-integrated VSM

There is no existing standard requiring a modular manufacturer to record their data for production line performance analysis. Often the available data collections from factories are limited due to the absence of (i) a standard collection process, (ii) an established purpose for the collected data, or (iii) an understanding of the expected outputs. PBS provides a guideline for factories to understand the need of collecting different types of data with various levels of detail.

Therefore, the purpose of investing in data collection needs to be clear, with expected outputs defined.

3.2.3.1 Data collection

In this case study, the most detailed data available is man-hour collection for each activity on the line. The limitation of the collected data is the level of accuracy, although for the purpose of this thesis and industry partner expectations, it can be used as input data for the PBS and VSM. Other limitations which hinder manual data collection include limited on site observation times.

The case study company provided a production line schedule of the targeted working duration, spanning December 2, 2014 to June 12, 2015, in which the code, size, and type of the units are included. A total of 126 units have been recorded, out of which 43 units are modular homes and 83 units are mini homes. As mentioned at the beginning of this chapter, each modular home comprises two separate modules whereas a mini home is composed of a single module. The collected data represents the number of man-hours necessary to finish a modular home or a mini home only. In other words, although the modular home is built with two separate modules on the line and two sets of data corresponding to the respective modules should be available for analysis, only one set of data which combines the performance of both modules was collected. The limitations of the collected data constrain the effectiveness of detailed simulation modelling implementation where the impact of product variation can be studied; however, the available data is sufficient for VSM analysis implementation where Lean construction within the manufacturing environment is the target.

The header of the master schedule of the collected raw data is pictured in Figure 3-17 below.

Order No.	Retailer	Customer	Prov	Specs.	Crk	Heat	Walls	Fr.	Bath.	Trim	STD.	CATH.	Pitch	Model	Date Ordered	Cabinet P.O.#	On Line	Off Line	Delivery	Date Required	Sales Plan Sent	Sales Plan In	Delivery/Erection Code	W	L	Area	CODE
BOUCTOUCHE PRODUCTION SCHEDULE - JUNE 12, 2015 - REVISED																											
				Specifications								Roof trusses	Cabinets				Planned							Size			
56419	KENT HOMES	STOCK		K	N	EB	6	W	1B	M	0		4/12		30-Jul	239484	02-Dec	26-Jan	02-Feb					16	72	1152	Z240
15998 A	HARMONY GRO	KIRSTA &	NS												21-Nov	243493	03-Dec	27-Jan	03-Feb					15	46	690	A-277
15998 B	HARMONY GRO	KIRSTA &	NS												21-Nov	243493	03-Dec	28-Jan	04-Feb					15	46	690	A-277
56447	HAVILLS	STOCK	NS			EB	6	W	1B	M			4/12		25-Nov	243533	04-Dec	29-Jan	05-Feb					16	67	1072	Z240
56449	HAVILLS	STOCK	NS		N	EB	6	W	2B	M	0		4/12		25-Nov	243536	04-Dec	30-Jan	06-Feb					16	67	1072	Z240
56448	HAVILLS	STOCK	NS		N	EB	6	W	2B	M	0		4/12		25-Nov	243535	05-Dec	02-Feb	09-Feb					16	72	1152	Z240
56442	KENT HOMES	STOCK		K-P*CHAIR RAIL*	P	EB	6	W	1B						02-Dec	243734	08-Dec	02-Feb	09-Feb					16	66	1056	Z240

Figure 3-17: Case study production schedule

The actual time durations from the Kronos system[12] are provided in a separate file, called a "Labour Exception Report", for each defined activity of each unit. Figure 3-18 provides the total man-hours of every defined activity across the entire production line. It contains both the expected man-hours and the actual total man-hours for each activity, as well as the work performance measurement indicator, Variance to Standard (VTS).

	A	B	C	D	E	F	G
1				PLA039 - LABOUR EXCEPTION REPORT		Report Run by:	Michael Bernard
4	EVLEV1 - Unit No.	EVLEV2 - Trade	WDDESC - Description	Total Swiped Hours	EVSTDH - Standard Hours	Variance	VTS
5	15994	T52	CRACKFILL	46.68	23.05	23.63	2.03
6		T15	ROUGH ELECTRICAL	59.89	36.42	23.47	1.64
5662		T17	WALL BLOCKING	3.22	5.15	-1.93	0.63
5663		T6	CUSHION FLOOR	11.65	13.82	-2.17	0.84
5664		T13A	STACK PLUMBING	2.03	4.2	-2.17	0.48
5665		T34	HARDWARE	2.4	4.76	-2.36	0.50
5666		T21	ROOFING INSTALLATION	17.67	20.06	-2.39	0.88
5667		T38	PAINT SHOP AND SANDING	5.32	7.83	-2.51	0.68
5668		T9	WALL ERECTION	9.35	12.86	-3.51	0.73
5669		T11A	ROOF DRYWALL	4.61	8.56	-3.95	0.54
5670		T5	FLOOR INS+BOTTOM B&J HANGERS	7.64	13.26	-5.62	0.58
5671	56511	- Total		703.3	596.51	106.79	1.22
5672	Overall - Total			77,758.11	65,662.766566	12,095.33	1.33
5673	Run Date Jun 29, 2015					Run Time 8:24:05 AM	
5674	Report Author: Dan Lomax					Last Revised Date:	May 1, 2014

Figure 3-18: Labour exception report–summary

Figure 3-19 provides a sample of detailed labour hour data, which is the input data of the total man-hour calculation for each activity in Figure 3-18. As shown in the figure, each activity can have one or more workers, and each worker will have their working hours recorded, with this

[12] Kronos system: a data collection system compiled by the industry partner. It requires workers to swipe their ID before and after the assigned tasks are completed for each unit so that the total man-hour consumption can be collected.

information used to calculate the total man-hours. The exact starting and finishing time of their work is not shown in the database, but the durations of the tasks are available.

	A	B	C	D	E	F
1	The image part with relationship ID rId...		PLA039 - LABOUR EXCEPTION REPORT		Report Run by: Michael Bernard	
2						
3						
4	EVLEV1 - Unit No.	EVLEV2 - Trade	EVEMPN - Employee Number	EENAME - Name	Total Swiped Hours	EVSTDH - Standard Hours
5	15994	T1	10097	COLLETTE, JERRY	1.87	1.71
6		T10	13098	VAUTOUR, GABRIEL	3.17	5.8
7		T11	11381	CORMIER, WILLIE JOSEPH	8.05	46.54
8			11488	LOSIER, RICHARD	6.28	46.54
9			11865	CORMIER, PAUL O.	4.8	46.54
10			12025	CORMIER, MARC	20.38	46.54
14434			13479	SURETTE, SYLVIO	6.12	11.82
14435		T7	10951	BASTARACHE, PAUL J.	5.34	13.1
14436			11765	CAISSIE, CLAUDIO	5.88	13.1
14437			13069	DALLAIRE, NORMAND	5.92	13.1
14438		T8	10099	HEBERT, JEAN-NOEL	4.37	13.47
14439			12172	ALLAIN, MARIO	4.85	13.47
14440			12222	GALLANT, FRANCOIS	4.9	13.47
14441		T9	10887	HEBERT, CHARLES	4.15	12.86
14442			13464	CORMIER, DAVID	5.2	12.86
14443	Run Date Jun 29, 2015					Run Time 8:24:05 AM
14444	Report Author: David Rowe		***REPORT IN DESIGN PHASE***		Last Revised Date: May 1, 2014	
14445						
14446						

Figure 3-19: Labour exception report–labour details

3.2.3.2 Input database for PBS-integrated VSM

The collected data is re-organized and calculated into a new database as the input for the PBS-integrated VSM. (The reader may refer to Table 3-7 for a summary of the parameters and KPIs at each PBS level.) As these data will be presented together with the VSM analysis, which will be addressed in the next section, only a sample of calculated data for floor panel fabrication with detail from PBS level 4 is shown below as an example (refer to Table 3-8). The complete mathematical expression and data calculation methodology for Table 3-7 can be found in section 3.3.1.

Table 3-7: Summarized parameters and KPIs for PBS-integrated VSM input database

	Factor	Plant property	Ideal condition	Current condition	Performance Indicators
Level 1	Labour	• Number of workers • Shift working hour	• Customer demand/ plant target • Takt time [(1)] • Lead time [(2)] • Man-hour [(3)]	• Current plant capacity • Average station cycle time • Actual total lead time [(4)] • Actual total man-hours [(5)]	• Average variance to standard (VTS) [(6)] • Average percentage finish on time (PFT) [(7)]

	Space	• On line operation space • Number of workstations	• N/A	• N/A	• N/A
Level 2 / Level 3	Labour	• N/A	• N/A	• Number of workers • Average station cycle time • Actual total lead time [(4)] • Actual total man-hours [(5)]	• Average VTS [(6)] • Average PFT [(7)]
	Space	• N/A	• N/A	• Number of workstations	• Workload density [(8)] • Workforce density [(9)]
Level 4	Labour	• N/A	• N/A	• Number of workers • Station cycle time [(10)] • Actual total lead time [(4)] • Actual total man-hours [(5)]	• VTS [(6)] • PFT [(7)]
	Space	• N/A	• N/A	• Number of workstations	• N/A
Level 5	Labour	• N/A	• N/A	• Number of workers • Activity motion's cycle time [(10)] • Change over time • Actual total lead time [(4)]	• N/A
	Space	• N/A	• N/A	• N/A	• N/A

Table 3-8: Sample database for floor panel at PBS level 4

Floor Panels										
Production line station	Activity ID	Activity Name	**Actual Average Manhour**	Planned Average Manhour	**VTS (mhr)**	Planned number of workers	**Number of recorded labor**	**Duration & C/T**	**PFT**	Area (ft2)
Ff-1	T3	FLOOR FRAME	5.54	6.27	0.88	2.09	1.54	3.58	78%	
	T4	FLOOR PLUMBING PEX	2.23	1.59	1.49	0.53	0.79	1.87	19%	
Ff-2	T4	FLOOR PLUMBING PEX	2.23	1.59	1.49	0.53	0.79	1.87	19%	
	T15A	FLOOR ELECTRICAL	2.30	1.33	2.51	0.44	0.65	1.94	17%	
	T3A	FLOOR SHEATHING	14.26	13.16	1.11	4.39	3.38	4.22	35%	
Ff-3	T4A	FLOOR PLUMBING ABS	4.95	4.42	1.13	1.47	1.26	3.91	37%	
	T15A	FLOOR ELECTRICAL	2.30	1.33	2.51	0.44	0.65	1.94	17%	
	T16	AIR EXCHANGER	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	T5	FLOOR INS+BOTTOM B&J HANGERS	11.56	10.62	1.05	3.54	3.84	3.01	42%	
	T28D	WOOD BEAM INSTALLATION	3.32	3.07	1.12	1.02	1.08	2.52	44%	
	T28C	WALL LAYOUT	3.88	3.07	1.28	1.02	1.00	3.77	30%	
Ff-4	T28D	WOOD BEAM INSTALLATION	3.32	3.07	1.12	1.02	1.08	2.52	44%	
	T6	CUSHION FLOOR	8.49	9.52	1.30	3.17	1.85	3.61	54%	
Ff-5	T6	CUSHION FLOOR	8.49	9.52	1.30	3.17	1.85	3.61	54%	
	T6B	LAMINATE FLOORING	5.57	6.24	0.88	2.08	1.21	3.02	66%	
Ff-6	T6B	LAMINATE FLOORING	5.57	6.24	0.88	2.08	1.21	3.02	66%	
		Sum of floor fabrication	84.00	81.02	N/A	27.01	22.22	**28.78**	N/A	23000
		Average data of floor fabrication	N/A	N/A	**1.34**	N/A	N/A	**3.84**	42%	N/A
		Sum of production line	631	563	N/A	188	130	N/A	N/A	99925
		Percentage	13%	14%	N/A	14%	17%	N/A	N/A	23%

3.2.4 Preliminary 3D model

Another important application at step 1 of the improvement process is to become familiar with the plant, a task which is facilitated by the development of a preliminary 3D model. The preliminary 3D model is used as a visualization and communication tool. During the improvement phase with the industry partner, a 3D model of the current production line is drawn using SketchUp, a simple software tool for building 3D models. The following are the beneficial aspects of this type of representation:

1. A fast and effective communication tool that promotes more efficient discussion between internal and external personnel.
2. A validation tool to help with internal communications.
3. Easily edited, thereby providing potential for use in future-state visualization.
4. The first step in 3D animation.

In Figure 3-20, two examples of targeted study area layout are presented.

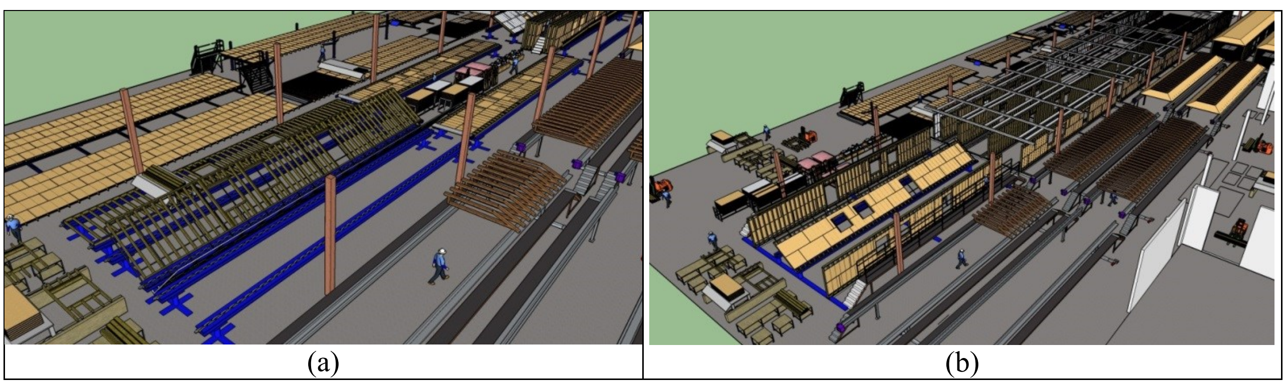


Figure 3-20: Two example 3D models for plant layout visualization

3.3 Improvement process step 2 & 3—problem identification and problem solving

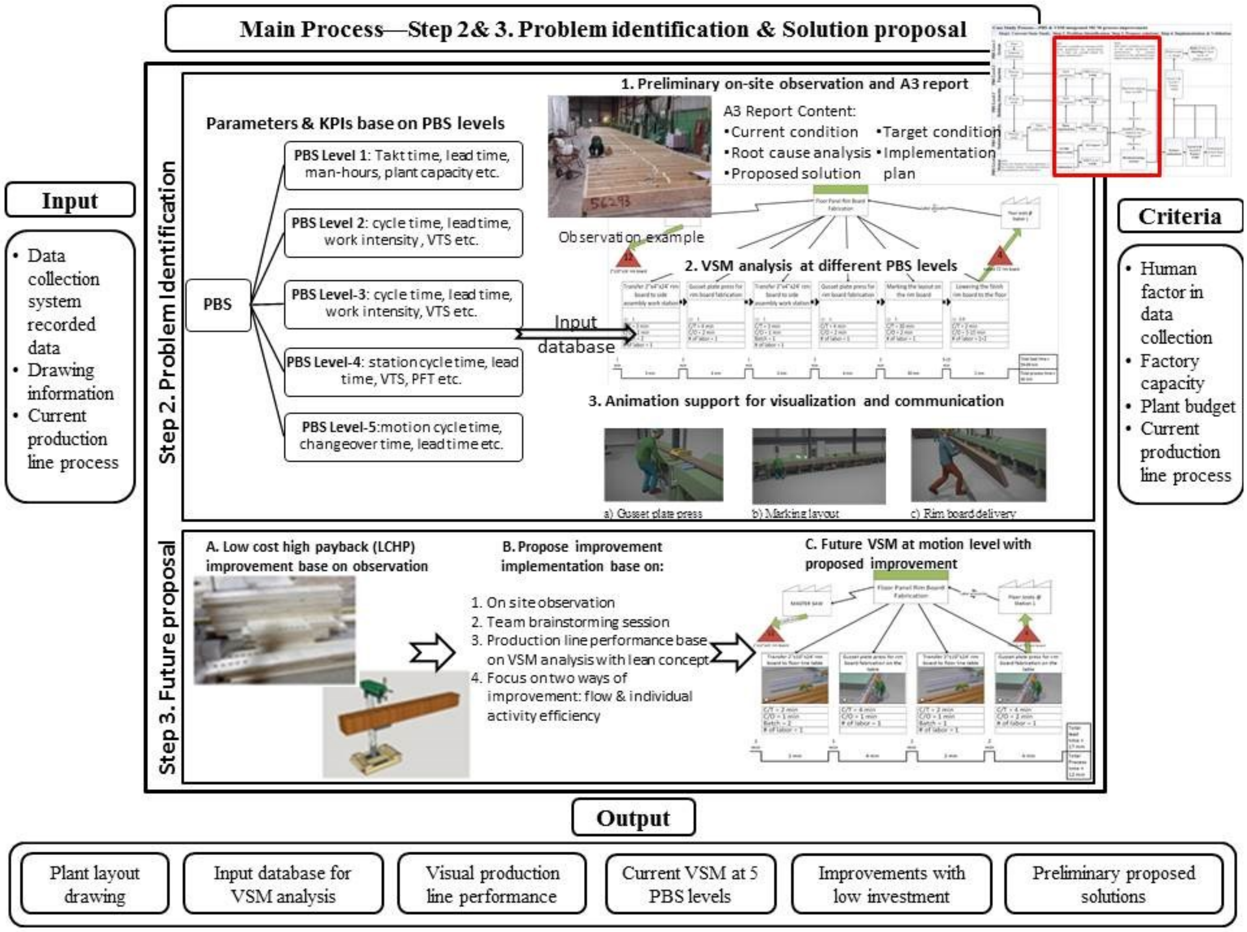


Figure 3-21: Research methodology Step 2 & 3—Problem identification and proposal of solutions

Figure 3-21 summarizes the steps of the methodology that are described in this section. Based on the study of the current state, the problem identification process for step 2 is conducted with two main processes: (1) PBS-integrated VSM analysis, and (2) low hanging fruit observations and A3 report. 3D animation is utilized to provide visual support for the analysis as well as promote the efficiency and effectiveness of communication between different teams.

When proposing future improvement for step 3, easy solutions can be implemented soon after the preliminary on-site study, where the observed activity requires small changes with high payback (i.e., low hanging fruit improvement). Other problems that are expected to require a higher investment may have a significant impact on the overall production line flow, and a long-term plan can be explored based on the output from the current-state VSM analysis. The proposed solution can be visualized and validated with future VSM at PBS level 4 and level 5.

3.3.1 PBS-integrated VSM analysis

3.3.1.1 Integration of PBS and Value Stream Mapping (VSM) analysis

The integration of PBS with VSM breaks down the MCM process into different levels to support an effective performance study and to provide feasible improvement options following Lean production principles. Company management can be selective based only on the low-level detail analysis to locate a central problem area and slowly progress toward addressing the entire production line. It enables a method by which to assess the entire production line comprehensively without complicating the process with excessive detail. At this stage, managers can focus on identifying any violation of the five principles of Lean thinking: (1) value from the customer's point of view; (2) working in value streams; (3) maximizing the flow and pull; (4) empowering company personnel; and (5) aiming for perfection through continuous improvement. The higher detail level of analysis will be valuable for production line managers and foremen for precise process improvement and to assist in decision making in planning for a practical and detailed improvement proposal. Violations of Lean principles can also be identified at this stage, but the key focus is on the third principle, maximizing the flow and pull, which involves eliminating the seven types of waste[13] introduced by Ohno in 1988 as well as carrying out analysis of every step on the line based on customer demand—in other words, Takt time.

The collected data and VSM will not reveal an absolute result for a best performance production line; however, they can be used as tools to encourage a continuously improving journey. It is thus important to understand that the output from using the proposed framework does not give a

[13] Ohno's seven types of waste: (1) overproduction; (2) waiting; (3) transporting; (4) inappropriate processing; (5) unnecessary inventory; (6) motion; and (7) defects.

static result, but should be a dynamic result as the improvement process continues to inspire the team to shift from conventional construction thinking to manufacturing construction thinking. This will cultivate a Lean culture of building upon these procedures and approaches.

An input database for VSM, which is developed following each level of PBS, is collected and calculated. The specific parameters and indicators that are chosen for each PBS level are introduced in this chapter at section 3.3.1.1.1. The output of the current-state VSM analysis following the PBS will ensure a quantitative production line diagnosis and clear guidance for future improvements.

3.3.1.1.1 Input database adjustment for PBS-based VSM

Traditional Lean production VSM application uses a set of parameters originally designed for automobile manufacturing, which is a less complicated manufacturing process compared with that of construction manufacturing. For MCM, due to the size and the properties of the product, solely following the parameters designed for traditional VSM to fit VSM for MCM is unrealistic. For example, work station up-time (in operation) is used as a critical measurement for workstation efficiency and its equipment performance on the line, but is simply not applicable to current MCM, which mainly involves manual work. Another critical input value of VSM, workstation cycle time, becomes a challenging indicator to be measured in the MCM context with the associated activity-based man-hour data collection and significant variability of work duration due to the considerable manual component of work processes. Making VSM practical to use for MCM is also a challenge under current practice. Using the case study in this research as an example, there are more than 50 necessary activities along the production line spanning more than 40 workstations. Some activities need to be completed in a complex workstation, and each workstation could have one or more activities involved with multiple working crews. Yu (2009) utilizes VSM for construction in his study, and addresses the issue of having one single VSM to handle the entire line of a construction project due to the complexity of the product compared with other industries. He suggests that as a rule of thumb having no more than 12 activities can ensure the effectiveness of the VSM. He highlights the importance of not only being able to assess the production line at a workstation level within a readable VSM (having more than 50 activities in one VSM is not practical for targeted analysis), but also of not compromising the unique complexity of the construction process. If Yu's recommendations are heeded, an adjusted input database for VSM for MCM is rendered quite valuable (Yu et al. 2009). The integration of VSM and PBS will help to maintain the effectiveness of VSM, as each level of VSM will serve a different analysis focus, and the targeted areas can be easily located at the less detailed information level and broken down into a more detailed information level for further analysis.

The parameters and KPIs for VSM input in this study are summarized in Table 3-7. The parameters for each level are given based on two aspects, labour and space. (Although equipment and material are two other aspects that need to be considered in the manufacturing plant, they are outside the scope of this research.) Both levels have parameters representing the basic statistics of current conditions as well as the calculated indicators, which could be referenced as an index to quantify the performance for each level. The columns for "ideal condition" and "plant property" are presented for level 1 as a sample to provide an overview of the MCM plant. However, the detailed equations and example calculations are presented along with the case study following each level of PBS to avoid repetition.

3.3.1.2 Case study: PBS level 1 Production line performance overview

The data calculation required for PBS level 1 is summarized in Table 3-9. By following the given equation as well the background study of the industry partner's manufacturing plant, the output data supporting the assessment at level 1 is presented using VSM format in Figure 3-22. The process of collecting raw data is explained in Section 3.2.3.

Table 3-9: PBS level 1—input parameters and KPIs

Factor	Plant property	Ideal condition	Current condition	Performance Indicators
Labour	• Number of workers • Shift working hour	• Customer demand/ plant target • Takt time [(1)] • Lead time [(2)] • Man-hour [(3)]	• Current plant capacity • Average station cycle time • Actual total lead time [(4)] • Actual total man-hours [(5)]	• Average variance to standard (VTS) [(6)] • Average percentage finish on time (PFT) [(7)]
Space	• On line operation space • Number of workstations	• N/A	• N/A	• N/A

The equations are given as follows:

1. Takt time

   Maximum time (Takt time, T) allowed for a single unit being produced based on customer demand (D).

$$T = \frac{T_a}{D} \tag{1}$$

   where

   T: Takt time;

   T_a: available time in a period of time; and

   D: customer demand in a period of time.

2. Lead time (LT) (Ideal condition for the plant)

   The total latency time from initiation of a project to completion, from an MCM perspective, is the total time required to transfer the raw material from the first workstation to the last workstation on the line. Ideally, the aggregate workstation cycle time will be equal to the plant target Takt time.

$$f(LT) = \begin{cases} n * T, preceding\ activities \\ (n - x) * T, parallel\ activities \end{cases} \quad (2)$$

where

LT: lead time;

n: total number of workstations;

x: number of workstations that are parallel to main line workstations; and

T: Takt time.

3. Total man-hours (T_{mhr}) (ideal condition for the plant)

   The recorded total manpower input for a single product—under the ideal circumstance, target man-hours should satisfy the equation below:

$$T_{mhr} = \sum_{s=1}^{n} (T_s * Nm_s) \quad (3)$$

where

T_{mhr}: total man-hours;

s: the given workstation;

n: total number of workstations;

T: Takt time; and

Nm: number of workers.

4. Actual lead time (LT_a) (current condition for the plant)

   The total latency time from initiation of a project to completion, from an MCM perspective, is the total time required to transfer the raw material from the first workstation to the last workstation on the line.

$$f(LT_a) = \begin{cases} \sum_{s=1}^{n} (ct_s + wt_s), preceding\ activities \\ \sum_{s=1}^{n} Max.(ct_s + wt_s), parallel\ activities \end{cases} \quad (4)$$

where

LT: lead time;

s: the specific station;

n: total number of workstations;

ct: workstation cycle time; and

wt: waste time (production line delay, rework, waiting time, transportation, etc.).

5. Actual total man-hours (T_{mhr}) (current state)

The recorded total manpower input for a single product: under the ideal circumstance, target man-hours should be equal to the calculation below:

$$T_{mhr} = \sum_{a=1}^{n} (D_a * Nm_a) \quad (5)$$

where

T_{mhr}: total man-hour;

a: activity;

n: total number of activities;

D: activity work duration; and

Nm: number of workers.

For case study data, the actual total man-hours are collected directly from the data collecting system.

6. Variance to standard (VTS)

The comparison between the planned[14] and actual data helps to visualize production line performance.

$$VTS = \frac{T_{mhr}}{PT} \tag{6}$$

where

T_{mhr}: total man-hours; and

PT: planned time.

7. Percentage finished on time (PFT)

The number of products that can be finished within the scheduled (workstation)[15] cycle time/Takt time.

$$PFT = \frac{n}{N} \tag{7}$$

where

n: number of products that were completed within the scheduled time; and

N: total number of products produced.

Figure 3-22 clearly indicates the current condition of the industry partner's manufacturing plant: (1) the main section includes the calculated data from the level 1 database; (2) the two side tables beside the main section in the figure summarize the general plant background information; and (3) the data pertaining to the ideal condition that the factory is pursuing is also presented.

[14] To optimize the effectiveness of the comparison, planned cycle time/man-hour should follow the manufacturing production line scheduling rather than conventional construction project scheduling. However, due to the limitations of the existing production line scheduling, planned cycle time/man-hour is assigned based on activities instead of workstation.

[15] This parameter was originally used to measure the performance of a specific workstation rather than activity, so the influence of this station in regard to the production line can be revealed. Due to the limitations of the existing MCM data collection, only the performance of activities could be measured.

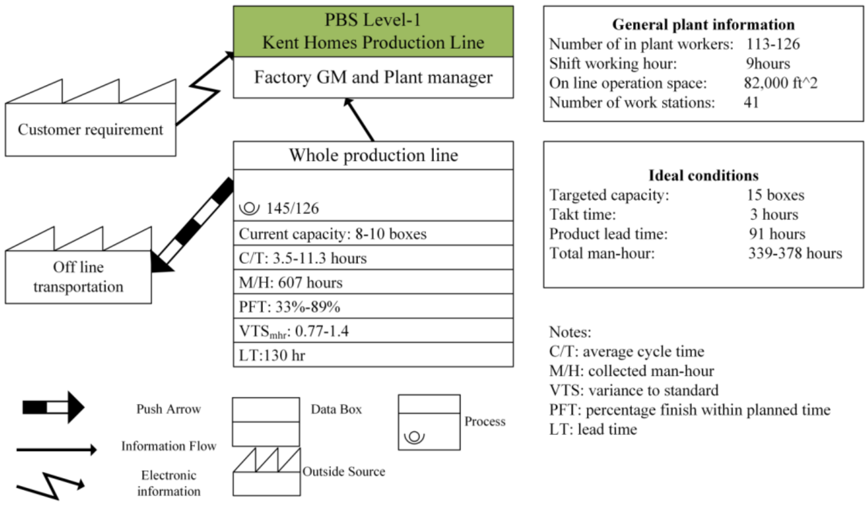


Figure 3-22: PBS level 1 VSM for plant performance overview

As shown in the figure, the existing production line can produce 50% to 70% of the targeted plant capacity with 113 to 126 workers on the line. Another key parameter comparison is between the average cycle time of workstations and the factory Takt time, which is based on ideal plant capacity (which in turn is based on customer demand). The existing plant capacity gives a 4.5 hr production line Takt time, which is 1.5 hr slower than the targeted plant Takt time. With the current 3.7 hr to 11.3 hr workstation cycle time, the large variation reveals a considerable amount of uncertainty in the existing process. The existing total man-hour requirement and the total lead time substantially exceed the ideal condition that the factory is targeting for the future state. Two performance indicators, percentage finished on time (PFT) and variance to standard (VTS), reveal the unpredictable and imbalanced production line performance. An average PFT ranging from 33% to 89% for all the workstations on the line means that for some activities only 33% of work can be completed within the planned hour. Average VTS quantifies the PFT performance. Throughout the production line, the VTS is found to range from 0.7 to 1.4, which indicates that some areas of the line are less problematic than others.

Another noticeable problem is the mismatched number of available on-site workers and the number of workers recorded during the process. According to the calculation, on average, 28% of the workers require multi-skill trades in order to work at different workstations for each module. Even though workers with multi-trade skills are preferred and can be of benefit for an efficient production line flow due to the flexibility of labour resource allocation, this can also contribute to waste activities, time delays, and interrupted production line flow, among other issues. In addition, since the daily scheduling at the plant is assigned based on the man-hours requirement instead of the number of employees and workstation cycle time, miscalculation during the planning can also lead to poor labour resource allocation on the production line, which causes unnecessary additional production line delays. This kind of man-hour and manpower estimation also leads to a poor PFT performance on the line.

As there is no other detailed information provided at this level, further assessment of the production line needs to be addressed. With the focus on improving the current condition in terms of (1) workstation activity efficiency improvements and (2) production line workload balancing, the next level of PBS analysis is examined.

3.3.1.3 Case study: PBS level 2 three construction zones overview

The data calculation required for PBS level 2 is summarized in Table 3-10. Four of the parameters required at this level are the same as those for level 1, while workload intensity and workforce intensity are two new KPIs that require additional calculations for the analysis of level 2. Again, the raw data collection is explained in Section 3.2.3. A sample calculation will be provided following Figure 3-23.

Table 3-10: PBS level 2 & level 3 input parameters and KPIs

Factor	Current condition	Performance Indicators
Labour	• Number of workers • Average station cycle time • Actual total lead time [(4)] • Actual total man-hours [(5)]	• Average VTS [(6)] • Average PFT [(7)]
Space	• Number of workstations	• Workload density [(8)] • Workforce density [(9)]

The equations are given as follows:

1. Workload density

   The workload intensity at a specific area of the production line.

$$\rho_{mhr} = \frac{T_{mhr}\%}{A_x\%} \tag{8}$$

   where

   ρ_{mhr}: man-hour density of an area;

   $A_x\%$: targeted operation space percentage; and

   $T_{mhr}\%$: percentage of the total man-hours.

2. Labour density

   A term that indicates the level of congestion in a specific working area.

$$\rho_m = \frac{Nm\%}{A_x\%} \tag{9}$$

   where

   ρ_m: labour density of an area;

   $A_x\%$: the targeted operation space percentage; and

   $Nm\%$: the percentage of the number of workers.

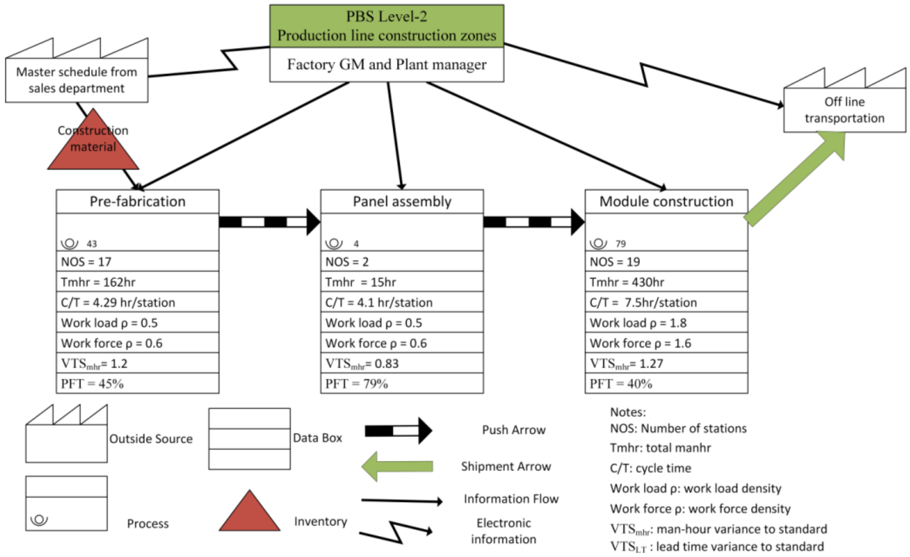


Figure 3-23: PBS level 2 VSM for production line construction zones analysis

Sample calculation of pre-fabrication sections:

Given value:

- Number of assigned workers = 43
- Number of stations (NOS) = 17

Calculated parameters and KPIs:

- $T_{mhr} = \sum_{a=1}^{n}(D_a * Nm_a) = \mathrm{D_{floor}} \times \mathrm{Nm_{floor}} + \mathrm{D_{wall}} \times \mathrm{Nm_{wall}} + \mathrm{D_{wall}} \times \mathrm{Nm_{wall}}$

  $= 3.6 \times 22 + 4.3 \times 8 + 3.5 \times 13 = 160 \text{ hr}$

- Cycle time (C/T) = Max (D_a) = $\mathrm{D_{wall}}$ = 4.3 hr/stations
- Workload intensity $(\rho_{mhr}) = \frac{T_{mhr}\%}{A_x\%} = \frac{\frac{T_{mhr}\, of\, pre-fab}{T_{mhr}\, of\, single\, module}}{\frac{A_{pre-fab}}{A_{production\, line}}} = \frac{\frac{162hr}{608hr}}{\frac{45000ft2}{79400ft2}} = 0.5$
- Workforce intensity $(\rho_m) = \frac{Nm\%}{A_x\%} = \frac{\frac{Nm\, of\, pre-fab}{Nm\, of\, single\, module}}{\frac{A_{pre-fab}}{A_{production\, line}}} = \frac{\frac{43}{126}}{\frac{45000ft2}{79400ft2}} = 0.6$
- Variance to standard $(VTS) = \frac{T_{mhr}}{PT} = \frac{162hr}{145hr} = 1.1$

- Percentage finished on time $(PFT)^{16} = \frac{n}{N} = 45\%$

The VSM for this level (Figure 3-23) summarizes the performance measurement of the three key sections of the production line. The study at this level not only reveals the activity and workstation performance at each zone, but also provides general information about the production line flow among different zones.

Two of the key indicators in this VSM that represent the performance of each section individually are the VTS and PFT. As shown, the pre-fabrication section and module construction section both have a VTS greater than 1.2, which indicates they are both more than 20%[17] over budget in terms of man-hours. The PFT at these two sections can be as low as 40%. Regardless of the potentially misleading line scheduling mentioned in the previous PBS level, this funding underscores the challenge of finishing the assigned work on time, especially for the module construction zone. In addition to the unpredictability of activity duration on the line, limited understanding of how individual activities will affect performance on the line also contributes to low PFT.

Average workstation cycle time at each zone is another parameter that reveals the problem area. The cycle time of the module construction zone is almost double that of the other two zones. This dramatic difference draws the attention to the overall production line workload distribution. Although the workloads on the line can be adjusted by changing the number of workers assigned in a given area so that the estimated work duration stays relatively constant throughout the line, a congested working area with heavy work intensity can lead to inefficient work processes,

[16] Percentage finish on time is measured per activity over various modules. Because level 2 & level 3 only provide less detailed information and present performance for 17 workstations with 23 activities, detailed data cannot be shown in the equation. All the calculations are done in an Excel sheet and the average PFT for the 23 activities is the data input for pre-fabrication section's PFT.

[17] The budget is measured based on the planned working man-hours. Ideally, the budget should be defined by the Takt time of the production line; however, at present the industry partner does not plan the work based solely on Takt time.

unexpected delays, and potential safety hazard. In reference to Figure 3-23, the workload density and workforce density at the module construction zone are 1.8 and 1.6, respectively, which is more than three times that of the other two sections. Considering its 7.5 hr current average workstation cycle time, the module construction zone poses the risk of bottlenecking from upstream activities.

In summary, the pre-fabrication section and assembly section have smoother flow than does the module construction zone according to the cycle time and density analysis. Module construction seems to be the bottleneck of the production line which requires workload re-distribution and process improvement. The plant in its existing configuration is scheduled to operate on an approximately two unit per day basis, and the production line performance can produce approximately two modules per day at the first two sections, but experiences trouble at the main production line—specifically, the module construction section.

3.3.1.4 Case study: PBS level 3 production line building elements analysis

The required equations for input data calculation of VSM are the same as those for level 2 and thus will not be repeated in this section. Facilitated by the same type of information that is provided in the previous level, this level breaks down the production line into different building elements in order to present greater detail. More importantly, it also helps to target the focused area based on order of priority on the production line without ignoring other related sections, all this to ensure the effectiveness of the proposed improvement plan.

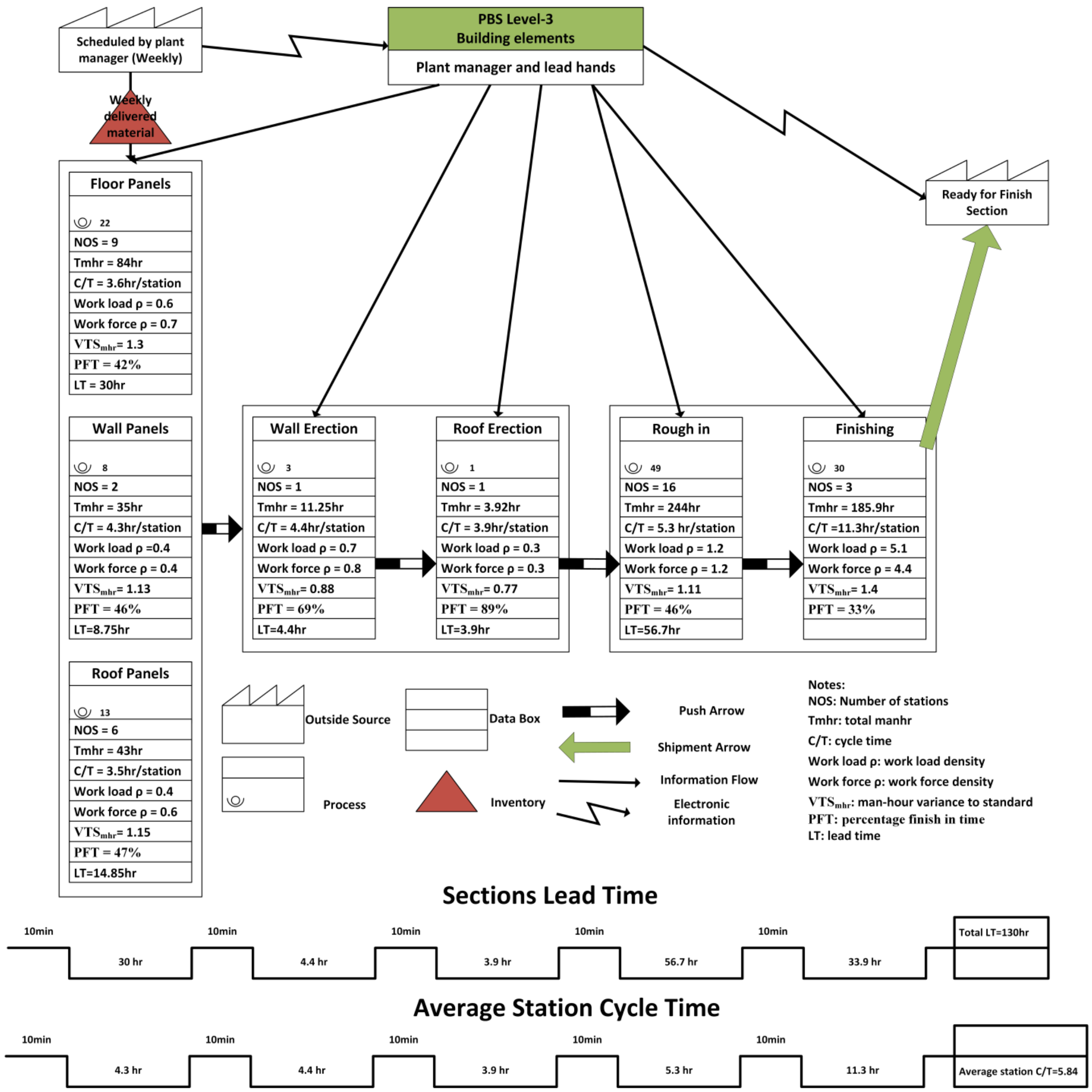


Figure 3-24: PBS level 3 production line building elements breakdown analysis

In Figure 3-24, VSM at level 3 is illustrated. To adjust to the typical MCM production line (the industry partner's line is used as an example), floor panels, wall panels, and roof panels are located parallel to each other, and contrary to typical VSM there will be no flow among these three sections. However, the three sections will flow to downstream sections and the performance of any of these three sections will have an impact on or be impacted by downstream activities. Although floor, wall, and roof panels are pre-assembly components and are used as inventory for downstream activities, the unique characteristics of the housing industry, including aspects such as large panel size, limited factory storage space, difficult transportation procedure, and the need for JIT (Just in Time) delivery, make analyzing these pre-fabrication sections equally crucial to any other sections on the line. The amount and type of value "pre-loaded" to these panels will have an impact on the main production line, which is another reason not to treat them as inventory input in production line VSM. To better explain the resulting data, a graph is created to highlight the findings (Figure 3-25).

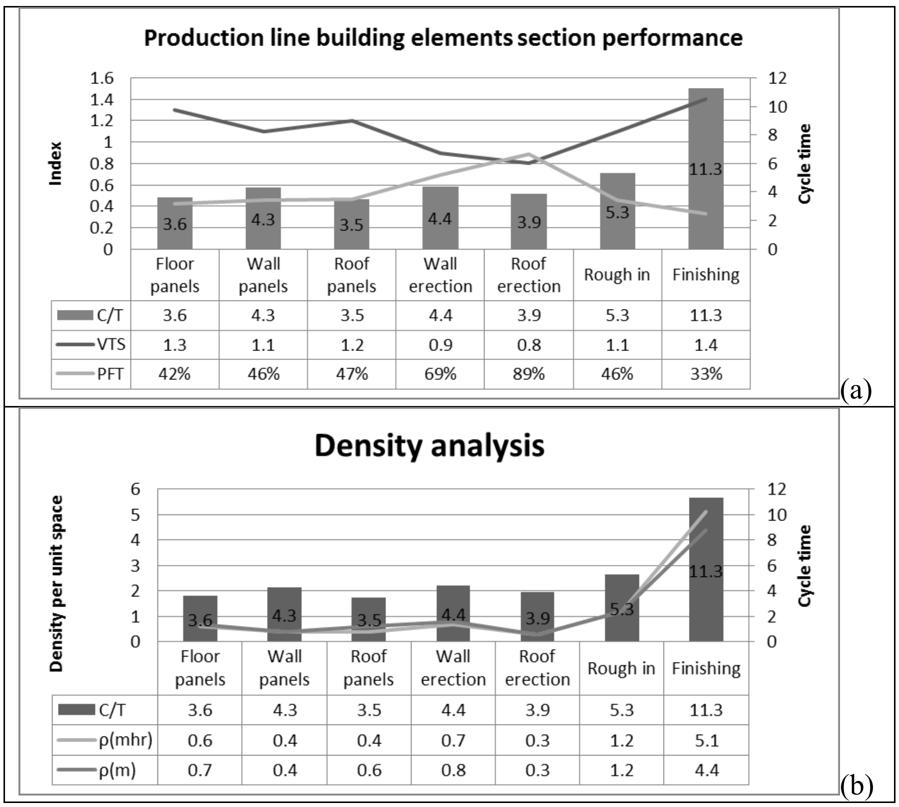


Figure 3-25: FBS level 3 performance data summary

The findings can be summarized as follows:

1. The three building elements in the pre-fabrication section all show relatively stable cycle time, which helps to ensure that the capacity of two units per day is realized; yet there are challenges associated with achieving a 3 hr Takt time in the future. The wall panel production line has the highest workstation cycle time in this section, but has better VTS (1.1) and PFT (47%) data, which means the wall panel production line performance is

closer to current schedule planning. On the other hand, the VTS and PFT for the floor panel production line indicate that the performance on the floor line is less predictable than others based on the current practice.

2. Current workstation cycle time at the wall and roof erection sections does not meet the future Takt time target, yet the overall performance at these two sections based on VTS and PFT indicators is above average.
3. The cycle time at the rough-in section increases to 5.3 hr, and extends to 11.3 hr at the final finishing section. The performance indicators for the finishing section fall to 1.4 VTS and 33% PFT. In other words, the work process is 40% over budget with only 33% of processes finished within the planned schedule. Although the unpredictable working duration can be expected for conventional construction where weather delays and inventory control are influencing variables, construction within an indoor manufacturing environment should have better control of scheduling and estimation.
4. Workload and workforce density also show a similar trend to workstation cycle time at each section. The wall panel section has comparatively low density (0.4), which reveals the possibility of underutilization of the plant space.
5. Given the rise in density particularly at the rough-in and finishing sections it can be inferred that the end of the current production line is congested due to intensive workload assignments. This is one of the consequences of poor performance from both workers and production line.

Based on the above findings, two types of improvements can be targeted with a specific focus on key areas. The first type of improvement has to do with workstation cycle time and individual activities performance. For activities upstream on the production line that have less impact on the procedure of other activities on the line, improving the performance of each activity itself can be effective to help meet the targeted Takt time. Workstations at the floor panel and roof panel production lines are studied in detail in the next level of VSM.

The second type of improvement is to readjust the production line flow among different key sections so that the workload can be evenly distributed and the plant space can be utilized efficiently. This type of improvement requires comprehensive assessment of both upstream and downstream targeted areas, where the changes at one section are related to changes at other sections. In PBS level 4 VSM analysis, to provide a solution for the key findings from this chapter, process improvements among wall panel, rough-in, and finishing sections will be illustrated in detail.

3.3.1.5 Case study: PBS level 4 & level 5 detailed assessment and problem solving

The data calculation required for both PBS level 4 and level 5 is summarized in Table 3-11. Station cycle time and activity motion cycle time are two of the new parameters that need to be calculated specifically for level 4 and level 5. Again, the pertinent raw data collection methods are explained in Section 3.2.3. The calculated data is presented using VSM in Figure 3-26.

Table 3-11: PBS level 4 and level 5 input parameters and KPIs

Factor	Current condition	Performance Indicators
Labour	• Number of workers • Station cycle time [(10)] • Actual total lead time [(4)] • Actual total man-hours [(5)]	• VTS [(6)] • PFT [(7)]
Space	• Number of workstations	• N/A
Labour	• Number of workers • Activity motion cycle time [(10)] • Change over time • Actual total lead time [(4)]	• N/A
Space	• N/A	• N/A

The equations are given as follows:

1. Cycle time

   Cycle time (*C/T*) is the actual work duration at a workstation. In Lean production, the ultimate goal is to achieve a cycle time equal to plant Takt time at every workstation in order to eliminate production line flow delays or congestion.

$$f(C/T) = \begin{cases} \sum_{a=1}^{n} t_a \text{, precede activities} \\ Max(t_a)\text{, parallel activities} \end{cases} \tag{10}$$

   where

   t_a: is the time durations of activities within a workstation, assuming that every worker is permanently assigned to a particular station; and

   n: number of activities with the same workstation.

The calculation of the cycle time of a given motion is very similar to that for workstation cycle time and therefore shares the equation with workstation cycle time. The difference is that analysis of motions breaks down the activities into more detailed steps.

For future-state VSM input data, the key parameters would only include man-hours, cycle time, and lead time. Without a consistent test run period, KPIs, including VTS and PFT, cannot be calculated. As the original data is collected based on man-hours, the future activity cycle time is calculated as per (10). The workstation cycle time for the future state is calculated using (11).

$$t_a = \frac{i\% * t_{mhr}}{N} \tag{11}$$

   where

   t_{mhr}: original man-hour requirement;

   i%: future man-hour percentage required based on original collected man-hours; and

   N: number of assigned workers.

According to the previous PBS level analysis, two types of improvements are used here: (1) reduce the cycle time internally, which serves to improve the critical activity and workstation performance itself without changing the work sequence or procedure of others; and (2) retool the work sequence workload allocation among different activities using an innovative manufacturing-specific process—in other words, re-designing the work process externally.

3.3.1.5.1 Internal work process improvements

Floor panel production line:

As mentioned previously, performance improvement at the floor and roof panel production line focuses on increasing the performance of the procedure itself. In Figure 3-26, each activity on the floor production line is presented and the activities are grouped based on the actual corresponding workstation on the line. The first three floor stations each have a buffer station, an extra workstation with the same crew; the final cycle time at this workstation equals the cycle time of the activity which has the longest duration.

The summary of the findings from PBS level 4 floor panel section VSM includes:

1. Critical activities in the process are found to comprise floor framing, sheathing, floor plumbing, and cushion floor.
2. Buffer zones are underutilized.
3. The station cycle times are found to range from 3.0 hr to 4.2 hr.
4. Floor plumbing, electrical, air exchanger, wood beam installation, and flooring each requires more than one workstation; yet only one work crew is assigned for each activity, which can cause delay and work process interruption due to the constant workforce mobilization and switching from one workstation to another.

5. Floor plumbing and floor electrical activities show poor performance compared with other activities based on the VTS and PFT data. This is likely due to the non-standardized work procedures, constant workforce mobilization, and limited accuracy of schedule planning.
6. Flooring installation utilizes three workstations with the same crew, and it is proven to be one of the bottlenecks on the floor panel production line.

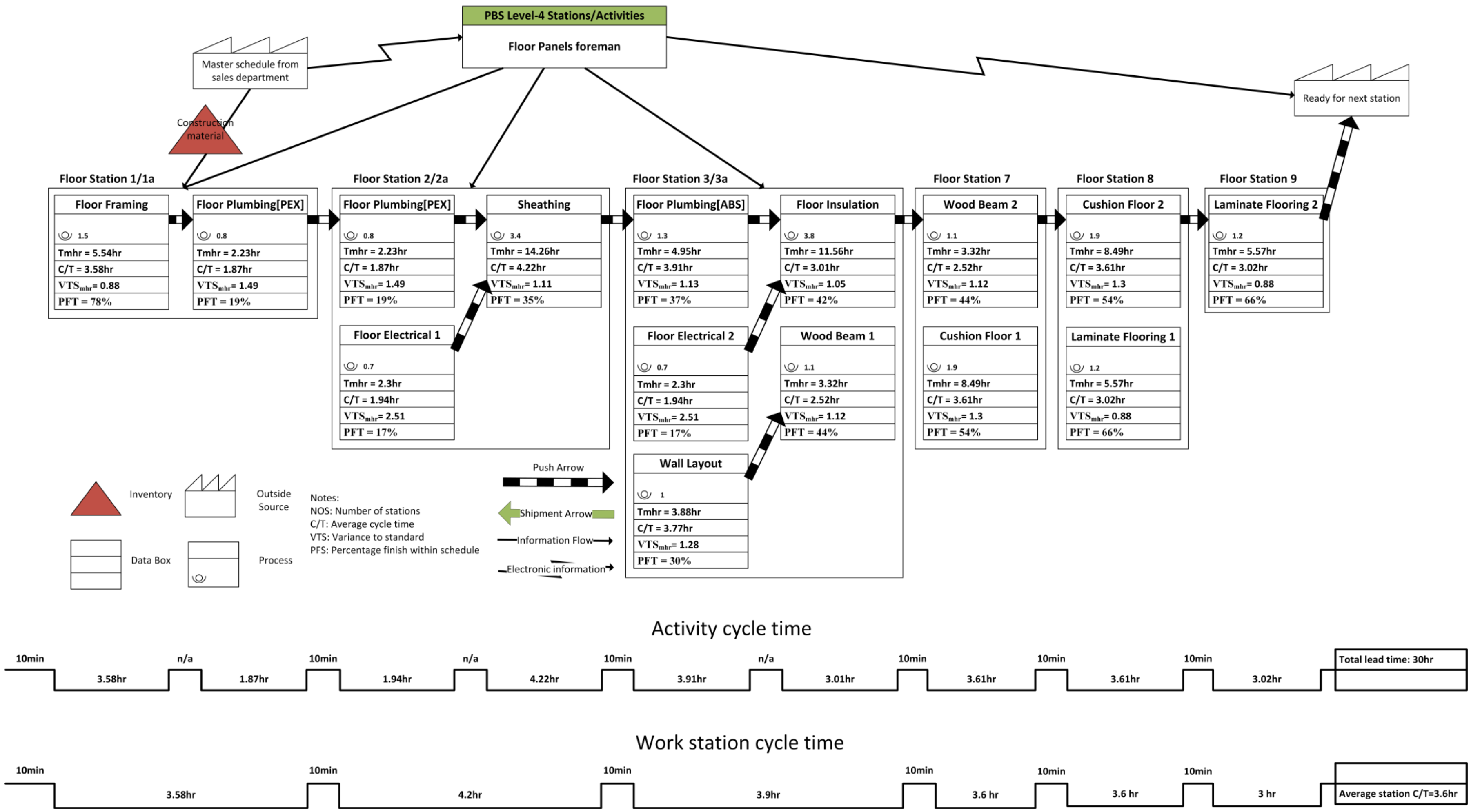


Figure 3-26: PBS level 4 Stations/Activities VSM for floor panel production line

Based on the findings mentioned above as well as the feedback industry partner personnel, the following modifications of the existing floor panel production line are discussed and studied.

1. Reduce the working durations of critical activities by utilizing the Lean manufacturing concept in order to eliminate waste and add value.
2. For activities that cannot be completed within the 3 hr Takt time after process improvement, consider re-distribution of the workload (shifting workstations or construction zone).
3. To reduce unpredictability, avoid having the same crew working on different workstations.
4. Minimize the variation (standardization of the working duration) by innovating the work process to create standardized work, and pre-assembly work.
5. Resolve bottleneck stations and activities by increasing the performance of the activity, reducing the duration for other activities at the same station, and relocating the workload throughout other stations.

Recognized as one of the critical activities at the floor panel production line, as seen in Figure 3-27, floor framing is further broken down into separate work motions so that the barriers of reducing the process duration can be identified. The first part of the floor framing is rim-board assembly; as shown in Figure 3-28, five out of six activities can be identified as waste in this operation and only the gusset press is recognized as a value-added activity.

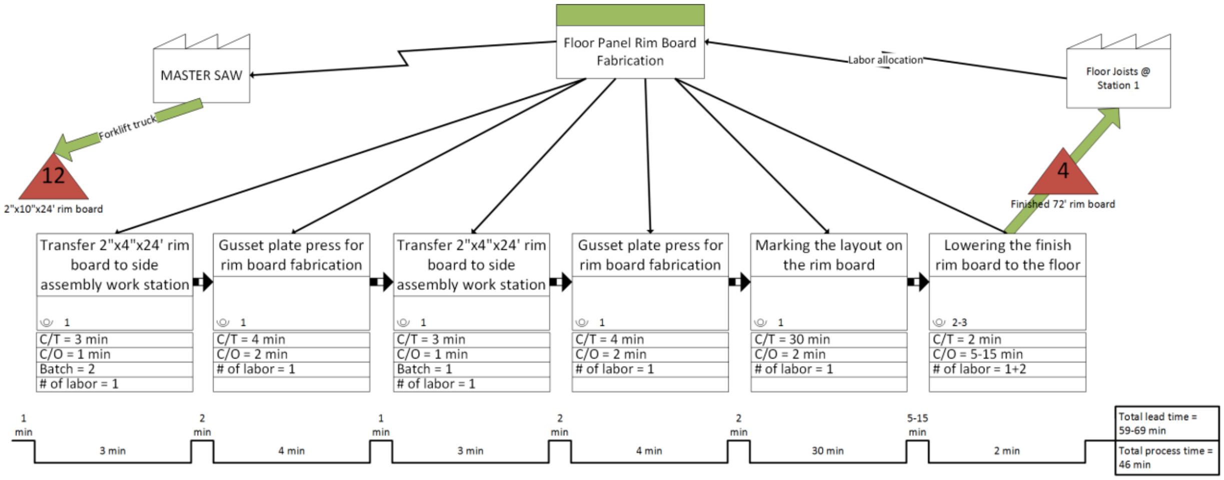


Figure 3-27: Current-state level 5 VSM - Floor panel rim board fabrication

(a) Gusset plate press (b) Marking layout (c) Rim board delivery

Figure 3-28: Floor panel rim board fabrication (current-state)

As an example, Figure 3-29 shows the future-state VSM to reduce the working duration for this process. In the figure, the potential improvements include: (i) modify the gusset plate machine to vertical position and combine the mechanism together with a jig table, thus eliminating the side table and extra workforce; (ii) deliver the unit lot material and relocate to a position where gravity can be employed to facilitate convenient transporting of lumber; and (iii) use a laser screen on the table to mark the joist layout automatically. Implementation of these recommendations can substantially reduce the cycle time of rim board fabrication from nearly 1 hr to 20 minutes. Waste motions for material delivery and heavy manual work, such as drawing the layout on the rim board, are also eliminated or minimized.

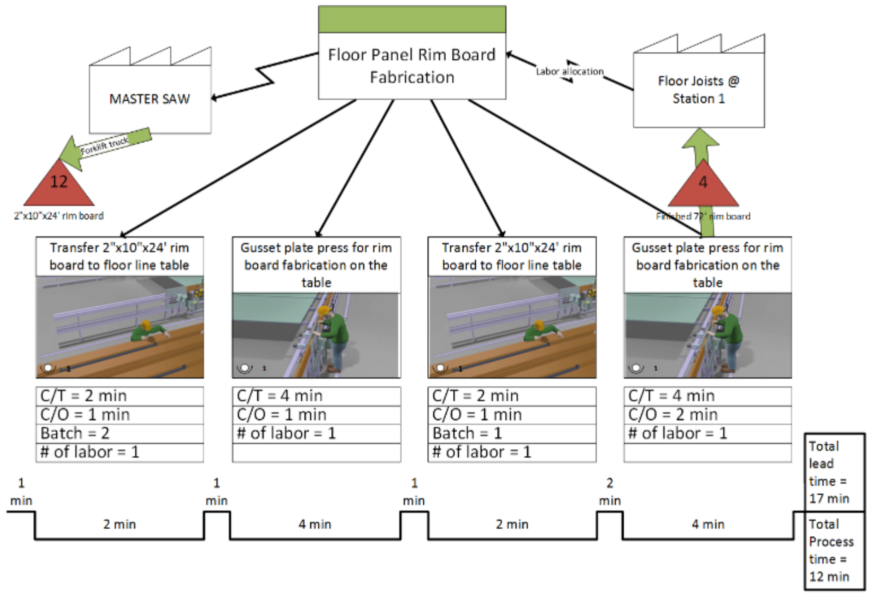


Figure 3-29: Future-state level 5 VSM - Floor panel rim board fabrication

Similarly, a current-state VSM for structural framing of the floor (Figure 3-30) reveals another low-efficiency, highly manual work-based process. There are excessive walking motions involved in this framing process, and the only value-added motion is the nailing motion. To better quantify the amount of waste generated from this process, the following calculation is made.

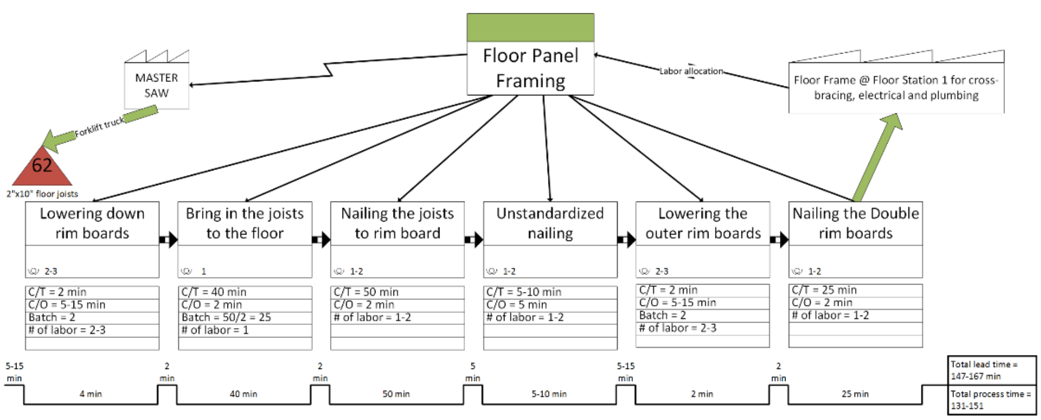


Figure 3-30: VSM level 5—Current practice of floor framing

(a) Lowering the rim board (b) Carrying joists to the floor (c) Nailing joists to rim board

Figure 3-31: Current practice for floor framing

As shown in Figure 3-31, joists are usually carried by workers one by one to the assembly area (on the floor). On average, workers walk over 1,800 ft per floor framing unit, carrying a joist or a heavy nailing gun. Assuming every joist delivery takes 1-2 minutes, to complete the joist delivery task for a floor panel 70 feet in length can take up to 40 minutes. Yet these 40 minutes represent waste motions that do not add value to the product. To fasten the rim board to the joists, five nails are needed for each side of the joists, totalling an average of over 500 nails/floor framing, which can take approximately 50 minutes to complete. By employing a true manufacturing approach, this physical effort can be reduced substantially through the implementation of manufacturing-based processes and technologies.

Figure 3-32 shows a proposed future-state map for a floor framing assembly station.

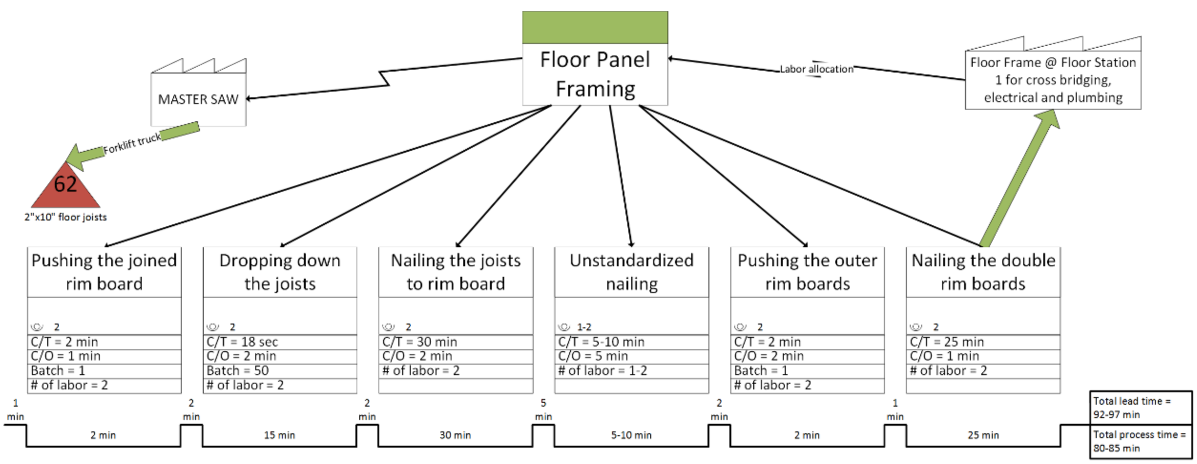
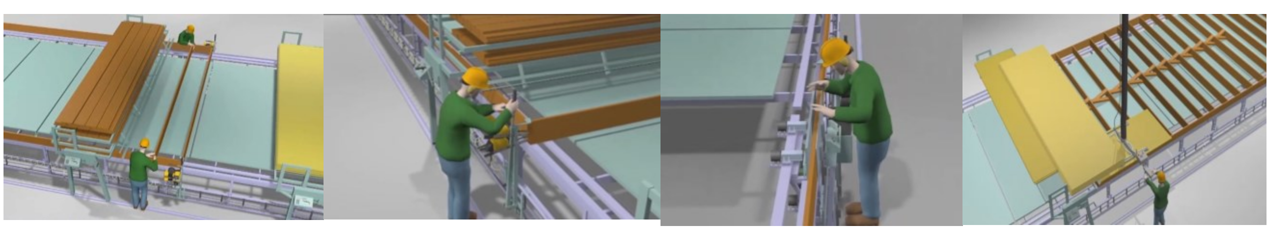


Figure 3-32: Future-state VSM level 5—Proposed floor framing process



(a) Lowering the joists (b) Nailing (c) Rim board butting (d) Material lifting

Figure 3-33: Proposed floor framing process

As illustrated in Figure 3-33, workers and tools (e.g., nailing gun) are assigned fixed positions, and material is also positioned for workers and tools by a mobilized material handling bridge.

The bridge will not only allow for unit lot material delivery to eliminate material defect; it will also allow the use of gravity to easily slide the material to the table.

Roof panel production line:

Figure 3-34 is the current VSM of the roof panel production line. With an overall balanced process, there are three activities that are more time consuming than others: roof framing, roof drywall, and Gyptex ceiling. Additionally, at station 3 of the roof line, the station cycle time cannot meet the expected cycle time. However, in the existing practice, since the overall man-hour requirement at this section is well controlled within the planned hour, it rarely becomes the bottleneck of the overall production line. The work at station 3 can generally start early as the work assigned to the first two stations tends to finish ahead of schedule. It is therefore also worth the effort to study the more time consuming activities in order to carry them out more efficiently by applying Lean manufacturing principles and the introduction of innovative work processes.

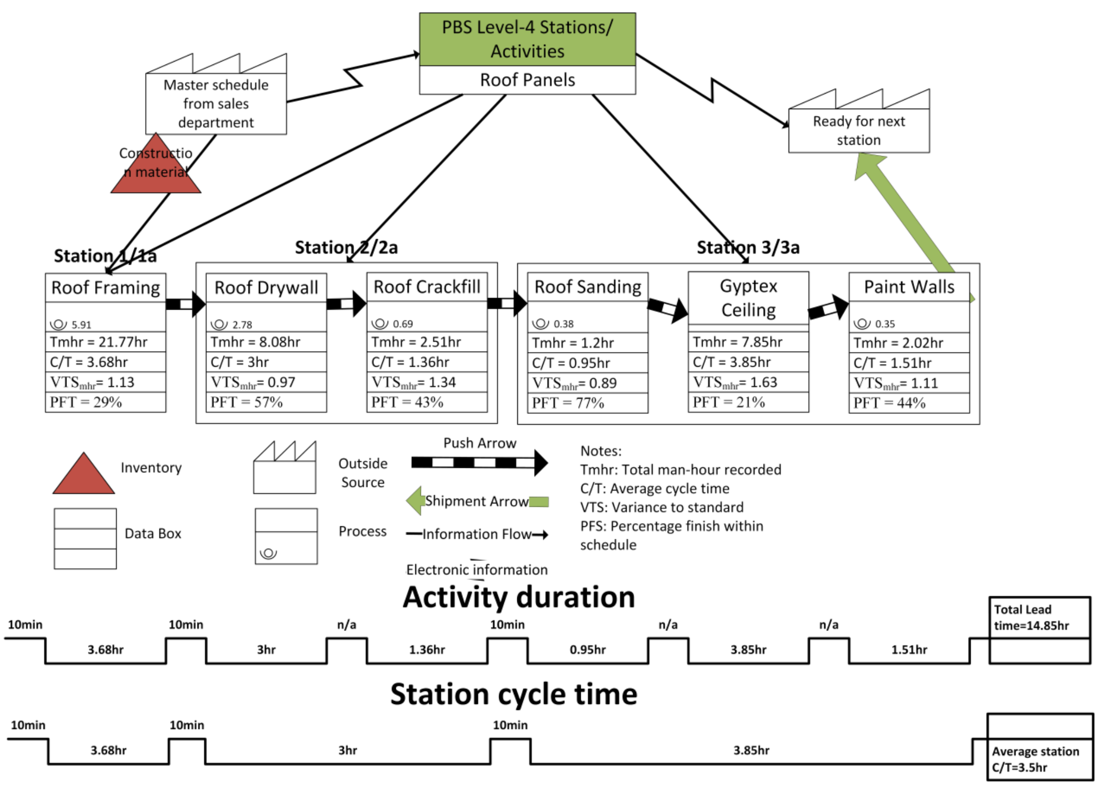


Figure 3-34: PBS level 4 Roof Panels

A motion detailed VSM study for roof drywall procedure is presented as an example of proposed improvement. In Figure 3-35, a typical standard process for roof drywall installation is illustrated. By identifying the waste motion and value-added motion, it is found that none of the first three activities in the process are adding value to the product. Instead, it is determined to be an inefficient process. Half of the overall processing time is consumed by the material transportation activity, involving workers walking back and forth between the workstation and inventory pile carrying heavy loads. As there is one extra worker required for the nailing process, it also causes instability for the duration of this process due to the possibility of delay or change in labour resource. The reader may refer to Figure 3-36 for photographs demonstrating the actual process on the line.

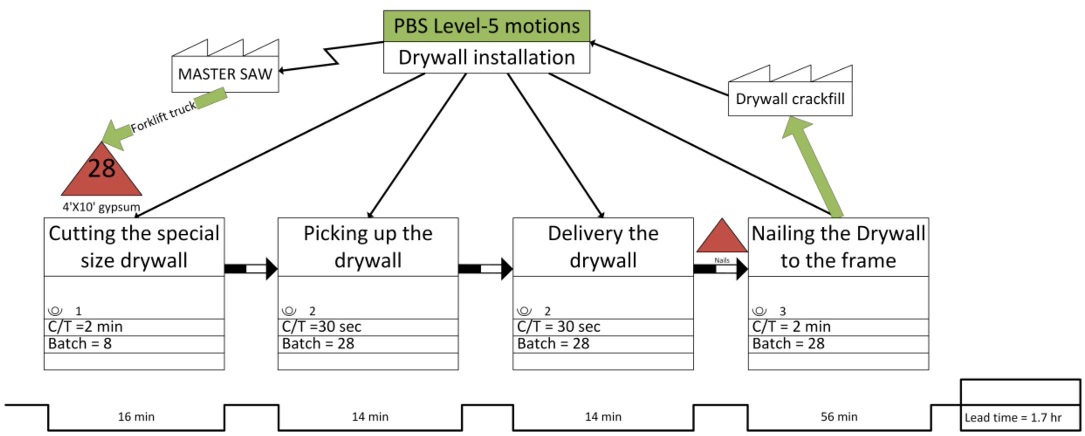


Figure 3-35: Current-state level 5 drywall installation standardized process

(a) Retrieval of drywall | (b) Delivery of drywall to the workstation | (3) Nailing of drywall

Figure 3-36: Roof drywall installation process

Figure 3-37: Roof workstations with access from above and below

Another finding from the PBS level 4 roof panel is the space availability from above as the roof panel is lifted for the operation underneath the panel. Work can be carried out from above and below the roof panel simultaneously. Figure 3-37 presents an on-site operation example of the accessibility from above and below the roof panel. Since the area above the roof workstation is left empty, the addition of potential value-added activities (such as installation of electrical wiring, HVAC, or plumbing) at this workstation is recognized and recommended to the plant to help alleviate downstream congestion on the line.

As shown in the previous section on plant operation figures, internal process improvement focuses on seeking the activity procedure itself, avoiding violations of Lean principles, and thereby reducing the process duration to meet the target Takt time.

3.3.1.5.2 External production line adjustment for process improvement

The external adjustments of the production line are based on investigations of workstation within the entire production line as well as making the modifications of the production line sequence in order to increase the overall performance by balancing workload distribution and creating innovative work procedures. Comprehensive assessments of the wall panel, rough-in, and final finishing sections of the industry partner's production line and a post-assessment proposal are described below.

Wall panel production line:

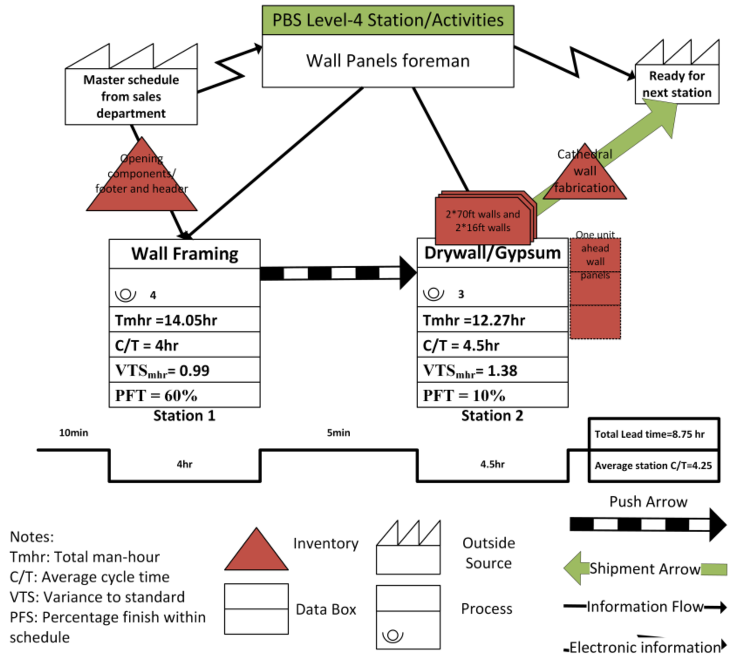


Figure 3-38: PBS level 4 current-state wall panel VSM

The other section studied on the production line is that of wall panels, which has a similar process to that of the floor panel. Based on the data from PBS level 2 study, in the current state the wall panel section has the lowest workload and workforce densities. It also produces the lowest average cycle time. As there are only two workstations that add limited value to the wall, the benefit of the true manufacturing process is applied to a limited degree in this section. Figure 3-38 shows the current process of the wall panel section.

Figure 3-39: Current-state exterior wall panel

As VSM is not able to represent the simultaneity of the wall framing process, it thus combines the time required to frame each single wall panel for one module in one cycle time, and applies the same procedure to the drywall installation cycle time. Therefore, although it appears the current process cannot deliver a wall batch in less than 8 hr, it can complete the wall framing within the planned hour as expressed in the level 2 data. The goal for this VSM is to reveal (a) the inefficient space utilization at the wall framing section, and (b) the potential to add more value to the wall panel in this section, thus reducing the pressure downstream. Based on the current wall panel VSM, a wall panel consists of a wall frame and partial drywall only (refer to Figure 3-39). However, full wall panels can potentially include a number of additional components. As presented in Figure 3-40, a wall panel can include not only framing, but also drywall, sheathing, windows, doors, electrical wiring, plumbing, insulation, and any other components that belong to the given wall in the finished module.

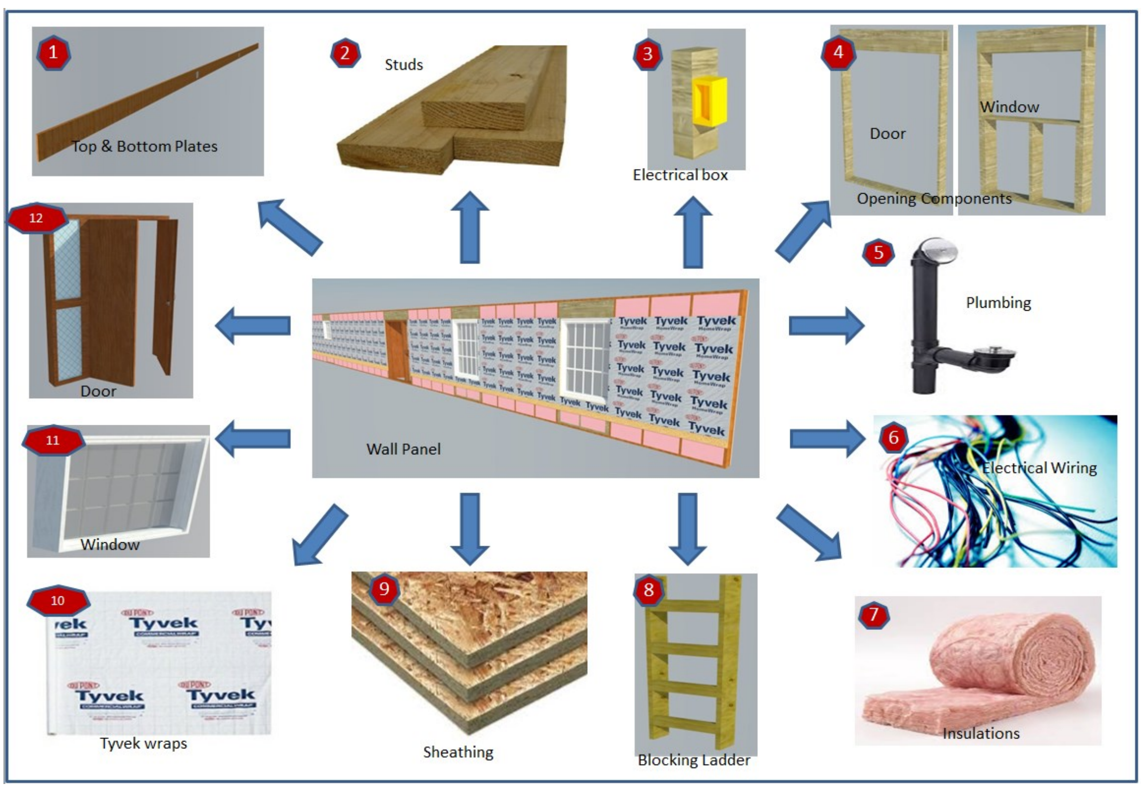


Figure 3-40: Components of wall panel

Based on the current VSM as well as the two characterizations of what a wall panel represents (wall panel with a wood frame only or a fully value-added wall panel), the following proposals are offered.

1. Similar to with the floor framing station, framing process improvement can be conducted with regard to wall framing in order to reduce the work duration by eliminating waste and promoting the efficient value-added process.
2. More value can be added to the wall panel in the form of sheathing, insulation, and building envelope system, and even electrical and plumbing.
3. To make the previous recommendation feasible, those extra values need to be added within the same space capacity and same delivery time.
4. The space needs to be utilized more effectively and more efficiently. Bringing the wall vertical instead of horizontal will not only free up more available space, but also makes the activities at this station easier to complete. The additional workstation using the same amount of factory space means more man-hour distribution within the same work space without delaying the product delivery to downstream workstations.

Based on the above recommendations as well as the suggestions from experienced personnel in the case study plant, a future-state VSM for the wall panel production line is created (to be discussed later in this chapter). It integrates the idea of fully utilizing the available space, taking advantage of the manufacturing process, and considers the balancing of the overall production line, particularly for the activities that occur downstream.

Rough-in and final finishing sections:

The next target section for detailed study is the rough-in section on the main production line. The assigned activities and the man-hour/labour distribution become less balanced compared with the prefabrication panels in regard to the workstations flow performance. For example, workers may be required to work at different workstations, and the same activities may extend across three or four workstations. In other words, at this section of the production line the concept of working within the same station is insufficiently implied, or more difficult to adhere to. The overall process sequence differs only slightly compared with the stick-built work process and this inhibits the application of innovative ideas thereby discouraging the shift from the conventional construction process to the manufacturing construction process.

In Figure 3-41 the activities in the production line rough-in section are summarized. Noting the existence of parallel activities operation and in some cases the same activity extending to several workstations at rough-in section, assumptions are needed in order to adjust input data for the VSM in which value and activities are assigned to the workstations. Based on the VSM, the following analysis steps are implemented to identify problems and uncover potential improvements.

1. Summarize the overall rough-in section performance.
2. Identify the absolute bottleneck on the line.
3. Integrate the scientific findings with the expert feedback from company personnel.
4. Implement the improvement.

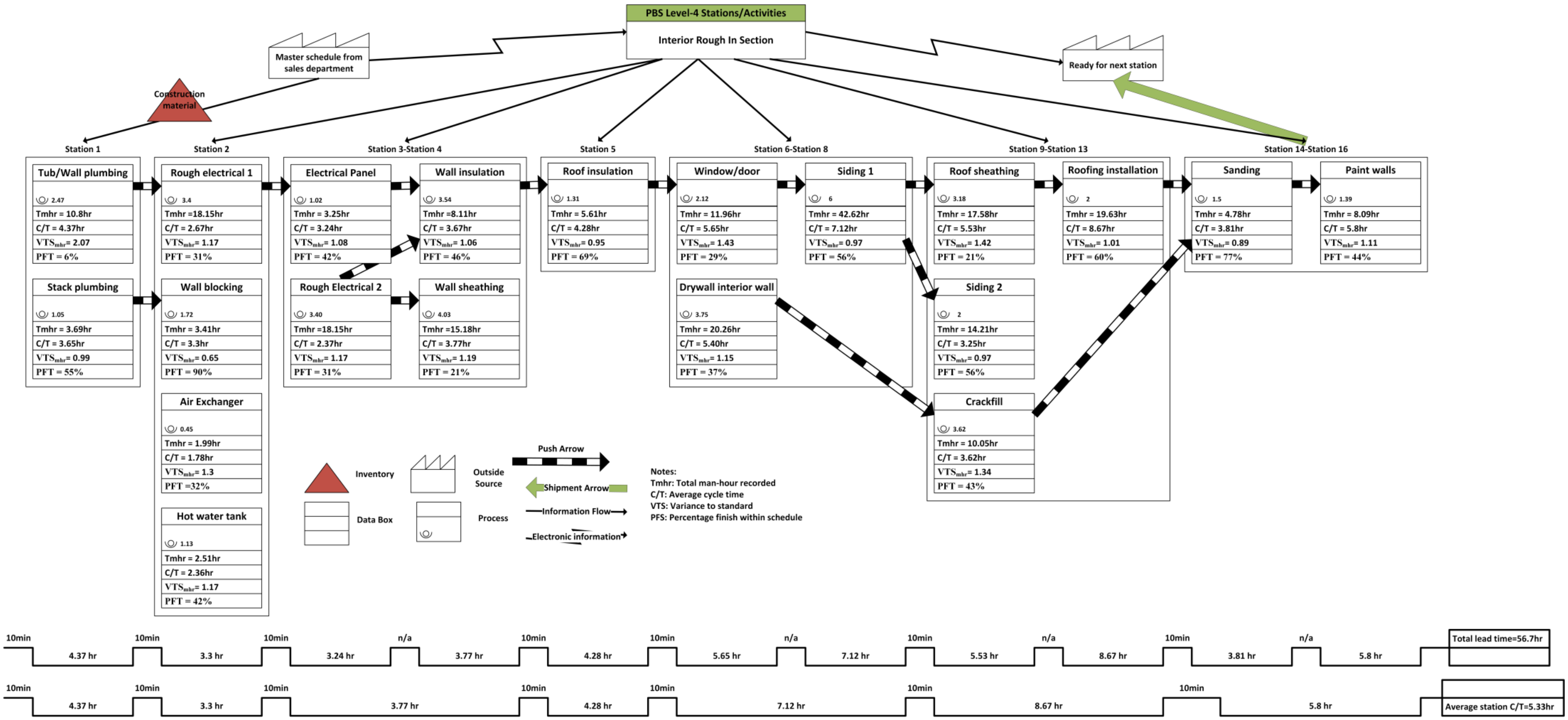


Figure 3-41: PBS level 4 Rough-in section

To recall the overall performance of this section from PBS level 3 analysis, a screenshot of the VSM is presented in Figure 3-42.

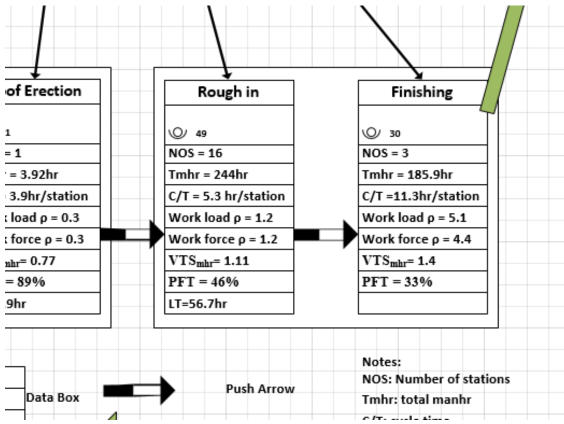


Figure 3-42: Rough-in section performance from PBS level 3 VSM

There are 49 workers assigned to 16 workstations with a total 244 man-hour workload. The average workstation cycle time is 5.3 hr, which is greater than the current 4.5 hr ideal Takt time and almost double that of the targeted 3 hr Takt time. Although a 1.2 workforce density is not the largest on the line, it shows a dramatic increase in workload and workforce density compared with the previous sections. Although an average VTS of 1.11 indicates an acceptable performance on meeting the schedule, a PFT of 46% still shows inconsistency with finishing the task on time throughout the rough-in section.

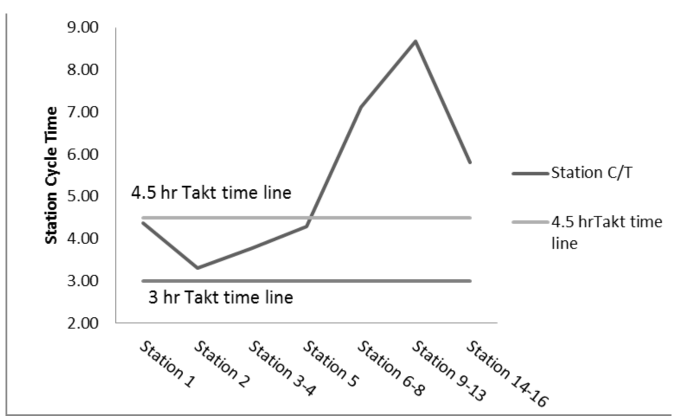


Figure 3-43: Rough-in section station cycle time

Based on the PBS level 4 VSM in Figure 3-41, a summarized workstation cycle time table is presented in Figure 3-43. Although the cycle times of the first five workstations remain within a 3.0 to 4.5 hr range, the cycle times of the remaining workstations increase to a maximum of 8.7 hr. These valleys and peaks throughout the section indicate a poor workload distribution. Because some of the activities are extended into three or four stations with only one crew for each activity, the additional physical stations serve as buffer zones rather than actual working stations, which is the current assumption by the plant manager. These extended working areas will therefore lead to unpredictable work duration, non-standardized working procedure, delays to upstream and downstream activities, wasted motion for mobilization, and poor tool management. Figure 3-44, contains performance indicators for all the activities at the rough-in section, illustrating the instability of the activity performance. One of the key findings illustrated in this figure is that although some of the activities can be identified as bottlenecks based on the workstation cycle time performance, this should not necessarily be considered a key issue on the line based on VTS or PFT performance indicators. For example, roofing installation defines the longest cycle time based on Figure 3-41 and Figure 3-43, yet it has the near-perfect VTS value 1.01, which indicates that the activities in this section can finish within the planned work hours. This type of performance conflict is the result of having interior and exterior work operating simultaneously, but where one requires more stations to finish than the other. As interior work involves more man-hours than exterior work, during the scheduling phase, exterior activities are assigned longer work durations due to the lower intensity workload. Although the impact of this practice is outside the scope of this research, it should be noted that production line bottlenecks ought to be identified based on a comprehensive understanding of the overall performance of activities rather based solely on workstation cycle time.

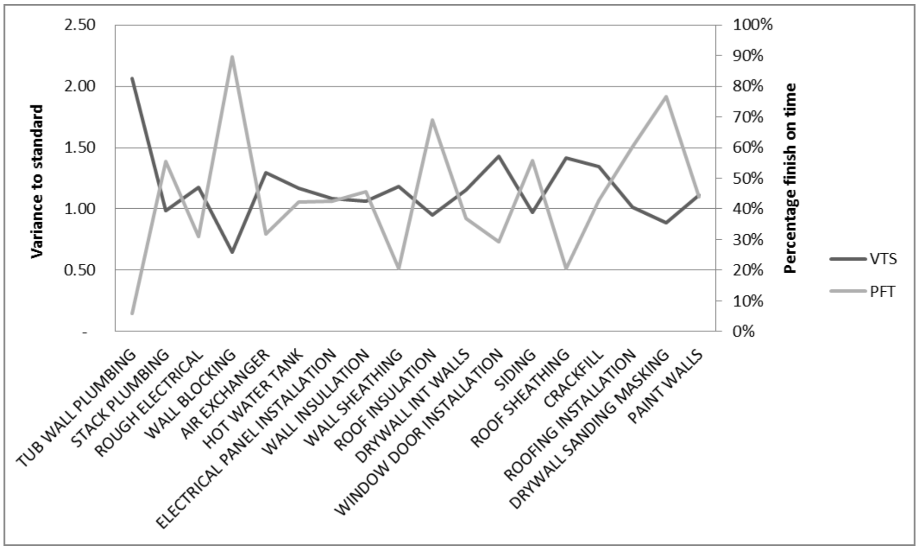


Figure 3-44: Performance indicators VTS vs. PFT at rough-in section

To identify the exact bottleneck activities, a grading chart is created based on the indicators from Figure 3-41: PBS level 4 Rough-in section. The grading category and ranges are set according to the ideal Takt time, as well as the performance expectation of the plant manager. The reader may refer to Table 3-12 for the grading index.

Table 3-12: Grading index

Grading	C/T	VTS	PFT	N of workers
1	> 4.5 hr	> 1.5	< 25%	> 5 workers
3	3.0 to 4.5 hr	1.1 to 1.5	25% to 45%	3 to 5 workers
5	< 3.0 hr	< 1.1	> 45%	< 3 workers

The grading for each activity in the rough-in section is collected in Table 3-13. The total grade shows the priority of the activities that should be considered, yet it cannot represent an absolute priority due to the accuracy of the data as well as the objective base on company's needs. The activities with the lower grade have higher priority than those that have a higher grade.

Table 3-13: Priority identification-performance grading

Activity	G:C/T	G:VTS	G:PFT	G:N of Labour	Total Grade
Rough electrical	1	3	3	1	8
Roof sheathing	1	3	1	3	8
Tub wall plumbing	3	1	1	5	10
Wall sheathing	3	3	1	3	10

Drywall interior walls	1	3	3	3	10
Window & door installation	1	3	3	5	12
Siding	1	5	5	1	12
Crackfill	3	3	3	3	12
Paint walls	1	3	3	5	12
Air exchanger	5	3	3	5	16
Hot water tank	5	3	3	5	16
Electrical panel installation	3	5	3	5	16
Wall insulation	3	5	5	3	16
Roofing installation	1	5	5	5	16
Stack plumbing	3	5	5	5	18
Wall blocking	3	5	5	5	18
Roof insulation	3	5	5	5	18
Drywall sanding & masking	3	5	5	5	18

Based on observations in the plant, communications from manufacturing personnel, and the final grading result, activities that have a grade of 12 or lower are considered to be potential improvement activities. Rough-in electrical, tub wall plumbing (install plumbing at the wall that is attached with the tub), and interior drywall are not only time-consuming, but also delay the progress, hindering the crack fill activity from starting early. One of the most significant problems mentioned is that the mudding (crack fill used by factory) starts at the station where it is designed to finish. In other words, crack fill is planned to finish prior to station 9 whereas in the current state it finishes at station 13. This causes delays for downstream activities that have only three stations to work with rather than seven or eight workstations. The performance of the rough-in section and its downstream sections are illustrated in Figure 3-24. The figure shows that the average cycle time at the downstream section (finishing section) is double that of the rough-in section and the workload density at downstream sections is four times greater than at the rough-in section. The total number of workstations dramatically decreases from rough-in to finishing section as well.

Based on the studies of both the wall fabrication line and the rough-in section production line, proposed improvements are summarized below.

3.3.1.5.3 Summary of improvement proposal

According to the findings presented in the previous section, an improvement proposal can be drafted to solve the key problems in the target areas. The following are the summarized points raised during the problem identification process; the proposed solutions are described accordingly.

1. There is imbalance in the production line flow, where the prefabrication section has the lowest workload and workforce density, the rough-in section extends into a larger area with comparatively relaxed workload and workforce, and finishing section is congested with extremely high workload and workforce density.
2. In the floor panel production line, the framing procedure involves more than 50% of non-value-added activities; the entire process is physically demanding and inefficient. Sheathing, plumbing, insulation, and flooring are highly time-consuming activities. The flooring process is extended into a larger space. Although there is no data recorded for the transportation duration, according to plant personnel, shifting around the floor panel due to a disruption in production line flow not only creates extra non-value-added activities, but is also time-consuming.
3. In the wall panel production line, little value is added to the wall panel prior to its being transported to the assembly line. As with floor panel framing, the wall framing process is inefficient. The space utilization at the wall panel section is poor, a fact which points to the potential for value-adding and process improvement. There is also great potential in this section for workload balancing from downstream rough-in sections.
4. The roof panel production line has the highest level of value-adding as well as schedule planning, even though the drywall installation process produces some wasted motions.

The work space above the roof panel is also seen as a potential opportunity to improve space utilization as well as workload balancing for downstream rough-in sections.

5. Imbalanced production line flow is identified in the rough-in section. Time-consuming activities, including installation of plumbing, electrical wiring, window/doors, and drywall, are generally critical activities on the line that create bottlenecks and disrupt flow. These activities delay the production line for four to five workstations, which consequently results in a congested work section at the end of the production line. Some of the workload at the rough-in section should be relocated to a more suitable working area (i.e., wall panel fabrication line) to smoothe production line flow.
6. Based on observations of the existing working processes, the production line generally follows the traditional construction process with limited innovation with respect to operational procedures and working tools. The activities tend to be non-standardized and the work durations vary greatly.

Based on the issues summarized above, a potential improvement plan is proposed with the focus on the prefabrication and rough-in sections. For the prefabrication section internally, the framing section for both floor and wall panel lines are being offered a new process by a semi-automated framing jig table. The material is suggested to be delivered per house lot by forklift to a cross bridge on top of the jig table, improving the efficiency of the material delivery process.

Changes are also recommended regarding the interactions between sections in order to achieve better workload distribution. An innovative way to consider a wall panel is presented in Figure 3-40. The amount of value contained in a wall panel can be more than just frame and drywall/sheathing itself. Therefore, to help redistribute the workload from the rough-in section, it is proposed to move some activity operations, in part or in full, upstream to the wall panel production line. Figure 3-45 shows the potential value that can be contained within a wall panel.

Figure 3-45: Wall panel with good value inputs

By creating additional workstations in the wall line, these extra workloads will be able to fit within the same area and finish within the same timeframe. The proposed activities to be relocated include rough-in electrical, blocking, plumbing, insulation, sheathing, Tyvek, windows/doors, and siding. In order to accomplish this, four additional workstations are required in the wall panel area, and the current side stations and on-site storage area need to be eliminated or relocated. In Figure 3-46 to Figure 3-48, the current and proposed wall panel section layouts are illustrated using 3D visualization.

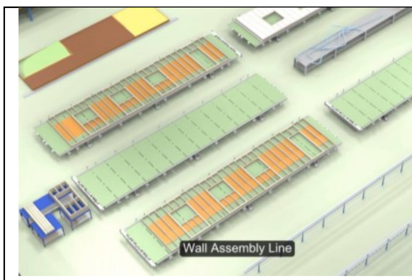
Figure 3-46: Current wall panel production line

Figure 3-47: Vertical future wall panel production line

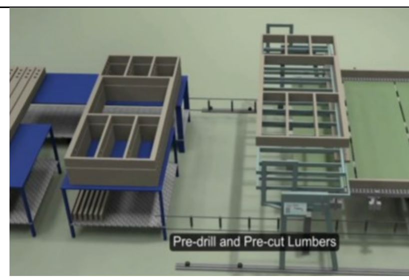
Figure 3-48: Horizontal future wall panel production line

In the proposed improvement, in order to ensure enough work space after adding additional workstations, and to ensure that the extra work will not delay the wall panel delivery to the main production line, it is suggested to keep the wall panel in the vertical position rather than laying it horizontally. As a result, the allowable man-hours can be doubled at this station and workload can be reduced.

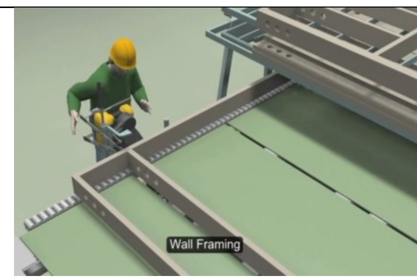
In Figure 3-49, a series of animation frames of the wood framing process illustrate the proposed wall production line adjustments combined with the future rough-in section workload reallocation.



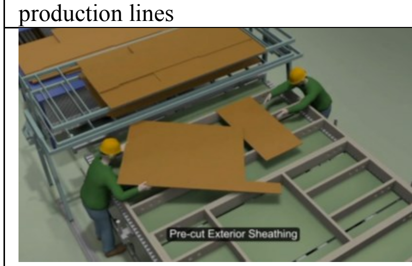
(a) One framing table feed two production lines



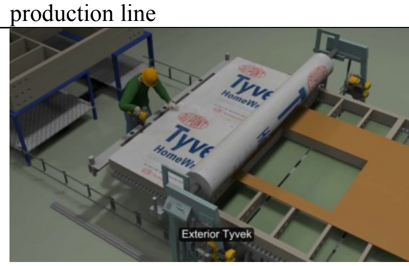
(b) Pre-assembly table aligned with production line



(c) Pre-drill lumbers, gravity usage for material layout, fixed nailing guns



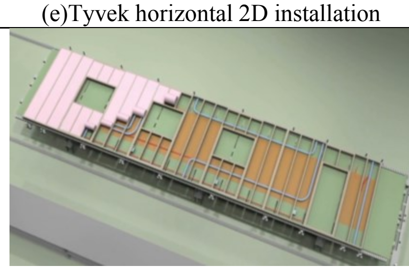
(d) Pre-cut sheathing

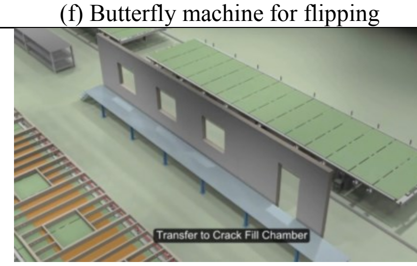


(e)Tyvek horizontal 2D installation

(f) Butterfly machine for flipping


(g) Electrical vertical 2D installation


(h) Insulation horitonal 2D installation



(i) Potential drywall mudding chamber

Figure 3-49: Future wall panel fabrication details

For the roof panel line, the efficiency of drywall installation is considered a low-investment improvement. Combining this improvement with the jig table upgrade, which can help improve the framing process, both framing and drywall installation can be expected to finish at the same station within the 3 hr Takt time. Figure 3-50 to Figure 3-53 showcase the proposed change for the first station of the roof panel line.

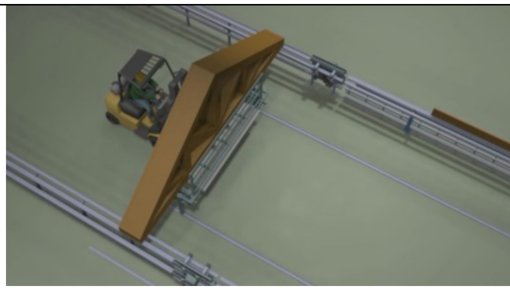


Figure 3-50: House lot material delivery with low height jig table

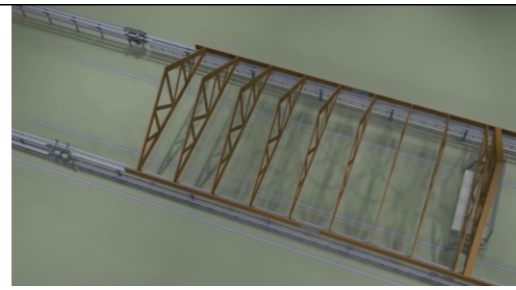


Figure 3-51: Using material delivery cart to fix operation with material

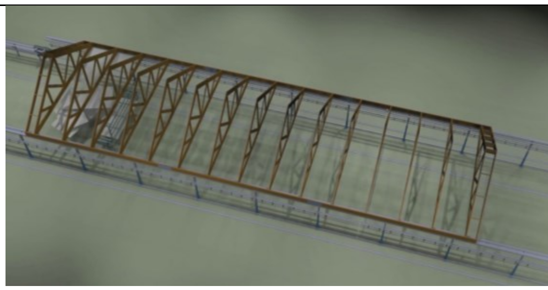


Figure 3-52: House lot drywall delivery

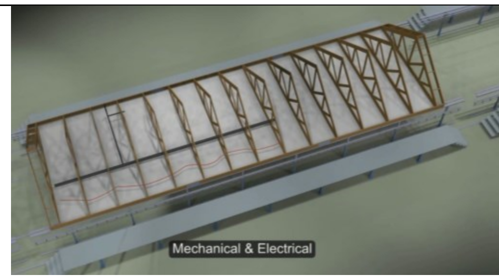


Figure 3-53: More value-added on top of the roof panel

In addition to relocating the workload on the line, exploiting the benefits of manufacturing where product components can be planned and pre-assembled under a controlled environment will also help to reduce stress on the main production line. The current-state practice of having wall openings pre-assembled before being transferred to the wall framing section plays a positive role in preparing the components for the production line. Similar activities are suggested for future improvements based on the analysis. Unit lot material delivery, lumber with pre-drilled holes, pre-assembled wood blocking, and pre-assembled plumbing sections are four of the key elements that could improve the on-line work efficiency directly. These pre-assembly improvements are implemented at the case study factory, and the detailed photographs can be found in the on-site testing report, refer to 3.3.2.1.

3.3.2 Assistive tools for PBS-integrated VSM analysis

In addition to the VSM analysis, other tools are also required during the production line study process as subjective supports for manufacturing performance study. They are equally critical to the success of manufacturing process improvement. Three key tools are included in this integrated framework: (1) on-site observations with A3 report, (2) 3D animation, and (3) team brainstorming sessions. The observations usually occur prior to the key process, the VSM analysis, and provide first-hand interpretation to teams involved with the process improvement project. Key challenges of the production line are revealed, as well as those activities which can be improved quickly with little investment. This diagnosis process (observation) is efficient, effective, and beneficial for VSM analysis. The findings and even some quick solutions can be recorded using the A3 report. 3D animation plays multiple roles within the proposed framework: communication, visualization, and validation. Having a committed and engaged project team and ensuring full commitment from company personnel is crucial for any Lean improvement project. Regularly scheduled brainstorming sessions and communication meetings between different teams are essential for gaining valuable suggestions, ideas, and even critiques for lesson learning based on collective experience. The following section introduces in detail the three key tools, which are explained in conjunction with the case study.

3.3.2.1 Field observations and A3 report

The focus of plant observation is not only on finding the key issues on the line but also on the activities that can be improved with low cost and high (fast) payback (LCHP)—in other words, low hanging fruit problems. In the context of the production line, LCHP represents those activities or motions that have potential to be improved quickly and effectively without front end investment and production line interruption. Any operations on the production line can be the focus of observation, and the goal is to observe the process with Lean principles in mind and to question even commonly used processes. Repetitive motions, heavy lifting, time-consuming activities, walking motion, and tool usage are the key elements that should be observed. Low hanging fruit observation is also recognized as a good starting point for any manufacturer seeking production line improvement. Gaining swift feedback from the low hanging fruit improvement plays a key role in convincing the managers, foremen, lead hands, and workers that questioning as well as being creative, innovative, and rebelling against the traditional processes can be challenging but also rewarding, even if Lean manufacturing is not yet part of their everyday vocabulary. The implementation is not always successful, yet the process makes the seemingly impossible visible and feasible. Also, many of the "quick fix" suggestions are proven to be capable of increasing efficiency immediately upon implementation.

A number of A3 reports are used to document the findings during the observation and serve as a reference to any further analysis. A 10-year employee of Toyota addresses the A3 report as the secret of how Toyota "solves problems, creates plans and gets new things done while developing an organization of thinking problem-solvers" (Shook 2009). He mentions that the A3 report not only serves as a document and measurement for the Lean production line but also provides strong "mechanisms for managers to mentor others in root cause analysis and scientific thinking, while also aligning the interests of individuals and departments throughout the organization by encouraging productive dialogue and helping people learn from one another". It also creates cycles of learning to lead the organization toward a continuous improvement process (Shook 2009). As a way to approach continuous improvement, self-examination, process documentation, and results measurement, A3 report should be applied to current modular construction manufacturers, with some adjustments to accommodate the unique complexities of construction manufacturing. In fact, Meiling & Johnsson (2014) apply A3 report as part of the plan-do-check-act (PDCA) method to help solve issues raised from a modular construction plant for continuous improvement. They recognize that their method functions better for isolated activities which require a more standardized process and less manpower. In the case study, the observation and subsequent A3 report also focus on the low hanging fruit issues, whereas those challenges that require further investigation can benefit from the proposed PBS-integrated VSM analysis. Based on suggestions by Shook (2009) and Meiling et al. (2014), the key contents for A3 report can be summarized in the following five steps:

1. Theme and background: a brief background of the report target and purpose.
2. Current conditions: may include the primary findings from field observations, and describes clearly and succinctly the conditions observed. Supportive visualization tools like photographs or drawings can be highly valuable in this regard. A brief root cause analysis and target condition regarding the specific issues should also be addressed in this step to ensure an effective problem solving plan is established.
3. Propose countermeasures: it is recommended by Shook that "countermeasure" is a better term than "solution" as there may be no absolute solution for the problem being discussed but only improvement. It is normal to raise a new problem as the old issues are solved; however, this should not hinder the manager from providing plans for continuous improvement in various problem areas as the process steadily moves toward an ideal condition.
4. Follow-up plan: it is important to ensure the operational effectiveness of the improvement process.

5. Result report: the result from the previous improvement process can provide lessons learned as well as create new challenges for continuous improvement.

3.3.2.1.1 Case study: Problem identification by observation and A3 report

Observations are conducted at the industry partner both before the improvement process and after implementation of proposed improvements. As mentioned above, the observation is mainly focused on time-consuming activities and high intensity, physically demanding work procedures with a goal to propose the potential work procedure adjustments that lead to low cost and quick payback results. Some adjustments that are suggested after the observation can be costly and may require long-term assessment and detailed feasibility studies. One of the common findings for both prefabrication sections is the deficient working procedure for framing. A number of violations of Lean principles are discovered throughout the process, including a large amount of wasted motion and non-value-added activities. Due to the limited material delivery supports, framing for floor panels becomes extremely physically demanding. The size of floor panel (up to 75 ft long) also necessitates a great deal of walking motion, which translates to time-consuming wasted motion. Another key issue is the excessive amount of repetitive non-value-added activities during the process. For example, to pass the wiring through the floor panel or wall panel, workers are required to drill holes on every single joist (there are more than 50 floor joists per floor panel) or stud (there are more than 100 wall studs per unit), which is repetitive and time-consuming work adding only minimal value to the wall panel. Often the wall panels are waiting for a finished floor panel in order to begin the wall erection activity and also vacate the space in order to begin fabrication of the next unit. As the main production line develops a bottleneck directly following the erection section, where more values need to be added to the wall, it is observed that the workload along the line is distributed unevenly; (further study needs to be carried out in this regard).

The following are the documented A3 reports[18] for the industry partner, where the key issues of the production line are initially communicated to the partner. Summarized key issues addressed during the VSM analysis in this research are also presented in the previously mentioned analysis.

[18] Although the A3 report is typically suggested with paper size 11.7 in × 16.5 in (A3), to be consistent with the thesis format, the report will be adjusted accordingly.

A3 report for wall production line

BACKGROUND:

Walls are currently being framed lying horizontally on the main framing tables for both exterior and interior walls. The two tables next to the main framing table are where drywall is added to the interior walls. Components are fabricated and stored on the ground. Finished exterior walls need to be stored in the pit beside the main framing tables, and the interior walls are stored on a mobilized cart which can be transferred to the assembly station by an overhead crane.

CURRENT CONDITION:

- Exterior wall plates are measured and marked manually for the stud layout, which is a waste activity. The wall plates are then moved to the framing table in order to locate studs and nail framing components.
- For some walls, it is necessary that two top plates are nailed together according to wall specifications.
- Interior and exterior walls are framed on the same tables. Because of the length limitation of the wall framing table and imbalanced framing duration for different types of walls, idle time increases as a consequence of continually being short by a small margin (approximately 3 ft to 5 ft) to start a new wall.
- Electrical boxes are added to the framing, and then poly and drywall are installed.
- Exterior walls are stored in the wall storage pit after framing, and remain idle for an average of 3 to 4 hr until the floor is ready for wall assembly. Up to nine walls can be sorted in the pit (Figure 3-54).

Figure 3-54: Wall storage pit

- Long exterior walls usually undergo extensive deformation during transfer by the overhead crane (Figure 3-55).

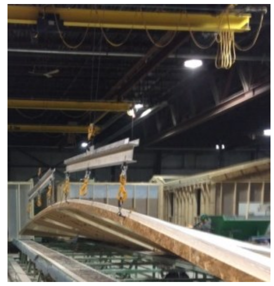


Figure 3-55: Lifted deformed exterior wall

- An average of five minutes is required to move the finished walls into the storage pit by crane, resulting in a considerable amount of time wasted on a non-value-added activity.
- The outside exterior walls are left open without adding much value.
- The wall station can finish one unit much more quickly than the floor station does. As a consequence of the limited storage space, wall panel productivity is affected when storage space reaches capacity.
- Many activities occur simultaneously throughout the production line, which limits the assignment of activities to the workstations based on the number of workers available to simultaneously work on a given module.

Proposal:

- Double plates can be pre-stocked or purchased instead of nailing two regular plates together on the line.
- Interior and exterior walls should be produced on different lines to avoid time and space conflict between two imbalanced activities.
- One side of the wall has to be left open for the wiring, which cannot be done until the cube is formed. However, nudges are required at the same location for every box on the main production line (Figure 3-56). Therefore, rather than spending 2 hr on the nudges for each box, a time-consuming task that risks deficiency, it is recommended to pre-nudge the studs prior to the wall framing activities. If the engineering department can provide more detailed and accurate MEP (mechanical, electrical and plumbing) drawings, the exact locations of the pre-nudged holes can be known in advance, as can the necessary length of the wire. Therefore, MEP drawings may play a significant role in adding more value to the walls.

Figure 3-56: Nudges for wiring

- Semi-automated jig with nailing guns located at both sides of the framing table with two workers on either side to locate and nail the studs in place and one worker feeding the lumbers into the system can improve efficiency. To reduce the time required for measuring and marking exterior wall plates, a laser point projector can be used to project the drawing onto the framing table. Because all workers will remain fixed in their designated position for the entire process, they will not block the light source. However, the accuracy of the projected image needs to be investigated.
- Ideally, an automated framing machine, which reads the drawings, measures spacing, and nails the studs, will improve the productivity and allow for more activities to be completed at the wall station. A return on investment (ROI) study should be conducted to assist in the decision-making process.
- The overhead crane lifting method needs to be adjusted for the purpose of protecting the finished wall structure.
- Using the proper jig and butterfly machine for transfer and storage of the finished wall can dramatically decrease the Takt time for the wall station. However, adding a butterfly machine and updated jig requires more space. It is also a challenge to design a new sequence for wall framing that can fit the new system perfectly. The design of the butterfly machine needs to fit within the available space, thus further feasibility study is required.
- More activities can migrate upstream to the wall station, including insulation, sheathing, window assembly, and sidings. This option needs to be investigated along with flooring activity. Moving wall activities upstream will allow flooring to migrate downstream. In the current state flooring is taking place upstream from wall assembly, which means the finished flooring requires protection, and some damage still occurs.

TARGET CONDITION:

- Automating/Semi-automating the wall framing process by application of high-tech machinery.
- Finishing wall activities prior to cubing the module: A preliminary investigation of the prospect of spreading activities upstream and simulating the process shows a 15% reduction (from 148-168 man-hours to 124-142 man-hours within a 95% level of confidence) in module fabrication time compared to the existing practice. Further investigation is required to evaluate the future work sequence, manufacturing techniques, and advanced equipment needed to achieve the efficiency improvement objective.

IMPLEMENTATION PLAN:

- June 1st to June 15th
  - Simulation of one production line with mixed wall types and two production lines for two types of walls.
- By end of June
  - Investigation of use of laser projector for wall stud spacing.
  - Investigation of purchasing/pre-stocking double-plates.
  - Feasibility study for MEP drawing application on the current production line, including how to add value to the wall.
- By end of July
  - Conceptual drawing of the proposed jig.
  - Revised overhead crane lifting method.
  - Feasibility study of the application of the butterfly machine, including the proper working sequence for the new system.
- By end of August
  - ROI study for semi-automated machine approach.
  - Visualization of the revised plant layout and working sequence.

FOLLOW-UP:

- Framing components are stored and organized in areas around the framing table.

A3 report for floor panel

BACKGROUND:

Currently, floors are framed manually in two parallel rows. Only the second row is equipped with an overhead crane. The framing begins with pre-cutting the side lumber and setting it down on the floor, floor station 1. Joists and trusses are placed and nailed, where plates are only nailed on the upper side. The floor is then covered by sheathing after it is moved to floor station 2. At floor station 3, the floor is raised and held by several jacks for installing plumbing and wiring, nailing hangers, nailing the bottom side of the plates, covering with bottom board, and locating the beam underneath while the measurement for the wall layout is carried out manually by one worker located above the floor. The floor is then moved to floor station 4 to add carpet, cousin floor, and laminate. In floor station 5, the wall layout is marked by wood straps, and the entire floor is protected with plastic cover and then moved to the next station for wall assembly.

CURRENT CONDITION:

- The side lumber for every floor frame comprises three short lumber members combined using gusset plates, which is a time-consuming process.
- Lumber is set down manually, which causes safety and ergonomic issues and is also a waste activity.
- Adding sheathing (using waste material) to side lumber in order to provide more strength increases the Takt time.
- Pre-cut plates are laid on the ground and nailed to the joists. For a floor with more than 30 joists, the above process is repeated 120 times for pre-cutting and 480 times for nailing, which is a deficient task compared to using truss (open-web) joists, taking into account the extra time spent creating nudges later for plumbing and wiring (Figure 3-57).

Figure 3-57: Pre-cut plates

- Nailing and framing is carried out manually by workers, requiring them to walk long distances during their daily work, which is a waste activity.
- The lack of an available overhead crane for the first row causes difficulty and deficiency in manually transferring the floor using the tracks and rails, which is an issue throughout the entire floor station. Existing practice includes various waste activities and poses ergonomic risks (Figure 3-58).

Figure 3-58: Moving floor manually

- In floor station 3, the floor is raised and lowered using temporary jacks or a hydraulic platform as supportive equipment, which entails potential safety hazards and is a non-value-added activity (Figure 3-59).

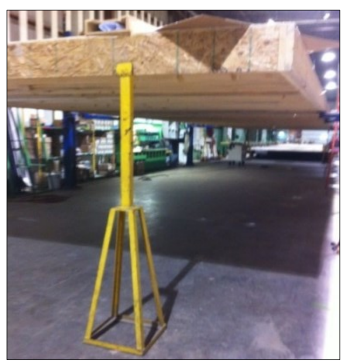


Figure 3-59: Temporary holding jack

- Once the floor is raised up on the jacks, workers need to work in an up-facing position (looking upward) for a long period of time, which is an ergonomic concern.
- Jacks are then switched to a hydraulic platform in order to install bottom board, which is a waste activity.
- Covering the pipe location on the bottom board after cutting the opening (for later access) wastes time.
- Wall layout is placed by measuring the location of walls based on the printed draft, followed by measuring wood straps and cutting them to proper size and also cutting the laminate located under walls, all of which are waste activities.

- The carpet and laminate station becomes the bottleneck on the main production line due to a longer Takt time of the entire floor framing station.
- In order to meet the target Takt time, up to six workers need to be working on the floor finishing station; and, to lower the potential risk of floor damage, different types of protective layers need to be added.

Proposal:

- Installing a permanent ruler to the layout table for measuring the side lumber will improve the work efficiency by reducing the amount of effort for measuring and marking. However, the ruler can only function with the drawing from which the measurements always start from the same end, and new drafting software can provide required data (Figure 3-60).

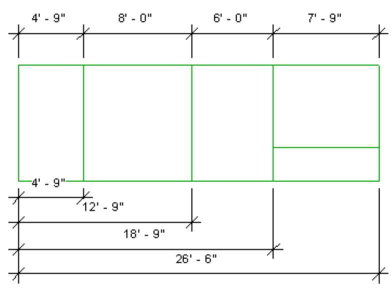


Figure 3-60: Measuring method

- It is recommended that hangers be nailed in place while measuring the side lumber at the layout table, thus solving the ergonomic issue downstream; also, hangers work as marking points to locate joists, providing more strength and accuracy. An automated machine to nail hangers in place is the optimum option; however, a semi-automated jig may be considered as an intermediate step to improve the current state (Figure 3-61).

Figure 3-61: Pre-installed hangers

- Purchasing engineered lumber instead of using gusset plates to fasten lumber members together will reduce the Takt time at the floor framing station. However, the cost of the product versus its benefit needs to be analyzed. Also, the product's weight may cause ergonomic issues for workers if machinery support is not considered. Therefore, further investigation on the cost trade-off, ergonomic impact, and supportive machinery is necessary.

- Adding a layer of sheathing to the end-joist is a time-consuming activity due to the need to cut the size of the sheathing from waste material, followed by nailing it to the joist. The task can be eliminated by either providing stronger end-joists or moving the activity downstream and adding a layer of sheathing to walls and end-joist altogether.
- Wiring and plumbing can be done while the frame is on the ground. Sheathing can take place after this stage and holes can be drilled for plumbing openings.
- An investigation is needed for decision making on whether to use pre-nudged or open-web joists. The purpose is to reduce man-hours and Takt time as well as to eliminate waste activities.
- Wall layout locating is deficient and needs to be replaced with semi-automated or automated marking machines. The first option is a rendering (Figure 3-62). The conceptual drawing can be provided and the objective of the design is to help the workers finish the drawing efficiently with a simple, highly mobilized, and low cost tool. The ideal situation is to design an automated machine that reads the layout from drawings (Figure 3-63).

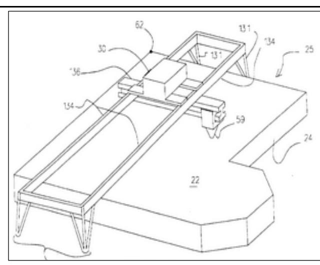


Figure 3-62: Render machine

Figure 3-63: Automated marking machine

- For floors, which are installed on site with no basement, the necessity of having full insulation is debatable. Some research indicates that insulation along the floor perimeter is crucial for protection against heat loss and freezing for the building envelope; however, the cost of full insulation protection for the whole floor may not acceptable when measured against the expected energy return. Therefore, further investigation must be provided to help with the decision making.

- If the bottom board installation is only for the protection of the floor panel insulation during transportation, this activity should be eliminated and the protection should be added at the end of the production line. By doing this, the protection for the floor panel can be permanently installed on the shipment trucks, and therefore only proper maintenance is needed, thereby saving time and material.
- Laminate installation can be moved downstream to reduce the floor finishing duration and reduce the risk of damage to flooring. However, further investigation is required on balancing activities throughout the entire production line with work crew assignment to evaluate the effect of this change on the overall processing time and labour requirement.
- The selection of a suitable semi-automated jig or fully automated machine plays an important role in productivity improvement for the production line. In order to fit with the floor operation, the entire line requires hydraulic extendable legs if the working levels vary as in the existing practice. Also, the jig needs to provide easy access in order for workers to move the floor frame so that overhead crane operation is minimized. Issues may arise where the finished floor frame needs to be transferred from floor production line to main production line. The ultimate choice would be to adopt a fully-automated operation which would involve high capital cost. It should be noted that both semi- and fully-automated options require ROI analysis before final decision making.

TARGET CONDITION:

- Remove waste and non-value-added activities from the floor station in order to reduce Takt time, increase production rate, and use only one row to frame floors.
- Upgrade the design of the production line with the involvement of ergonomic considerations.
- Reduce the overall floor framing cost while maintaining or improving the quality of the final output by choosing the correct material and proper tools.
- Automate the process to a certain extent with the application of high-tech tools to allow workers, rather than equipment, to play a supportive role.

IMPLEMENTATION PLAN (Not applicable)

3.3.2.1.2 Case study: proposed solutions based on observations

There are findings in the report that warrant deeper investigation before final decision making, and these are addressed in the PBS-integrated VSM analysis. However, some of the findings documented can be addressed immediately and thereby benefit the plant. For low investment implementation, the idea of eliminating waste during the process plays a key role. An example of shifting a non-value-added activity from the main production line to the pre-cut section is illustrated below.

Figure 3-64 presents photographs taken at both the floor panel fabrication line and the rough-in section. Drilling is recognized as one of the time-consuming activities on the line. For a common mini home, approximately 450 drill holes ($N = \frac{L_f}{S_f} \times n_f + \frac{L_w}{S_w} \times n_w$) are needed on joists and studs[19]. The man-hours required for this non-value-added activity can be determined using the following equation: 450 × 0.5 minutes/drill = 3.75 hr. Compared with the current 4.50 hr average workstation cycle time, this measure is found to be effective as it is low cost but yields payback quickly.

(a) Exterior wall holes for wiring | (b) Interior wall holes for wiring | (c) Floor panel holes for plumbing

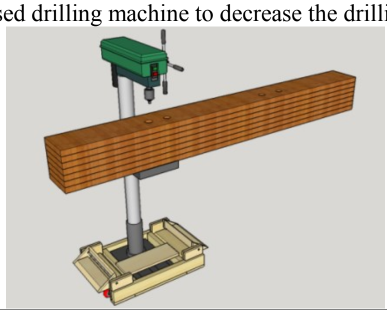
Figure 3-64: Drilling holes on the production line

Figure 3-65 includes the proposed solution from the factory. Although the new process requires pre-cut sections and new machines, having a pre-cut area is a common need for manufacturing

[19] Where L indicates the length of the target object, S indicates the spacing between the joists or studs, n is average number of holes needed to drill on each joist/studs; subscript "f" and "w" represent the "floor" and "wall", respectively.

production, and minimal investment is needed for acquiring an applicable drilling machines. With the new machine, even though the number of drills remains the same, each drilling motion can produce 15 holes (3 drills with a batch of 5 lengths of lumber) by machine within 40 seconds rather than manually drilling holes one by one. As a result, the new procedure not only eliminates 3.75 hr of non-value-added activity on the main production line, but the overall man-hour requirements are reduced: (500/15) drilling motions × 0.7 minutes/drilling motion = 0.4 hr, resulting in a 90% final man-hour savings.

(a) Proposed drilling machine to decrease the drilling motion



(b) Old drilling machine adjusted to low cost multi-drill machine

Figure 3-65: Proposed and implemented improvement for drilling

3.3.2.2 3D animation for visualization and communication

3D animation supports the manufacturing construction improvement from two perspectives; it is an effective tool to identify hidden problems and help the team to recognize the issue, and a tool to validate the proposed process. It is also proven to be an effective way to convey plant manager expectations, which is discussed below based on successful implementation.

To help identify hidden problems, 3D animation is created based on the current plant procedure. As mentioned in the previous section, an A3 report is another useful tool to assist the plant manager in identifying hidden issues and beginning to make the necessary changes in the plant. However, it not only takes time to allow management level personnel to recognize existing issues, but also requires effort for them to persuade their employees or front-line workers that their current practice needs to be adjusted based on suggestions by someone who spends only a fraction of their time in the factory. It may also be difficult for frontline workers to see how their own activities affecting the entire production line or to accept critiques from an outsider; prior to accepting (and implementing) the suggested changes, the employees generally ask for prerequisite changes to be made. The objective of creating a proper 3D animation is to mimic the actual production line procedure and bridge the gap between using an A3 report as a semi-visualization tool to a full visualization tool, thus remarkably reducing the potential of ineffective human-to-human communication, which from the Lean manufacturing perspective is a type of waste. Based on implementation in the case study, the following three critical factors for creating an effective 3D animation are concluded as follows:

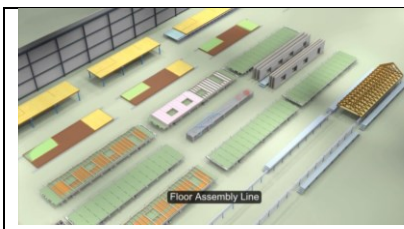
1. The animated process should be based on the real case scenario that mimics the best possible practice.
2. Based on the objective of the animation required by the company, providing the procedure with as much detail as possible (and avoiding unnecessary detail) is ideal. Details that do not bring any value related with animation objectives should be eliminated.
3. For the key issues that are hidden in the process, setting up the animation with proper speed or providing extra details will help to reveal and emphasize the problems.

Another way to use the animation is to help validate the future state in advance. When the plant manager seeks ways to improve the production line, aside from all the hard work to assess the ROI, effort needs to be put into persuading other management personnel. The best proof of the feasibility of an improvement measure without a high investment is to create a future-state animation that addresses the questions, “what, where, who, why, and how”. A simple animation can serve as a unique presentation tool with respect to manufacturing communication. It visibly presents questions, problems, challenges, opportunities, and progress, and avoids misunderstandings and ineffective communication. Five key points are summarized below based on the lessons learned from the case study.

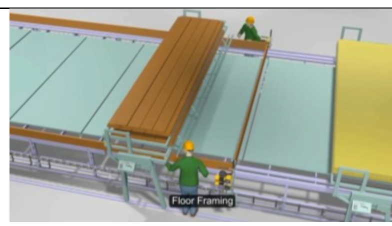
1. Being fully aware of the purpose of the video that mimic the actual process is the key to setting up the proper level of detail in the animation.
2. It is rare that all personnel can agree on a single plan; therefore, multi-scenario animations may need to be provided.
3. Animations must be consistent. If the objects created in the 3D modelling do not flow throughout the process there may be opportunities for mistakes where the same object in one scene appears differently in another scene.
4. Effective communication between the animation team and operation team, including the time frame, is the key to delivering a successful animation.
5. Editing and re-editing is part of the process in the future-state animation, as new problems will be revealed and fixed by using 3D animation rather than physically re-building the production line.

Three animations are created for the industry partner for the purpose of assisting in communication with the front-line workers as well as management personnel. One of the animations focuses on a particular station of the production line for current-state study, and two animations are delivered as supportive documents for a future-state proposal. The current-state animation provides a compelling illustration to the entire production line improvement team, allowing everyone to recognize the inefficiency of specific working processes. Based on the content of the animations, workers are able to accept the proposed changes right away. Figure 3-31 provides serials of scenes in the animation that indicate the amount of waste in the current state.

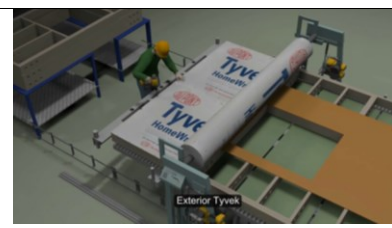
Not only does animation assist in the visualization of the factory's current practice, but it also inspires workers to utilize 3D animation to demonstrate their ideas in the future. Because of the debate between two possible options for the future state, two videos with different scenarios are created and used by the plant manager for implementation. The animation time frame, animation progress, content, and level of detail that should be included in the animation, as well as the key elements that should be emphasized in the animation, among others, are frequent topics of discussion during the process. It is a time-consuming process, but one that yields a large reward. The discussion and brainstorming sessions carried out based on this visualization lead to feasible and innovative ideas to push the improvement project forward. Figure 3-66 illustrates a number of scenes where the pre-fabrication area of the plant is animated with practical and effective solutions for the factory's future state.



(a) Production line layout



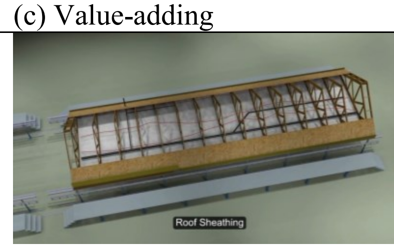
(b) Semi-automated jig table



(c) Value-adding

(d) Problem solving

(e) Potential opportunities



(f) Roofing process

Figure 3-66 (a-f): Future-state animation frames

3.3.2.3 Brainstorming session

Brainstorming session plays a key role during the improvement process, as these sessions contribute to organization commitment, implementation capacity, effectiveness of proposed changes, persuasion of all levels of personnel, and communication between interconnected parties. In order to attain these benefits, it is important to engage the right level of personnel in the right type of meeting. During the different stages of the process, different personnel are needed for generating specific outputs. The ideas and suggestions generated during these sessions should be recorded and followed up on, and feedback must be provided in order to ensure long-term effectiveness. Paulus & Nijstad (2003) discuss the effectiveness of group creativity through brainstorming compared with individual sessions. They have created a list of recommendations so that the brainstorming groups can perform more effectively. Considering that their recommendations align with the results of the brainstorming session in the case study, the following six points are implemented during the brainstorming session for the purpose of this research:

1. All participants and all ideas matter, even if the participants or the ideas do not seem to relate with specific parties. The participants should be carefully selected based on the purpose of the brainstorming session. Line workers, managers, problem specialists, experienced and active organization members, and experienced external personnel can all provide valuable ideas during the session.
2. Ensure the availability of objectives and expectations of the brainstorming session to all participants before the meeting.
3. A leader who has a high level of understanding of the production line process as well as the improvement process is required to guide any brainstorming group.
4. Group participants "with complementary or heterogeneous sets of task knowledge" together to perform their own brainstorming session and then combine the outputs from all the groups.
5. Provide an effective recording method to capture the generated ideas.
6. Focus on one problem area at a time with full details.

3.4 Improvement process step 4—implementation and validation

Any proposed changes are discussed to reach consensus and eliminate any unfeasible approaches. The brainstorming sessions prove a successful tool to engage industry partner personnel in committing to proposed changes. The ideal way to validate the changes and ensure an effective implementation is through a test run. The test run also provides valuable data for future-state performance estimation of the production line, which assists the factory manager to establish a continuous improvement strategy. It is also a critical piece for financial validation during the feasibility analysis. The following section presents a test report after implementing the proposed improvements and a preliminary study to quantify the benefits for the factory based on the improvements.

3.4.1 Testing

The highlighted changes that are implemented during the test run are summarized below.

1. Pre-drilled unit lot lumber package.

Photos	Before 	After 
Description	Rather than expending resources on the production line to drill the holes for wiring, the proposed method is to pre-drill the dimensional lumber at the pre-cut section. The holes are pre-drilled one by one with the assumption that up to five holes are needed at both top and bottom of the wall studs. 10 man-hours are required to complete pre-drilling for the whole unit.	
Feedback	**Advantages:**	

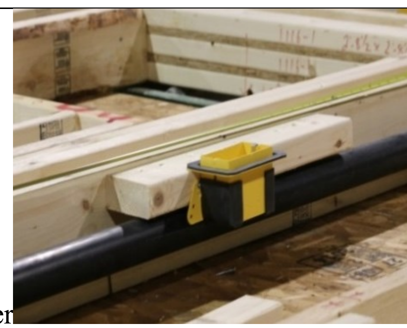
	• 3 man-hours of time savings can be expected on the main production line with clean and well-aligned holes. • Pre-drilled holes make the wiring process faster and safer (no sharp cutting point). **Disadvantages:** • Without a proper machine, this process can be very time consuming. • It requires the use of a pre-cut shop, which entails additional space, labour, and inventory management. **Considerations:** • What is the maximum load requirement for the future drilling machine? Should the machine be capable of drilling multiple holes simultaneously? • Can total engineering work effectively with MEP design so that fewer holes need to be drilled? • If the MEP can provide exact information for pre-drilling of holes on specific lumber, a coding system for a house lot lumber package would be valuable. • Inventory management for the pre-cut shop needs to be considered (i.e., storage space, delivery method).

2. Adding electrical wiring for heating system to the floor panel.

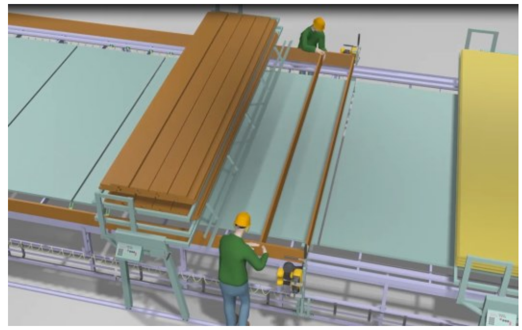
Photos	Before 	After 
Description	In order to decrease the wire installation activity time on the main production line, a partial wiring task is moved upstream to the end of the floor panel station.	
Feedback	**Advantages:** • Less material: save one roll of wire per house by eliminating the need to loop around the house. • Fewer working hours on the main production line: 1 man-hour in savings for the test module. **Disadvantages:** • Because the working procedure is not systematic during the testing, there is rework and figuring occurring throughout. The whole task is completed within 3 hr.	

	Considerations: • Drafting from engineering needs to be accurate and detailed so that no further measuring or problem solving is needed on the production line; the routing of the wiring can also be considered during the drafting stage so that more material can be saved. • In terms of safety during wall erection, it should be considered whether the holes should be drilled in the middle of the layout wood strip or have a notch at the side of the wood strip. By having the notches at the side, workers will not need to place their hands underneath the heavy wall during wall erection. **Lessons learned:** Internal communication: no system exists for updating information related to existing practice versus new changes. Existing practice is to drill holes at the side of the layout strip, whereas the new change for this specific test is to drill in the middle of the strips. If the details about the new practice are not communicated to all personnel who may be working on this task in subsequent workdays, rework is required as a consequence.

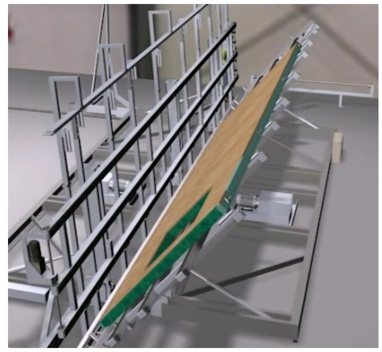
3. Blocking for electrical boxes.

Photos	Before The existing practice is to install the blocking for electrical boxes ahead of time so that the location of the electrical box is known.	After 
Description	The exact locations of the electrical boxes for the test unit exterior walls are not specified on the drawings. The final location of the electrical box could possibly have plumbing lines passing through its vicinity.	
Feedback	**Advantages:** • More than 90% of wiring and plumbing for exterior walls can be finished earlier at the pre-assembly stage, which saves time and resources along the main production line. **Disadvantages:** • Not knowing the exact location of the blocking, electrical box, and plumbing path necessitates extra problem solving time on the line, potential rework, and safety risks. **Considerations:** • Heavier frontloaded work (MEP) providing detailed drawings is essential • With the new drawing, pre-assembly/prefab plumbing should be considered (e.g., procedure, necessary information, storage space, transportation).	

4. New jig table for wall framing.

Photos	Before 	After 
Description	A new jig table for the wall production line is needed to create balanced flow. The location of the jig table also needs to be re-designed so that two wall lines will fit into the current available space. In addition, the new jig table needs to be designed in such a manner that either less material needs to be stored on site or less space is needed to store the lumber in the factory.	
Feedback	**Issues associated with the existing jig:** • Too much non-value-added activity involved • Extensive manual work required during the process • Material storage space utilization beside the jig is poor • The material delivery method is inefficient • The table is not equipped with smart functions (automated stud layout, squaring, etc.) **Expectations for the new jig:** • The new jig machine does not need to be fully automated; however, a semi-automated machine with enough functions to support a smooth flow is needed: ○ Fixed staple guns ○ Vertical gusset plate stapler ○ Automatic stud storing cross bridge ○ Wall layout indicator ○ Integrated framing and butterfly table system	

5. Supportive equipment for wall flipping.

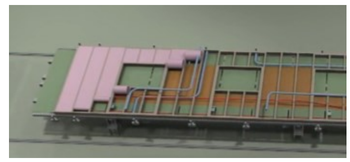
Photos	Before	After
		
Description	After finishing the sheathing for the outside wall, the wall panel needs to be flipped to the other side so that wiring, insulation and other components can be added in order to close the panel. Proper equipment should be selected for wall flipping. In the test, flipping the short wall takes 3 minutes with two workers; flipping the long wall takes 10 minutes with two to three workers.	
Feedback	**Issues with the existing overhead crane:** • The overhead crane is not efficient for material movement (lengthy set-up time and low transport speed). • With the significant weight increase for the closed wall panel, the existing overhead crane capacity is not sufficient. This is a safety concern for daily operation in the plant. **Benefits and concerns associated with new butterfly machine:** • The butterfly machine provides the ideal flipping movement for the wall. • The use of this machine reduces the necessary set-up time and labour. • No manual work is required during the process, which enhances safety. • However, space in the factory is limited such that using the butterfly machine for a 75 ft wall can be a challenge. • Whether it is preferable for the wall to be oriented horizontal or vertical for operation is yet to be determined. • The new wall production line could remain a single line or be modified to a double line.	

6. Adding wiring to the exterior wall for closed panel.

Photos	Before	After
		
Description	Adding wiring to the wall panel has always been a barrier to modular manufacturers seeking to deliver closed wall panels. In this test, however, wiring is added to the panel so that the wall panel will be at least 90% finished before being erected to the floor. The extended wiring used to connect with different portions of electrical work is wrapped at either end of the wall.	
Feedback	**Advantages:** • By working on electrical rough-in in 2D motion, more than one roll of wiring can be saved (exact material savings to be determined in future testing). • This material savings is also associated with savings of up to 3 hr on the main production line. **Disadvantages:** • All studs have pre-drilled holes on both top and bottom for wiring, even if they are not required. Specific pre-drilling locations can result in time savings. **Considerations:** • Wiring installation needs to be systematized so that no problem solving or measuring needs to be carried out in the sub-assembly line. MEP support is the key for systematic design.	

7. Sequencing for installation of plumbing, insulation, and blocking.

<table>
<tr><td>Photos</td><td>Before
</td><td>After

</td></tr>
<tr><td>Description</td><td colspan="2">Not only wiring, but also plumbing, insulation, and blocking will be installed in the wall panel prior to wall erection, resulting in the delivery of a closed wall panel by the sub-assembly line.</td></tr>
<tr><td>Feedback</td><td colspan="2">Findings:
• Plumbing needs to be laid out and aligned with the pre-drilled holes and minor errors are found to have occurred during the test. The electrical blocking could also prevent the plumbing installation, leading to re-work on the sub-assembly line.
• Plumbing needs to be wrapped in insulation.
• Blocking is easier to install horizontally.
• A minor adjustment to the location of the plumbing seems to be inevitable during wall erection; therefore, no glue should be added to the wall panel on the sub-assembly line.
• The optimal work sequence to avoid re-work or conflict is to install plumbing and wiring simultaneously, followed by simultaneous installation of insulation and blocking.
• The type of insulation could change to fixed-size rolled insulation for better working efficiency.

Considerations:
• Total engineering could provide detailed MEP drawings in order to ensure the pre-drilled holes on the floor can be aligned with the plumbing during wall erection.
• Plumbing can be prefabricated but should not be pre-glued, in case adjustments are needed during the erection process. Design for plumbing prefabrication is critical.</td></tr>
</table>

8. New blocking design.

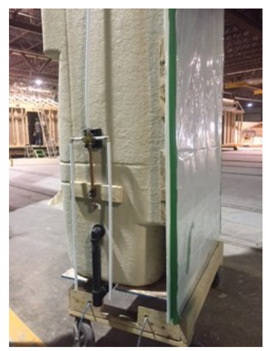
Photos	Before 	After 
Description	Most of the blocking is added accordingly on the main production line; however, the process is not consistent. For the closed panel process, the blocking must be pre-installed, but with modifications that address the inefficiencies associated with the existing approach.	
Feedback	**Issues and Considerations:**  • In order to close the wall panel, blocking needs to be pre-installed. • Locations of the blocking are not all specified in the drawings. • Blocking needs to be installed one by one due to size variation. • Exact locations of the blocking should be shown in the drawing, similar to how studs are shown in StrucSoft Solutions software. • The blocking installation method needs to be updated; a new system is required to mitigate the requirements to set up and nail every individual block that needs to be attached to the studs. • Blocking locations should not conflict with those of plumbing, electrical boxes, and wiring, or any other in-wall elements. • New progress since April 2015: blocking ladder has been designed as pre-assembled blocking components to be installed into the wall directly.	

9. Wall erection.

Photos	Before 	After 

Description	For the exterior wall erection, the new process requires installation for heavier walls. It also requires wiring connections during the installation. One of the major benefits of the new process is that the wall is properly squared, which eases the installation process.
Feedback	• The existing practice of wall erection does not require wiring connections between the wall and the floor since there is no electrical wiring in the wall. • The existing "open" wall panel is considerably lighter than the closed panel. • Rather than routing the wire through the bottom plate of the wall, the addition of a notch is a better practice due to safety concerns. This modification eliminates the need for workers to place their hands underneath the heavy wall during the erection process. • The new process requires less time for squaring the wall and adjusting the wall to align with the layout. • Once the wall is installed, 80% of the drywall and sheathing, 95% of the insulation, and 90% of the exterior wall electrical rough-in are completed.

10. Pre-assemblies.

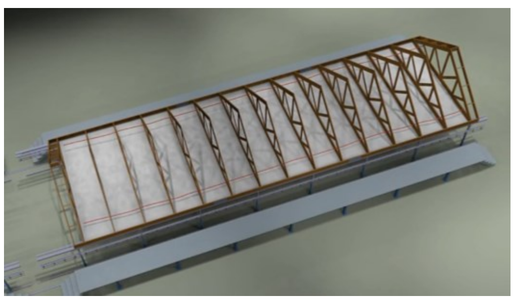
Photos	Before	After
	Only the waste and overflow of the tub is pre-assembled before the tub goes to the main line. 	
Description	A test is carried out to compare the time duration with and without pre-assembled plumbing components on washer & dryer and tub plumbing installation. The installation procedures are similar between the two selected units. Also, the same plumbing crews are assigned to work on both of the units. Therefore, the recorded time stays approximately consistent for both units. The table below summarizes the test results. The results show that assembling the plumbing components for the washer & dryer box can save up to 87% of time on the line, although the overall time savings (including the pre-assembly hours) is only about 18 minutes, which is 33% of the original working duration. The improvement of the tub assembly saves 20% of the original duration on the line; it provides an extra 30 minutes for other activities on the line.	
Feedback	**Advantages**: • Saves time on the main line. • Pre-assembled plumbing components create potential improvements on material savings, quality control, and ergonomic concerns.	

	Pre-Assembly Fabrication	On Line Manufacturing			
Pre-Assembly	**Hr/PC**	**Without Pre-Assemblies**	**With Pre-Assemblies**	Time Saved On Line	Total Time Saved
Washer & Dryer Box	0.50 hr	0.92 hr	0.12 hr	0.80 hr	0.30 hr
Tub	0.33 hr	2.50 hr	2.00 hr	0.50 hr	0.17 hr

Disadvantages and Considerations

- In order to fully benefit from the new processes, engineering support on MEP drawings and inventory control are critical.

11. Roof erection.

Photos	Before 	After 
Description	The roof erection follows the same procedure as before, except more plumbing and electrical work is added.	
Feedback	• The roof erection requires less effort to adjust the position of walls and roof considering the wall will be perfectly squared. This new process saves 10 to 15 minutes on the main production line at the roof erection section.	

12. Prototype of the finished product at the same point along the main production line.

Photos	Before 	After 
Description	The overall goal of this test is to shift some downstream activities upstream in order	

	to begin the crack fill earlier and to save space on the production floor. The photographs above illustrate a considerable amount of work that can be carried out at the same point in the main production line. By adding 8 working hours on the sub-assembly line, more than 15 working hours are saved on the main production line without adding supportive equipment.
Feedback	Advantages: • Addition of pre-drilled holes saves 2-3 hr on the main production line. • Having electrical wiring and plumbing installed upfront saves 2-3 hr on the main production line. • Installing sheathing, insulation, drywall, and vapour barrier while the wall is lying horizontally is more efficient and ergonomically friendly. • The wall can be squared once the panel is closed, which is a significant benefit for both roof erection and door installation. Disadvantages and Considerations: • Proper equipment is required for pre-drilling holes. • Working and storage space for prefabricated material is required. • Delivery of a house lot material package can dramatically save space in the plant for double-wall production line; however, proper inventory management is crucial. • Proper jig and transportation equipment (butterfly machine) is critical for the new processes. • Blocking installation is a time consuming activity, in the new process a systematic installation method is needed. • Total engineering is crucial for wiring, plumbing, and blocking installation in order to prevent potential bottlenecks in the new production flow.

Based on the aforementioned tests, the collected data is summarized for preliminary improvement validation. This will assist in the decision making on future implementations. The key data collection for the wall panel production line can be seen in Table 3-14 and Table 3-15, each of which represent a different test.

As seen in Table 3-14, the framing procedure for the test unit is the same as the regular procedure. Therefore, the duration is expected to be the same. However, because of the involvement of non-value-added activities in the process, a proper jig would likely replace the current jig. Based on an approximate calculation using the specifications shown below, the upgraded jig would eliminate at least 15 to 20 minutes of non-value-added activities per wall panel.

During the test process, the time duration for non-value-added activities is recorded, with detailed work breakdown for the purpose of more accurate time study. Manually transporting the wall studs from the on-site storage location requires 30 seconds to deliver four to five studs at the jig. The setup time for a long wall panel is approximately 5 minutes. To cut and measure the studs at the pre-cut table takes 2.3 minutes for every 4 studs. For a typical mini home, every long wall has approximately 50 studs (including double plates, special layout requirement) and every short wall has approximately 20 studs.

Table 3-14: Test unit 1 activity duration

	Short Wall 1		Short Wall 2		Long Wall 1		Long Wall 2	
	Time (mins)	No. of Workers	Time (mins)	No. of Workers	Time (mins)	No. of Workers	Time (mins)	No. of Workers
Framing								
Sheathing	14	2	14	2	50	2	35	2
Flip Over	2	2	2	2	12	6	10	6
Electrical Box					20	1	50	1
Electrical	20	2			150	2	120	2
Plumbing	N/A	N/A	40	1	N/A	N/A	75	1
Insulation	20	1	60	1	45	2	35	2
Blocking	N/A	N/A	N/A	N/A	N/A	N/A	30	3
Poly	5	1.5	5	1.5	10	2	7	2
Drywall	15	1	6	1	40	2	35	3.5

Sheathing, insulation, poly, and drywall installation requires less than half of the regular workload during the test run compared to the existing process. Moving these activities upstream not only leads to time savings, but it also allows crack fill to begin early on the line. The relative working hours associated with these activities are also dramatically reduced; for example, sheathing is reduced to one third of the original time in the existing process.

The blocking, electrical, and plumbing installation processes are not significantly simplified; therefore, the duration of these activities remains the same as if they were being carried out on the line. The future total engineering support, StrucSoft and MEP, are critical to the success of this project due to the fact that without them new bottlenecks for the wall sub-assembly line will be created.

Flipping the wall using the existing overhead crane can be a challenge due to the weight of the wall panel as well as the slow movement of the crane. As the data shows in Table 3-14, the long wall flipping time is the same as the poly installation time, which is recognized as a low-efficiency work procedure.

Table 3-15: Test unit 2 activity duration

	Short Wall 1		Short Wall 2		Long Wall 1		Long Wall 2	
	Time (min)	No. of Labour Personnel	Time (min)	No. of Labour Personnel	Time (min)	No. of Labour Personnel	Time (min)	No. of Labour Personnel
Framing	30	2	15	2	60	2	100	2
Sheathing	30	2	30	2	100	2	55	2
Flip Over	2	2	2	2	12	?	10	?
Electrical Box	15	1	N/A	1	20	1	110	1
Electrical	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Plumbing	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Insulation	15	1	15	1	270	2	160	2
Poly	15	1.5	20	1.5	30	2	7	2
Drywall	15	1	30	1	330	2	35	3.5
Tyvek	15	2	20	2	N/A	N/A	N/A	N/A

The data in Table 3-15 is summarized from the follow-up test unit 2 coded 56475 (an ID number given to the module). The framing duration for walls is recorded. Comparing the sheathing duration for these two units, the long wall sheathing duration increases by nearly 20 minutes and the drywall installation takes approximately the same amount of time, except for one outlier for the long wall. Although the insulation installation duration shows more than 2 hr in the summary, the actual installation is expected to be approximately the same as the previous test unit, which is 40 minutes for long wall insulation. However, more details need to be discussed regarding the proper sequence of plumbing and insulation installation in order to eliminate insulation rework due to the plumbing installation.

This summarized data is used as a critical reference to validate the effectiveness of the future improvements. The data also forms part of the input of the future-state VSM and simulation model. Another part of the VMS/future simulation model is determined through the brainstorming session, where the feasible working duration improving percentage from the current state to the future state is estimated by frontline personnel. The suggested rate of increase of the activity duration is presented as the percentage needed based on the current-state data in all of the future-state VSM.

3.4.2 Future-state VSM based on PBS

The future-state VSM at different PBS levels demonstrates an improved production line. Its inputs contain information from brainstorming session outputs and test run results as well as assumptions from the operation team based on their experience. The preliminary future-state validation begins from the most detailed level of PBS and moves to a highly summarized level.

According to the study of the current state, the internal work procedure improvement at the floor and roof panel prefabrication sections and the external production line process improvement between wall panel prefabrication and rough-in section are the focuses of this research.

3.4.2.1 Future-state VSM for floor panel at PBS level 4

In Figure 3-67, the future floor panel fabrication process is illustrated. New activities and work duration plan are assigned to each workstation. The process improvements will focus on framing and sheathing at station 1, wall layout process, and floor insulation. As wood beam installation is a non-value-added activity used as a support for transportation purposes, it may potentially be eliminated from the process. The efficiency of the flooring remains an existing challenge on the line for future study. In the proposed production line, pre-assembled and pre-cut unit lot material delivery plays a key role in smooth production line flow as well as in work efficiency improvements. One of the most significant changes is that floor framing and sheathing will be expected to be completed by the same workers within one workstation. To visualize the proposed changes, the reader may refer to Figure 3-29, Figure 3-32, and Figure 3-33 for details. As shown in the figures, a proper jig table is critical for the feasibility of this implementation. Four of seven workstations on this line have cycle times of approximately 3.8 hr, which is still greater than the 3 hour Takt time. Therefore, changing the working process of time-consuming activities such as wiring, plumbing, floor insulation, and flooring is necessary in order to decrease the cycle time. The data outputs with respect to overall production line section performance (average cycle time, lead time, etc.) are summarized in the higher levels of PBS.

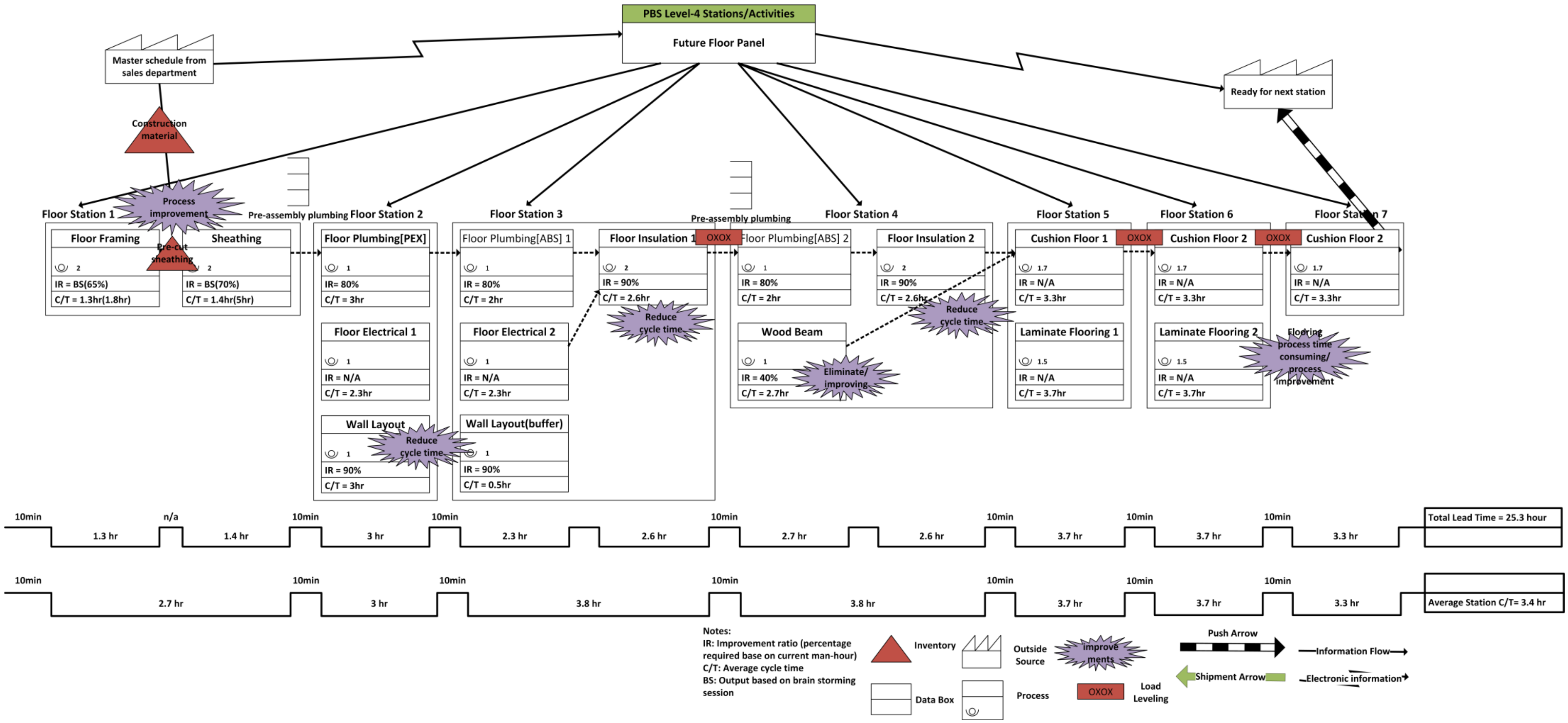


Figure 3-67: PBS level 3 VSM for future-state floor panel fabrication process

3.4.2.2 Future-state VSM for roof panel process at PBS level 4

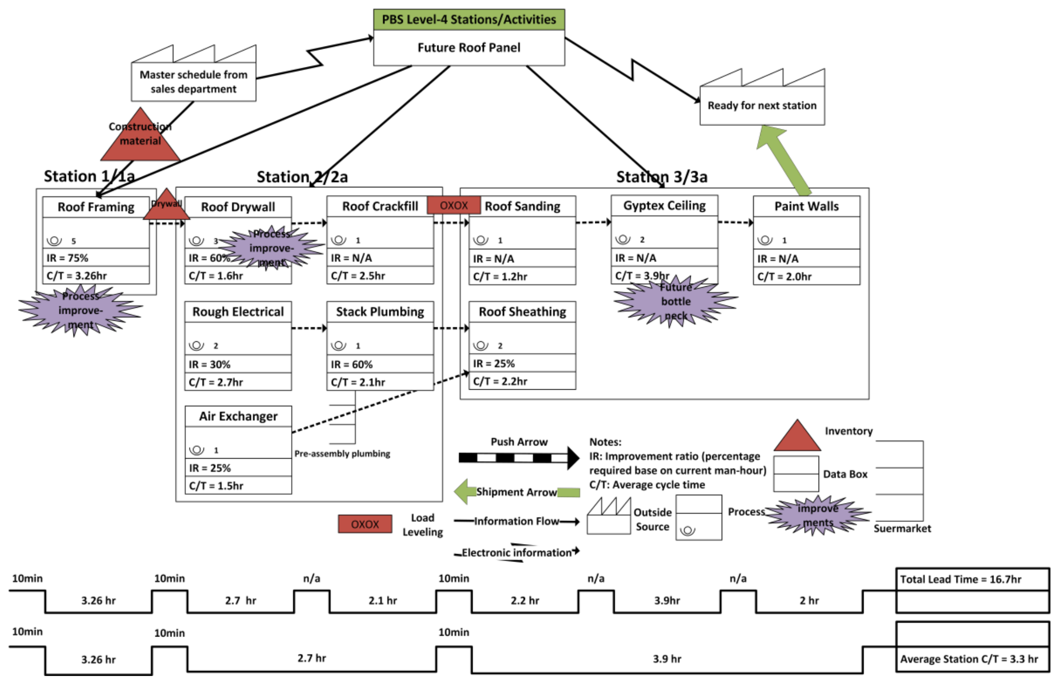


Figure 3-68: PBS level 4 future-state VSM for roof panel fabrication process

The general process of the roof production line remains the same except that there will be more value added simultaneously from above and beneath the roof. The processing time of roof framing and drywall installation are two of the activities that are expected to improve by nearly 30% to 40% by eliminating the non-value-added movement, as is described in detail in the previous section. In Figure 3-69, the future-state VSM of roof panel at PBS level 4 is presented. The last workstation on the line shows a cycle time of close to 4 hr, which is more than the 3 hr target time. This bottleneck is caused by the “Gyptex ceiling” activity; therefore, either assigning two work crews for the same activities or changing the working procedures would be required in order to achieve the targeted future state. Due to the flexibility of the roof panel fabrication procedure, the load levelling between station 2 and station 3 can benefit workstation 3 to reduce some of its workload pressure. It is noted that providing a buffer zone does not decrease the work duration unless additional crew is available, thus the extra workstation 3a will not eliminate the bottleneck caused by Gyptex ceiling installation. Rough-in electrical, stack plumbing, and air exchange are activities shifted from downstream, which helps reduce the workload for downstream construction zones. This redistribution improves the utilization of the roof panel space without interrupting the current production line flow, making the changes practical and feasible. For detailed roof framing process improvement, the reader may refer to Figure 3-50 to Figure 3-53.

3.4.2.3 Future-state VSM for wall panel and rough-in section at PBS level 4

The wall panel section is the main area where the Lean manufacturing and innovative process improvement are applied. It is also the area to which downstream areas with heavy workload and congested workforce redistribute their pressures. According to the analysis of the wall panel and rough-in section, as well as the test run based on the previous section, the following two VSMs illustrate the proposed future-state of these two sections (refer to Figure 3-69 and Figure 3-71).

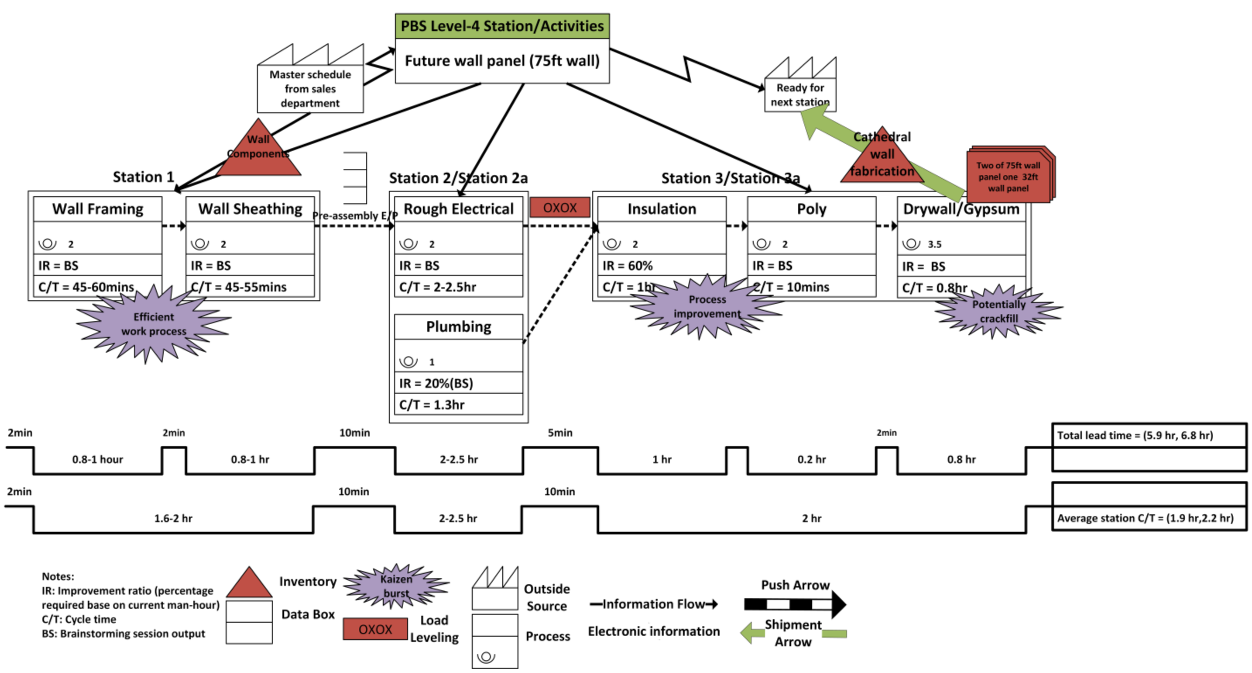


Figure 3-69: PBS level 4 VSM of future state for wall panel fabrication process

Compared with the current wall panel process, the proposed wall panel production line adds five activities, which are part of the downstream activities in the rough-in section. The five activities are wall sheathing installation, rough-in electrical installation, plumbing installation, insulation installation, and poly installation. Although only portions of each of these activities are shifted from the section, the workload is redistributed in order to achieve a better balance on the line. It also increases the wall panel section's space utilization. The wall panel fabrication is increased into three workstations from two, and the space is re-organized so that two more stations are added with a buffer production line after the framing station in order to eliminate interruptions due to product variation. The cycle time in the VSM is for a 75-ft exterior wall, which is the longest wall built by the industry partner. The largest complete module unit requires two 75-ft walls and one 32-ft multi-panel short wall. Not every panel requires electrical and plumbing installations, but every exterior wall panel does require framing and sheathing. For the purpose of this research, the problem is simplified and the worst-case scenario is assumed, where all the panels require electrical and plumbing work. According to the current estimation, the 1.6 to 2.0 hr framing and sheathing cycle time for one 75 ft wall results in a full wall panel package delivery at the wall erection section every 4.0 to 5.0 hr. This therefore becomes the bottleneck for the future process, which requires a 3 hr Takt time. It is determined that the remainder of the wall line can be assigned two teams working parallel to each other to ensure a 3 hr delivery time. However, there is some uncertainty as to whether the first framing table will be able to feed two other lines. Furthermore, jig table manufacturers must be able to frame and sheet at a linear speed of 1ft/minute in order to be considered. Another Kaizen burst is the duration of insulation installation; in the test run, the insulation processing time can be as little as 15 to 20 minutes for one single long wall panel, yet it is also recorded as 1 hr for some of the panels due to rework.

To be conservative, a 1 hr duration for the insulation activity is recorded in the future-state VSM; however, there is potential for continuous improvement in this regard, as the test run shows a benefit from laying insulation horizontally and finishing the installation within a reduced timeframe. At the end of the line, the finished wall panels will be batched and assembled at the wall erection section.

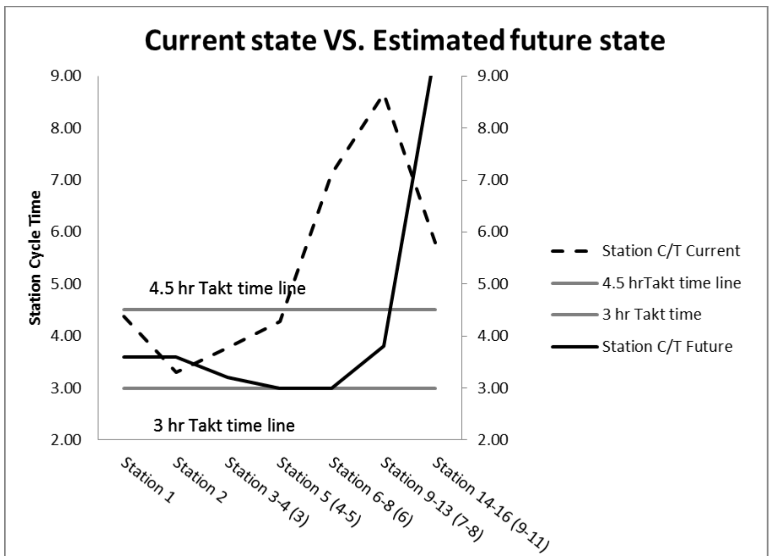


Figure 3-70: Workstations requirement and workstations cycle time comparison

As a result of shifting part of the work from the rough-in section to the upfront wall fabrication section, there are noticeable process improvements on the future rough-in section as well, which are presented by a summarized station cycle time in Figure 3-70 and a VSM in Figure 3-71. The comparison of current and proposed work processes is illustrated in Figure 3-70. Not only is the workstation organization changed, but the dark solid line demonstrates a well-controlled production line flow until station 8. The amount of work that is finished by this station is the same as that of workstation 13 in the existing line. The workload redistribution to the wall panel section can be credited for the improved cycle time performance, but further process improvements for the activities that remain at the rough-in sections are as critical as workload readjustment. Pre-assembly components for electrical and plumbing work can help to dramatically reduce the work duration (only parts of these activities are shifted). As mentioned in the test run report, a pre-assembled tub wall plumbing component saves 70% of working duration on the main line and 20% of the overall working man-hour requirement. One remaining problem is that from station 9 to station 11 the cycle time increases drastically to more than 9 hr due to the siding[20] process. Three methods are proposed that could potentially eliminate the bottleneck: (1) redistribute the work to a lower workload density area (which also leads to opportunities to generate new operational procedures for optimal work efficiency, for example, working at wall panel section with 2D working motion instead of volumetric working motion); (2) improving the work efficiency alone; and (3) adding additional crews. (An account of the detailed improvement of these activities is required in future work, though this is outside the scope of this thesis.)

As an overview of the improvements to the rough-in section, first, it should be noted that the workstation cycle times are less varied. Second, activities such as electrical wiring and plumbing, which in the current state prevent the drywall installation and crack fill from being carried out at their designated workstations, in the future state are finished two to three stations earlier along the line. Also, as most of the sheathing is installed at the wall fabrication section, which provides a rigid wall panel before erection, some of the downstream activities will benefit from the quality improvements and see an approximate 10% work duration improvement.

Due to the above changes, activities at the rough-in section can be completed within 11 stations instead of 16 stations as was previously the case. Seven activities are marked as Kaizen bursts to ensure the effectiveness of the process adjustments for the line. The overall impacts of these changes across the production line are further summarized in the higher level PBS below.

[20] Without considering the dramatic change of cycle time due to the siding process, the average rough-in section cycle time is 3.4 hr, which is a significant achievement compared with current 5.3 hr cycle time.

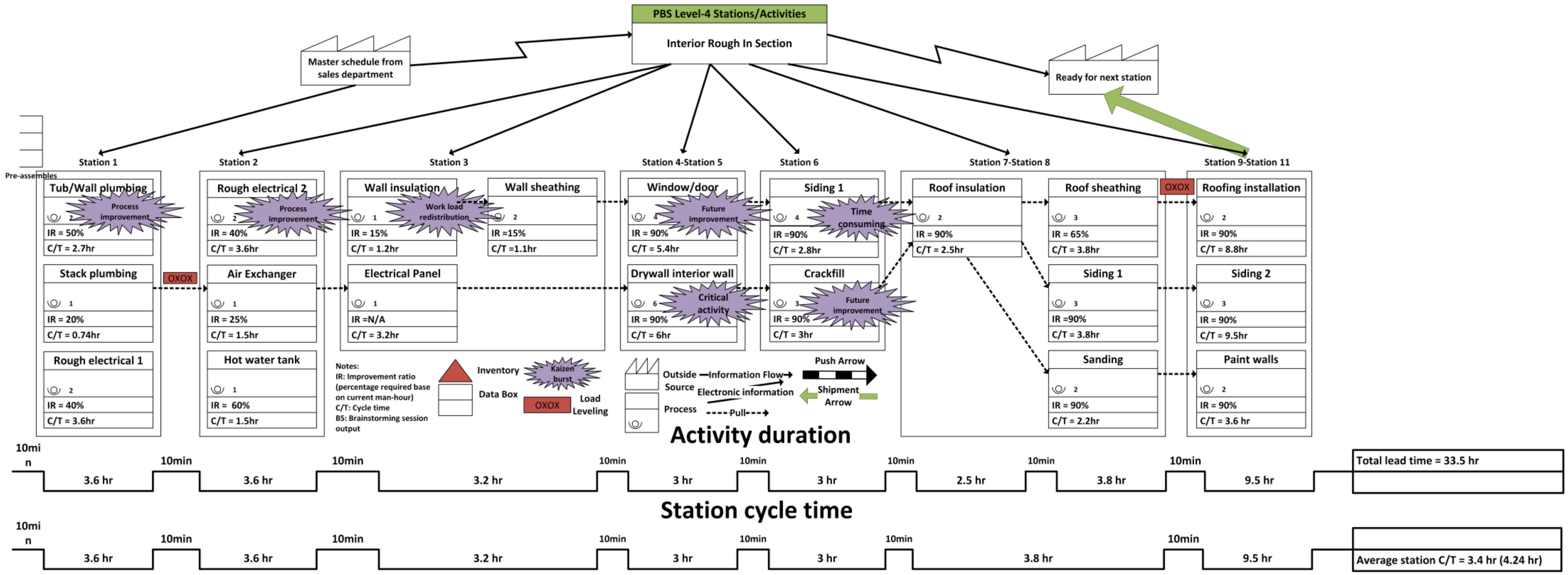


Figure 3-71: PBS level 4 future-state VSM for interior rough-in section

3.4.2.4 Future-state VSM at PBS level 3

Figure 3-72 summarizes information based on the outputs of level 3 VSMs and presents the entire production line with PBS level 3 details.

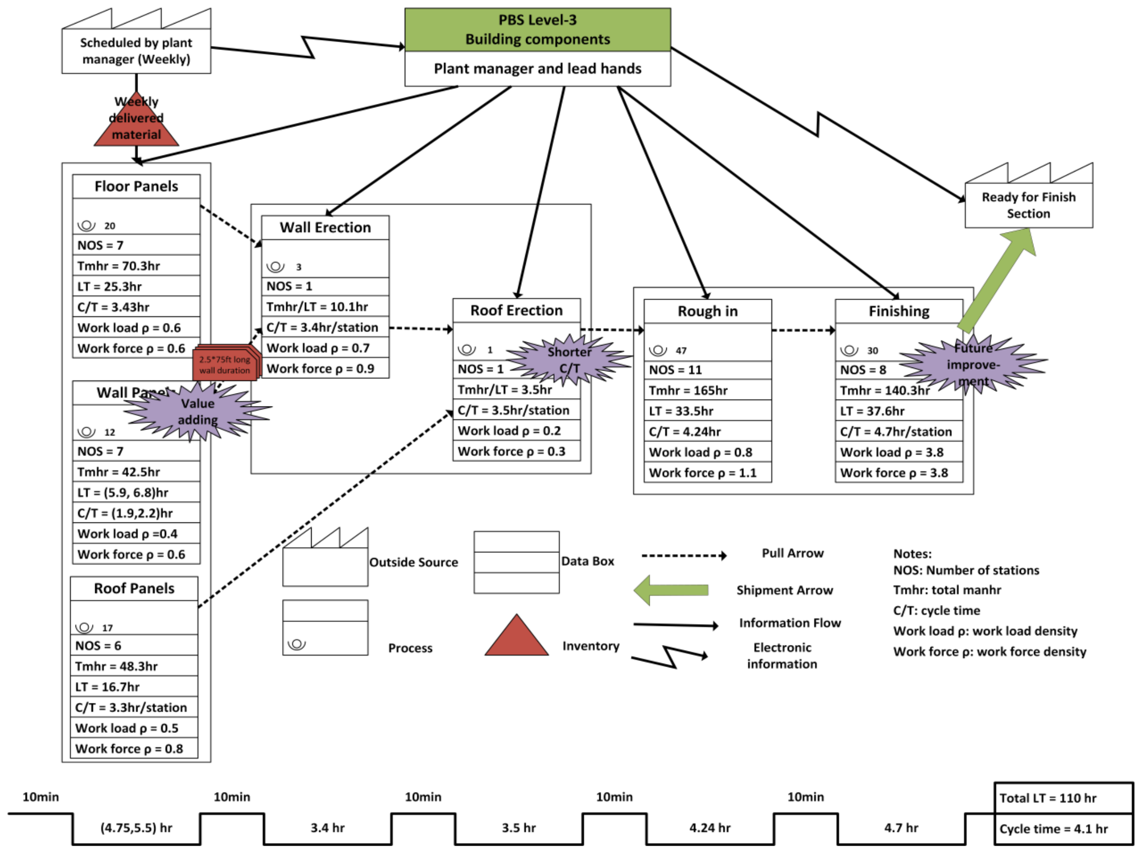


Figure 3-72: PBS level 3 future-state VSM

Although the final average cycle time at each building component section does not meet the 3 hr Takt time target, the resulting overall station cycle time shows less variation. Additionally, without putting any effort toward the finishing section, the five workstations that are eliminated from the rough-in station reduce the cycle time to 4.7 hr from 11.3 hr. It also reduces the workload density by approximately 1 man-hour per unit space and 0.6 workers per unit space. For the rest of the production line, the pre-fabrication area maintains a reasonable workload and labour force density, yet reveals a slight increase in workstation cycle time at the wall panel section due to the proposed value-adding from the rough-in section. As this future-state VSM shows a fairly stable cycle time throughout the production line, more study regarding increasing the performance within each section is required as part of the continuous improvement plan.

3.4.2.5 Future-state VSM at PBS level 2 and level 1

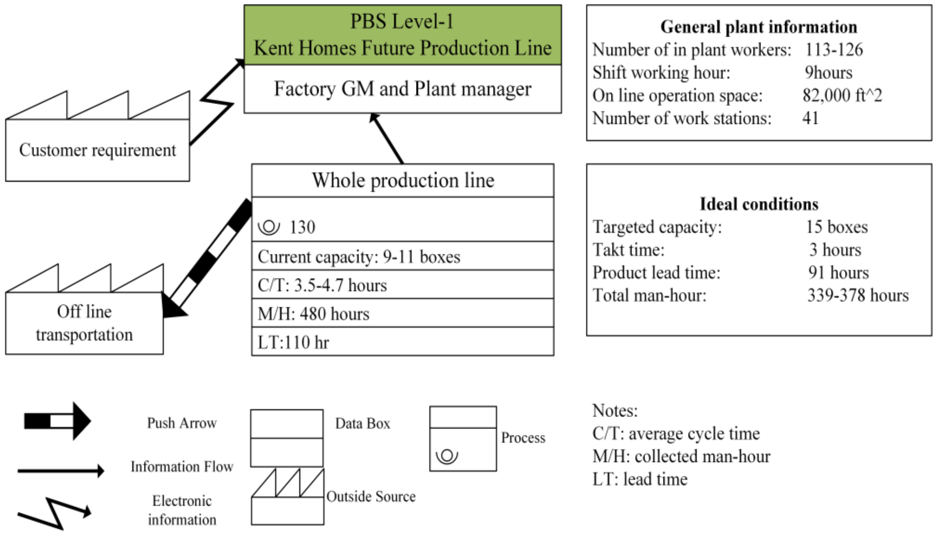


Figure 3-73: PBS level 1 production line performance with proposed improvement

Based on the plant management needs, the presentation of PBS level 2 VSM may not be necessary. In Figure 3-73, the final highlighted summary of the proposed production line performance is presented.

A final summary can be shown as follows. Figure 3-74 and Figure 3-75 depict the factory before and after proposed improvement. A large amount of value is added to the module without using extra work space and with little resource enforcement upstream on the production line.

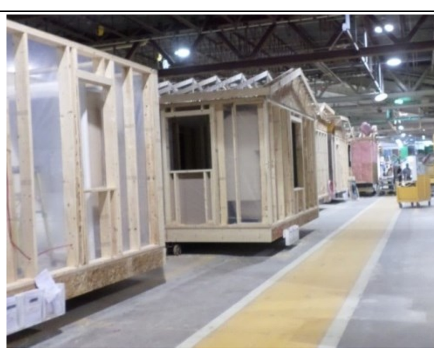


Figure 3-74: Module finish percentage before improvement

Figure 3-75: Module finish percentage after improvement

Comparing the current PBS level 1 data with the future data above, for each unit, 480 total man-hours are needed, significantly less than the average total man-hours of 607. The total number of workers is counted as 130 even though the total number of workers on site is only in the range 113 to 126. Although the final production line performance still shows a cycle time ranging from 3.5 to 4.7 hr, which is higher than the ideal 3 hr, the variance from the target is smaller. By eliminating the impacts of two of the identified future bottlenecks, “frame and sheath” station and siding process, the future cycle time can decrease to nearly 3.5 hr, which results in approximately 9 to 11 modules per week. The production line lead time for future process is calculated as 110 hr, 20 hr shorter than in the current state. Also, considering that in the existing practice some of the modules need to be finished off of the production line due to the heavy workload at the end of the line, the additional savings from the proposed process are likely more considerable than the present research can convey.

Chapter 4 Conclusion

4.1 Summary and conclusion

This thesis introduces a framework to conduct the assessment of an off-site modular construction manufacturing production line and to facilitate a shift from the dominant conventional construction process toward a more reliable, predictable, efficient, and innovative manufacturing approach. The framework, which integrates value stream mapping (VSM) with "Production Line Breakdown Structure" (PBS), is developed to aid in analyzing the current production line performance, identifying existing issues, assessing the proposed solution, and visualizing the future implementation for modular construction manufacturing (MCM) production lines. Considering the current limitation with MCM that the implementation of Lean construction is adapted from general Lean concepts with few clearly defined guidelines or well-designed applications, it is necessary to set up objectives for different types of assessment on the production line so that different levels of detail can be selected to serve different levels of decision making. Throughout the process, conventional construction methods, Lean manufacturing principles, and commonly used visualization tools are utilized in conjunction with the framework to promote innovative thinking within the MCM domain. The experience presented in the case study illustrates how the framework can be used to benefit the process improvement journey. Two approaches to process improvement are included, each one focusing on identifying different type of violations of the five principles of Lean thinking. First, at PBS levels 2 to 4, where the relationship between different sections and stations on the line is presented with lower levels of detail for individual activities, all five principles of Lean thinking are applied, including: (1) value according to the customer; (2) work in value streams; (3)

maximize the flow and pull; (4) empower company personnel; and (5) seek continuous improvement, aiming for making where implemented perfect. Second, at PBS levels 4 and 5, where it is more difficult to envisage the overall production line but where higher level details of individual activities are available, three out of five principles of Lean thinking are focused on, with the emphasis on maximizing the flow and pull by eliminating the seven types of waste. During the improvement process, innovative ideas and a manufacturing-centric way of thinking are promoted. For example, blocking on the wall panel could be installed by means of pre-assembled ladders instead of installing one block at a time; a pre-fabricated wall panel in a factory could represent a more than double value-adding product compared with a structure-framed wall panel on site. VSM, as another core process of the project, provides a quantitative visualization. PBS-integrated VSM provides a guideline so that proper data collection can be used to quantify the performance of the production line flow. The application of 3D animation for simulation of work procedures also plays a key role in validating both inefficient current-state processes as well as the proposed future improvement.

4.2 Research and contributions

The core contribution of this research is the creation of Production Line Breakdown Structure (PBS) and the integration of PBS with Value Stream Mapping (VSM) for MCM so that Lean application can be implemented to improve the production line flow and modular construction technology. The detailed contributions are listed below.

1. Design of a PBS for a modular construction manufacturer. The parameters and KPIs that should be considered at each level of PBS are summarized.
2. Adjustment of the application of VSM by integrating the PBS so that the conducted analysis using VSM can be more objective. By implementing VSM at different levels of

PBS, the results are able to serve different levels of decision making. It also provides a guideline by which for construction manufacturers to successfully implement Lean. For example, to effectively eliminate the waste motion found during the process, PBS level 5, which corresponds to the motion level of VSM, should be applied. However, to balance the overall production line workload and workforce distribution, PBS level 3, which corresponds to the building element level of VSM, should be applied.

3. From an industry perspective, the designed framework promotes key process improvement methods in practice:
    a. Early stage pre-assembly can reduce overall labour cost and dramatically improve the work duration on the main production line.
    b. Shifting volumetric activities to 2D activity (pre-fabrication section) has potential for quality improvement, reduction in man-hours, and factory space savings. It also promotes innovative construction methods as well as the design of semi-automated machinery.
    c. By implementing the proposed framework, the total lead time of the production line is improved by 20% with total man-hour savings of more than 15%.

4.3 Research limitations

This research is subject to a number of limitations, which are listed below.

1. The existing raw data collection system in the modular construction factory has low to medium level of confidence due to the following reasons: (1) the data collection process involves human factors, including the possibility of collecting non-operational activity durations (breaks, walking, meetings, etc.); (2) workstation cycle time is the base unit for production line flow analysis. However, this data needs to be calculated indirectly from

man-hours per activity and number of workers assigned, which are difficult to record in reality; and (3) the non-standardized working process causes difficulty in precise tracking during data collection.

2. Total man-hours for each activity are collected; the variations of working duration at each workstation for different modules are not represented in the current- and future-state VSM. Customization within the same house type (modular home or mini home as per the case study) could lead to work duration variations; however, only the average data is used as input data. VSM is able to present the data with statistical properties of the observed dataset. However, the low to medium level of confidence with regard to the selected raw database results in a lower confidence level for the comprehensive data analysis.
3. The actual activities involved in producing a module and the exact work sequence on the production line for different modules do not remain constant. One VSM will only represent a single process assuming that all the modules are sharing the same required activities and same work sequence. By using an average of the data as the input of the VSM may ensure a high level of confidence in the reference data for overall production line performance.

4.4 Future improvement

The proposed methodology serves as a guideline to ensure effective Lean implementation for the improvement of a modular production line. The framework can be improved continuously as the performance of the current modular manufacturer improves based on the following aspects:

1. There is no well-defined data collection method in the factory due to the limited knowledge of how to use data to support process improvement. However, the purpose of the data collection is explained through the proposed framework, and the collected data

will be more accurate if the key performance data is collected directly. Collecting the data from the most detailed level of the PBS is the most accurate method. Future study is needed to ensure a feasible collection method since the manual dominated work process can be difficult to track.

2. For every level of PBS, there are specific objectives that determine the required parameters and indicators; each level also focuses on a different group of personnel. It should also be noted that no two manufacturing companies are the same, as they differ with respect to market, management philosophy, human resources, production line layout, etc. Therefore, the parameters and indicators should not be limited to what has been provided in the present research. As further studies and innovations are being applied, parameters may change. Consideration regarding machinery usage and inventory control can be quantified or qualified and implemented as part of the framework in the future.
3. With a higher confidence level of raw data collection, adding simulation into the improvement framework could mitigate the disadvantage of VSM analysis, namely that only a single process can be studied.

References

Alves, T. D. C. L. (2012). Exploring lean construction practice, research, and education. *Engineering, Construction and Architectural Management*, 19(5), 512-525.

Arashpour, M., Wakefield, R., Abbasi, B., Lee, E. W. M., & Minas, J. (2016). Off-site construction optimization: Sequencing multiple job classes with time constraints. *Automation in Construction*, 71, 262-270.

Asri, M., Naim, M. A., Nawi, M., & Nasrun, M. (2015). Actualizing lean construction: Barriers toward the implementation. *Advances in Environmental Biology*, *9*(5), 172-174.

Bashir, A., Suresh, S., Proverbs, D. G., & Gameson, R. (2010). Barriers towards the sustainable implementation of lean construction in the United Kingdom construction organisations. *Arcom Doctoral Workshop*, 1-8.

Ben Fredj-Ben Alaya, L. (2016). VSM a powerful diagnostic and planning tool for a successful Lean implementation: A Tunisian case study of an auto parts manufacturing firm. *Production Planning & Control*, 27(7-8), 563-578.

Crowley, A. (1998). Construction as a manufacturing process: Lessons from the automotive industry. *Computers & Structures*, 67(5), 389-400.

Elnaas, H., Gidado, K., & Philip, A. P. (2014). Factors and drivers effecting the decision of using off-site manufacturing (OSM) systems in house building industry. *Journal of Engineering, Project, and Production Management*, *4*(1), 51.

Enhanced (web page name). Residential new construction [digital image]. Retrieved from http://www.padavich.com/Residential.html (Dec. 14, 2016).

Fernández-Solís, J. L. (2008). The systemic nature of the construction industry. *Architectural Engineering and Design Management*, 4(1), 31-46.

Gann, D. M. (1996). Construction as a manufacturing process? Similarities and differences between industrialized housing and car production in Japan. *Construction Management and Economics*, 14(5), 437-450.

Green, S. D. & May, S. C. (2005). Lean construction: Arenas of enactment, models of diffusion and the meaning of "leanness". *Building Research & Information*, 33(6), 498-511.

Hammer, M. (1990). Reengineering work: Don't automate, obliterate. *Harvard Business Review*, 68(4), 104-112.

Höök, M. (2006). Customer value in lean prefabrication of housing considering both construction and manufacturing. *Proceedings, 14th Annual Conference of the International Group for Lean Construction, IGLC-14*, (November), 583-594.

Johnsson, H. & Meiling, J. H. (2009). Defects in offsite construction: Timber module prefabrication. *Construction Management and Economics*, 27(7), 667-681.

Jones, D. T. & Womack, J. P. (2002). *Seeing the Whole: Mapping the Extended Value Stream*. Lean Enterprise Institute, Brookline, MA.

Jørgensen, B. & Emmitt, S. (2008). Lost in transition: The transfer of lean manufacturing to construction. *Engineering, Construction and Architectural Management*, 15(4), 383-398.

Kim, D. & Park, H.-S. (2006). Innovative construction management method: Assessment of lean construction implementation. *KSCE Journal of Civil Engineering*, 10(6), 381-388.

Kim, L. (1999). Building technological capability for industrialization: analytical frameworks and Korea's experience. *Industrial and Corporate Change*, 8(1), 111-136.

Koskela, L. (1992a). Application of the new production philosophy to construction (CIFE Technical Report No. 72). Stanford, CA, USA: Stanford University.

Koskela, L. (1992b). Process improvement and automation in construction: Opposing or complementing approaches? In: 9th International Symposium on Automation and Robotics in Construction, 3-5th June 1992, Tokyo, Japan. (Unpubilished)

Koskela, L. (1994). Lean construction. In *Proceedings of the National Construction and Management Conference, Sydney, Australia, February 17-18 1994* (p. 205). Institution of Engineers, Australia.

Koskela, L. & Vrijhoef, R. (2001). Is the current theory of construction a hindrance to innovation? *Building Research & Information*, 29(3), 197-207.

Lian, Y.-H. & Van Landeghem, H. (2007). Analysing the effects of Lean manufacturing using a value stream mapping-based simulation generator. *International Journal of Production Research*, 45(13), 3037-3058.

Liker, J. (2004). The Toyota way: 14 management principles from the world's greatest manufacturer [Electronic version]. *McGraw-Hill*. Retrieved November, 6, 2016

Liker, J. K. & Lamb, T. (2002). What is lean ship construction and repair? *Journal of Ship Production*, 18(3), 121-142.

McManus, H. L. & Millard, R. L. (2002). Value stream analysis and mapping for product development. *Technology*, 20(3), 8-13.

Meiling, J. H., Sandberg, M., & Johnsson, H. (2014). A study of a plan-do-check-act method used in less industrialized activities: two cases from industrialized housebuilding. *Construction Management and Economics*, 32(1-2), 109-125.

Meiling, J., Backlund, F., & Johnsson, H. (2012). Managing for continuous improvement in off-site construction: Evaluation of lean management principles. *Engineering, Construction and Architectural Management*, 19(2), 141-158.

Meiling, J. & Johnsson, H. (2008). Feedback in industrialised housing: Why does it not happen? In: *Dainty, A (Ed) Procs 24th Annual ARCOM Conference*, (September), 145-154.

Modular Building Institute (2010). Productivity with modular construction. Modular Building Institute, Charlottesville, VA, USA.

Moghadam, M. (2014) Lean-mod: An approach to modular construction manufacturing production efficiency improvement. (Doctoral dissertation, University of Alberta).

Nahmens, I. and Ikuma, L. (2012). Effects of lean construction on sustainability of modular homebuilding. *Journal of Architectural Engineering*, 18(2), 155-163.

O'Connor, J. T., O'Brien, W. J., & Choi, J. O. (2015). Standardization strategy for modular industrial plants. *Journal of Construction Engineering and Management*, 141(9), 04015026.

Ohno, T. (1988). *Toyota Production System: Beyond Large-Scale Production*. Productivity Press, Cambridge, MA.

Pasquire, C. & Connolly, G. (2002). Leaner construction through off-site manufacturing. *Proceedings, IGLC Annual Conference, Gramado, Brazil*, 1-13.

Rother, M. & Shook, J. (2003). Learning to see: Value stream mapping to add value and eliminate muda. *Lean Enterprise Institute*.

Salem, O., Solomon, J., Genaidy, A., & Luegring, M. (2005). Site implementation and assessment of lean construction techniques. *Lean Construction Journal*, *2*(2), 1-21.

Shafai, L. (2012). Simulation based process flow improvement for wood framing home building production lines. (Doctoral dissertation, University of Alberta).

Shook, J. (2009). Toyota's secret. *MIT Sloan management review*, 50(4), 30.

Smith, S. M., Paulus P. B., Nijstad B. A. (2003). The constraining effects of initial ideas. Creativity: Innovation Through Collaboration. *Oxford University Press.*

Stalk Jr, G. & Hout, T. M. (1990). Competing against time. *Research-Technology Management*, 33(2), 19-24.

Womack, J. P., Jones, D. T., & Roos, D. (1990). Machine That Changed the World . Free Press, New York.

Yu, H., Al-Hussein, M., Al-Jibouri, S., & Telyas, A. (2011). Lean transformation in a modular building company: A case for implementation. *Journal of Management in Engineering*, 29(1), 103-111.

Yu, H., Tweed, T., Al-Hussein, M., & Nasseri, R. (2009). Development of lean model for house construction using value stream mapping. *Journal of Construction Engineering and Management*, 135(8), 782-790.