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Simulation Based Process Flow Improvement for Wood Framing Home Building Production Lines

By

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ABSTRACT

This thesis describes a methodology for process improvement of panelized home building production lines through increasing productivity and reducing production cycle time based on lean production and simulation tools. In panelized home building, panels are produced in a factory and then moved to the construction site for assembly. The challenge here is the high customization level in home models and also the wide range of panel types with different design properties which lead to highly variant processing times. In this thesis, a regression-based methodology is proposed which formulates the task times of different activities based on the unique design properties of a panel. The regression models are used as input in the simulation model to validate the process improvement plans such as line balancing and panel sequencing. This methodology is implemented in a home building manufacturer in Edmonton in order to reduce the overall home completion time.

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Chapter 1

Introduction

1.1 Research Motivation

Construction companies have observed a shift in homebuyers' interests in recent years toward demanding customized homes that reflect personal life styles and conform to unique needs and requirements (NAHB, 2004). However, home builders are not willing to deviate from their standard models, as customization can disrupt production, delivery and quality related processes and reduce production efficiency. The question faced by homebuilders is how to improve production flow in order to cope with high customization in customers' choices without disrupting efficiency, and sacrificing quality, on-time delivery, and reasonable pricing.

Significant productivity improvements in the manufacturing industry have encouraged the home building construction industry to gain similar benefits through moving from traditional on-site construction to industrialized off-site prefabricated construction technology. Due to new developments in specialized automated machinery which are suitable for home building construction and computerized production control software, industrialized home building has changed the construction industry by reducing delivery

time and costs, increasing efficiency, simultaneously, preserving highly customized designs.

The United States and Canada have invested heavily in research and development of construction industrialization in the past decade, viewing it as a solution to satisfy the housing needs of the growing population. Industrialized homebuilding is now being applied globally, including in a number of European countries. The advantages of the industrialized home building can be summarized as follows (MBI, 2011):

- **Quality and standards:** A precise manufacturing environment, controlled by computer software and standard procedures to build home components results in higher quality homes.
- **Speed:** Standardized operations and procedures reduce waste times during production and delivery time.
- **Affordability:** More efficient processes generate less waste in time and material usage which results in significant savings in equipment, materials, transportation, labors, and energy consumption. Purchasing large volumes of materials results in strong negotiating power and further lowers construction costs.
- **Workers' health:** A controlled factory environment allows control of dust, insulation particles, glue fumes, and curing gases to prevent negative impacts on workers' health. Furthermore, automated operations performed by machines reduce labor work intensity and fatigue.
- **Workers' safety:** Factory prefabrication provides a safe environment for the workforce through removing on-site building risks such as, working at heightened elevations and in poor weather conditions.
- **Environmental impact reduction:** Through moving 40% of construction work from the site to a manufacturing facility, and reducing construction time by half, prefabricated home building can substantially reduce CO_2 emissions.

Although industrialized home building has evolved over the past few years, the associated manufacturing control and management tools and techniques need to be further developed in order to satisfy specific requirements and features of the construction industry, such as the high degree of customized products. Without these developments, industrialized construction cannot realize the potential efficiency, productivity improvement, and cost savings anticipated from manufacturing systems. O'Brien et al.

(2000) mention that the manufacturing management techniques applied in modularized home construction (as one type of industrialized construction) are very similar to the ones used in traditional on-site construction, that they still suffer from low productivity and high production wastes.

Lean concept tools (which have originated from The Toyota auto manufacturer production system) are recognized as a source of substantial improvements to manufacturing processes during the past decade. Moving toward industrialized and modularized homebuilding, which applies in-factory manufacturing processes to construction technology, the construction industry has been inclined to apply lean tools to improve process performance and efficiency. Although a number of studies report the usefulness of lean tools in industrialized home building processes, there are challenges involved in implementing lean tools in this construction sector. Without making the required adjustments, these challenges hinder the direct application of lean concept tools in the construction industry.

Unlike the products of most manufacturing processes, in which a particular set of tasks are repeated on a limited number of product types with identical properties and designs with a high production volume (mass production), each end product (such as a home) in the construction industry has specific features and properties (including floor area, number of floors, and architectural design) due to high customization. Also, each home consists of product components (different panels) require specific operational tasks and have unique properties according to each home's size and drawing specifications. As a result of the uniqueness of each panel, industrialized construction cannot benefit from tools which are designed for repetitive tasks.

This research contains a case study of a local manufacturer, Landmark Building Solutions, the prefabrication division of Landmark. As one of the largest home builders in Alberta, Landmark produces on average 1,000 dwelling units per year and has played a significant role in providing housing solutions recognized for sustainability, and for leading a revolution in industrialization of housing construction in North America. The Landmark Prefabrication Facility aims to increase capacity to produce wall and floor panels for 4 homes in one 8-hour shift. For this reason, this thesis studies the Prefabrication Facility in order to identify improvement opportunities to increase production line efficiency and throughput with lean technique implementation in industrialized home building. Landmark manufactures panelized houses with more than

15 base models and 7-14 sub-models, each composing less than 20% of the total production. Also, each home consists of 35-55 panels with different properties.

1.2 Research Objectives

The main objective of this thesis is to improve process flow in a panelized production system of single family homes through applying lean tools and ensuring process reliability and predictability. As discussed previously, the main challenge is to modify lean tools in order to apply them to the specific features of prefabricated and panelized home building: high product customization and low production volume. Considering this objective, this thesis addresses the following research questions:

- Which lean tools can be applied in industrialized home building?
- How should the lean tools be modified to fit industrialized home building specification?
- How can task times be estimated to represent actual task times in the process flow analysis which consider unique home design specifications?
- How can task time formulations be used in a simulation model to perform what-if analysis to help select the best options for process improvement?
- Which improvement techniques can reduce product cycle time and productivity of the production line?

1.3 Research Methodology

To achieve the research goals and objectives mentioned in Sections 1.2, this thesis follows the methodology illustrated in Figure 1- 1. The main contribution of this methodology is regression formulation of task times which considers the unique design specifications of each panel. The regression models are used in a simulation model to represent the actual situation of the production line. In the next few paragraphs, each phase is explained briefly.

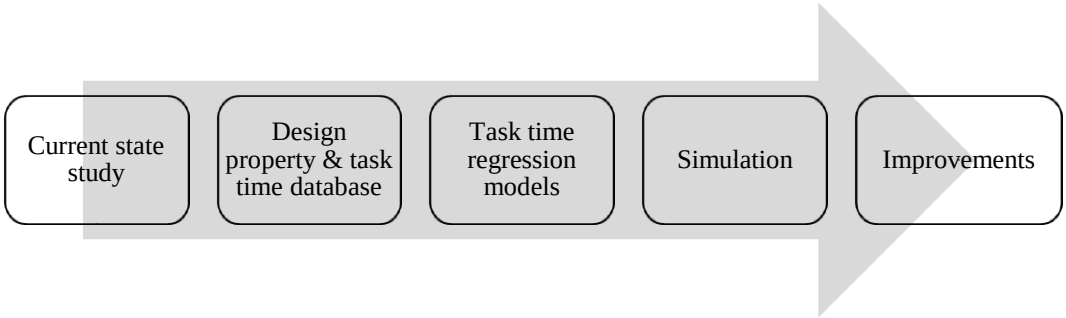


Figure 1- 1 Research Methodology Phases

1- Current state study: It is important to note that this phase was performed for both the floor and wall lines, whereas the next phases only focus on the wall line. This phase includes:

- **Work study:** In the work study, the floor and wall lines were monitored for almost two weeks and then the whole operation of each station was divided into tasks with specific breakpoints. In breaking the operations into tasks, we avoided having too short or too long task times.
- **Time study:** After station tasks were identified, task times for each task were recorded for 50 production cycles for the floor and wall lines. The time information gathered included: task processing time, station idle time, panel wait time between stations, and panel transfer time from one station to the next.
- **Current value stream map:** The value stream maps for the floor and wall line summarize the current performance of the process lines.

2- Panel design property & task time data base: This phase includes the following two steps:

- **Defining key design properties affecting task times:** In this step, we categorize the tasks in different stations into two categories depending on the variability observed in their task times: (1) low variability, and (2) high variability. The average task time is a good estimator of the actual times for tasks with low variability task times.

  On the other side, task times for tasks with highly variable times vary significantly based on panel characteristics and drawing properties. In this phase, we identify the product specifications affecting task times based on observations in the work and time study steps and expert consultation, including the line

manager and Landmark Research Representative. Examples of possible design properties affecting task times include number of studs (L-studs, multiple studs), number of window and door openings, number of short interior walls and etc.

- **Creating the data base for design properties and task times:** To implement statistical analysis on task times and run regression models, we created an Excel--based data base through extracting panel design property values which affect task times from drawing files. Then, we developed a data base which stores the recorded task times and associated panel design properties values for all 50 studied cycles.

3- Task time regression models: Regression models are used to predict a dependent variable (task times) by finding its relationship with one or several independent variables (design properties). For task times of activities with one identified design property, a simple linear regression (SLR) model is applied and for task times of activities with more than one design properties, multiple linear regression (MLR) is used. This phase includes:

- **Full regression models:** Based on the developed data base, regression models were fit for each task time of each activity (as the dependent variable) and all the panel design properties (as the independent variable) using the Excel-based SmartReg software. The linear regression models show how each of the panel design properties affect the task times. Based on the results of the full regression models, the design properties which have statistically significant effects on the task times can be identified. Statistically significant variables are those which have a real effect on task times based on the information provided in the data base.
- **Final regression models:** Here, we ran the regression models based only on the significant design properties. Then, the uncertainty in the task times were incorporated in the regression models. The advantage of the final regression models is that they require less information to estimate task times compared to full regression models.

Within the scope of the thesis, only the data for the wall line will be analyzed in the next steps.

4- Simulation model: The validated regression models, after incorporating uncertainties were used to estimate task times in the simulation model of the wall line. The simulation

software used in this research is "PrefabSim", the Landmark Shop Floor Simulation Program, developed by National Research Council of Canada (NRC). This simulation software uses estimated task times according to the unique design properties of each panel by extracting panel design property values from the WUP[1] files and replacing them in the regression models. The simulation model was validated against the actual data recorded in the time study step.

5- Improvements

We used a simulation model to verify the following proposed improvement plans:

- **Finding process bottlenecks:** In order to have continuous flow and process improvement, we identified bottleneck stations in the wall line. Bottleneck stations are slower than other stations and cause panels to experience long waiting times. Ultimately, the production pace is restricted by the speed of the bottleneck station.
- **Line balancing:** In line balancing, we address discrepancies in the task times of different activities through speeding up the slow stations (bottlenecks) and moving some activities to idle stations in order to level the workload.
- **Panel sequencing:** Panel sequencing techniques specify the order of panels entering into the flow line to achieve lower cycle times through eliminating station idle times and panel wait times.

1.4 Thesis Organization

This thesis is organized into six chapters. Chapter 2 consists of a literature review which explores lean concept implementation in industrialized construction and home building and recent initiatives to simulate industrialized home building with simulation modeling. This chapter also introduces the lean production concept and the lean tools applied in this thesis (including value stream mapping, line balancing, and job sequencing techniques). Chapter 3 covers the first phase of the proposed methodology in Figure 1- 1, including work and time studies and current value stream mapping. At the end of Chapter 3, the motivation for using regression models in estimating task times and incorporating them into the simulation model is discussed through referencing data facts extracted from the time study. Chapter 4 addresses phases 2 and 3 of the research methodology in Figure 1-

[1] WUP file is a readable file by machine which includes more information than a CAD file and stores the design specifications and components of a panel

1 and explains how panel design properties along with the collected time study data allow regression models to estimate task times more accurately. Chapter 5 introduces the simulation model in which task times are identified based on panel properties and associated regression models. Also, the simulation model is used to identify process line bottlenecks and propose improvement plans in order to decrease production time and increase production throughput.

Chapter 2

Literature Review

2.1. Overview

This chapter contains two main sections. The first section reviews literature which discusses the application of lean concepts in construction and industrialized home building. As improvement opportunities will be evaluated in a simulation model of the wall line later in this thesis, the literature review section also reviews simulation models developed for the construction industry. The second section provides background knowledge about manufacturing processes; and lean concepts, tools, and techniques which will be used in this thesis (for example, value stream mapping, line balancing, and operations sequencing).

2.2.State of the Art Literature Review in the Application of Lean Concepts in Industrialized Construction and Home Building

In the 1960s, industrialised construction referred to home building methods with prefabricated systems which produced large numbers of houses and large scale residential areas. Today industrialized construction refers to all technical and organizational aspects, the supply chain, and information management related issues involved in construction. Lessing (2006) proposed the following definition for industrialized home building to

describe the ongoing development in this field and to understand its characteristics and requirements:

> *"Industrialised house-building is a thoroughly developed building process with a well-suited organization for efficient management, preparation and control of the included activities, flows, resources and results for which highly developed components are used in order to create maximum customer value."*

Approximately 5% of all newly built homes in 2007 in the United States were built in factories either as panels (panelized homes) or units (modular homes) (U.S. Census Bureau, 2007). The idea in industrialized construction is to take advantage of similar construction operations and to define them as a manufacturing process in a plant with the aim of reducing on-site operations (Bertelsen, 2005). Industrialised home building, as a subset of the construction industry, consists of several sub-areas in a manufacturing system (production, procurement, planning, and control) which interact to deliver the desired homes to customers considering their specific and unique requirements (Roy et al., 2003). Lessing et al (2005) define the following eight required characteristics of industrialized home building:

1. Production planning and control of whole construction activities
2. Creation of a technical system for waste reduction
3. As many factory-built (off-site manufacturing) components as possible
4. Long term relationship between participants to save time and maximize value
5. Supply chain strategies based on JIT in construction activities
6. Use of systematic performance measurement
7. Customer focus on value delivery
8. Use of ICT technology for information exchange in production processes

Designing industrialized home building as a manufacturing process provides the opportunity for effective manufacturing control and management principles like lean production, and just-in-time (JIT) and supply chain management to enter and improve the construction industry. This opportunity has interested academics who research the construction industry in applying these principles to enhance productivity in

industrialized construction similar to the manufacturing industry (Naim and Barlow, 2003), (Gann, 1996).

The lean construction concept was first introduced when Koskela (1992) designed a framework which represented three perspectives in defining a production system:

- Process to *transform* inputs to outputs
- *Flow* of information and materials
- Generating *value* to customers

This frame work (as known as the TFV theory of production) was later discussed by Koskela (2000) who stated that the transformation viewpoint is the only viewpoint practiced in construction. Application of the other two viewpoints creates a foundation from which to transition from traditional on-site home building to industrialized home building in which lean tools can be applied to improve efficiency. The relationship between industrialized home building and production or manufacturing is debatable because of the following unique characteristics of production lines in industrialized home building (Mullens, 2004):

1. Complex product with large components
2. Few fixed stations are located along the production line
3. Labor and material flow to the product while the product flows continuously on the production line
4. Material transportation may stop the line (i.e. large components need a crane)
5. Measuring work content and cycle time for each product unit is difficult
6. Little material and finished product inventory due to lack of space and large components

Nahmens and Mullens (2009) identified high customization as one of the main characteristics of industrialized home building. They analyzed the effects of mass customization on lean implementation and vice versa based on a case study approach. This case study showed that high customization in industrialized home building increases the difficulty of the following tasks:

- Maintaining continuous process flow
- Using Pull systems
- Leveling the workload
- Developing a quality culture

- Developing standardized tasks
- Obtaining visual control
- Using technological applications

The aforementioned characteristics of industrialized home building may prevent the direct application of lean techniques which are borrowed from the manufacturing industry. Despite the known benefits of lean in manufacturing systems, some lean production specifications may limit its application in the industrialized home building, such as:

- Most lean techniques such as the pull system, kanban system, leveled scheduling, line balancing, and value stream mapping are applicable to stable repetitive production processes (Ohno, 1998). According to Bertelsen and Koskela (2005), home building lacks the benefits of repetitiveness in process flow (due to high customization) which leads to significant waste and process variations.
- Recording accurate operation times is a fundumental aspect of lean implementation. Although, in regular manufacturing processes, the time study can be easily implemented by site observation and monitoring the operations, it is difficult to collect meaningful data in construction processes due to long cycle times (Yu, 2010).
- Lean tools require the commitment of all organzational levels. The workforce level in mass manufacturing is usually stable as the demand market has little fluctuations, or at least predictable ones (Womack, et al., 1990). However, in construction, the work load depends on a) the competency of a construction company in bidding processes, and b) the project size and complexity. So, to prevent the need for massive organizational changes, most work is subcontracted to temporary contractors.

According to Yu (2010), some researchers believe that, despite the above mentioned constraints, construction is one type of production and all construction peculiarities can be mitigated through better process control and prefabrication. On the other hand, some experts emphasize that all planning, design, and management improvements should be within the boundaries of the existing production situation. So, they focus on developing lean construction tools to accommodate these construction peculiarities. Winch (2003) reconstructed the process model matrix of Figure 2-1 and categorized four basic manufacturing models, as shown in Table 2-1.

Table 2- 1 Manufacturing models (Winch, 2003)

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

Project-based industries, including the on-site construction industry, follow the concept-to-order strategy which is associated with low volume production of complex systems (Winch, 2003). The auto manufacturing industry enjoys demand predictability and relies on the make-to-forecast strategy to produce high volumes of products with limited variety with the opportunity of applying lean tools. Yu (2010) believes that the home building industry, as one of the construction industry sectors, uses the make-to-order strategy to build houses with different specifications in low volumes. As **Table 2-1** suggests, this construction sector has the opportunity to use lean manufacturing benefits.

Based on a study by Gann (1996), Japanese industrialized home builders have based their success on focusing on similarities between industrialized housing and the auto manufacturing industry and modifying product development, production processes, research and development initiatives, and marketing and sales to fit the specifications of the housing industry. Among the lean techniques, JIT, continuous improvement concept and quality management are widely applied by Japanese home manufacturers. Barlow et al. (2003) have reported success stories of Japanese companies which have delivered high levels of design customization while applying standard construction procedures.

Bashford et al. (2003) introduced an even flow production (EFP) control tool by focusing on the production scheduling aspect of lean production. EFP sets a fixed production schedule plan based on the delivery time of different houses and takt times, and provides an even production flow by removing idle times and speeding up bottleneck operations. The key point in the success of EFP is the reliability and accuracy of the activity cycle times. The EFP tool was used in a residential construction project in Phoenix, Arizona.

Sabharwal et al. (2009) redesigned the floor and wall assembly processes in a home building factory through eliminating material handling waste times and redesigning assembly process and production layout to minimize material handling costs and improve productivity. Although there are several reports which have mentioned the usefulness of lean tools in industrialized home building, a number of challenges remain:

- High level of customization in home building requires higher variability in the production process.
- A home consists of panels with different size and design properties which result in differing processing times for products (panels) in the production line.
- The Low production volume of each home model does not allow for full deployment of lean tools.

2.3. State of the Art Literature Review on the Application of Simulation Modelling in Construction

Researchers in construction management have used discrete time (or event-based) simulation models extensively in recent years to simulate construction projects. Simulation, in general, is defined as the mathematical imitation of events happening in a real system and their interactions with real-world objects (Farlex, 2011). In construction, simulation models are typically developed to simulate repetitive construction projects like construction of buildings, tunneling, and earth moving operations by defining the logical relationship among different activities and the associated resources required.

In discrete event simulation, the simulation time evolves according to the events of the system, such as the arrival of an empty truck to the loading site or departure of a loaded truck from the loading site to the dump site during earth moving operations. The logical relationship among activities determines the modelling elements (construction activities such as loading a truck) that the entities (truck) pass through. The time that each entity spends in a modelling element is usually defined by a statistical distribution with specific parameters. As well, resource elements, such as a loader, can be captured by the modelling element while loading to represent resource allocation within the model.

The advantage of a simulation model in a construction project is that the engineers can efficiently evaluate various construction scenarios based on their productivity, associated risks, required resources, and time and cost trade-off and then select a set of parameters resulting in the best overall performance before initiating the implementation phase of the

project. Situations where simulation models are more effective compared to other mathematical modelling tools include (AbouRizk, 2010):

- Some parmeters of the studied system are uncertain (for example, uncertainty in task times)
- The studied system is complex, in the sense that the interactions of entities involved in the system are complicated
- System processes are repetitive, meaning entities in the system pass through almost the same set of operations
- All details of the studied system are important during system analysis, making other mathematical tools with simplifying assumptions unacceptable

Different simulation softwares have been developed and used to model various construction processes. These softwares are suitable to model general construction projects. Halpin (1973) developed the Cyclone software in which modeling elements connected to each other based on their relationship with one another. Cyclone simplifies simulation modeling through removing the hurdle of computer programming and thus enables construction practitioners with a limited knowledge of simulation to use it easily. Constructo (Halpin & Woodhead, 1973), Insight (Paulson, et al., 1987), and DISCO (Huang , et al., 1994) are other general purpose simulation softwares which were developed later based on Cyclone.

Simphony, developed under the Natural Science and Engineering Research Council (NSERC)/Alberta Construction Industry Research Chair Program in Construction Engineering and Management at the University of Alberta, is a successful simulation software which provides a standard, consistent, user friendly, and intelligent environment to model construction projects (Hajjar & AbouRizk, 1999). System elements are represented by different figures considering their operational purpose and are connected to each other based on the logical relationship between them in Simphony.

In industrialized housing, in which home building can be considered as a production flow in a factory, simulation softwares used in the manufacturing industry can be applied in parallel with the softwares developed for construction. One of the most powerful softwares used to simulate manufacturing processes is Arena. Han (2010) used Symphony to simulate the manufacturing production processes of Kullman Building Company (KBC), a modular building manufacturer in the United States, and used the

simulation output to develop a 3D visualization model. Velarde et al. (2009) used Arena to simulate the flow of the modular manufacturing process and evaluate several improvement alternatives to increase production throughput and decrease production cost considerably.

2.4.Background in Literature

This section reviews the specifications of different types of manufacturing systems and introduces the lean concept as a tool to improve manufacturing systems' performance through production waste reduction. Furthermore, some of the lean tools and techniques which will be used later in this thesis (like value stream mapping, line balancing, and operations sequencing) are discussed.

2.4.1. Manufacturing Processes

Manufacturing systems are managed by one of five process models: (1) project process, (2) jobbing process, (3) batch process, (4) mass process, and (5) continuous process (Greasley, 2006). In the Figure 2-1 matrix, the five manufacturing processes are categorized according to product design specifications (customization and production volume) and process characteristics (the degree of manufacturing line complexity). Project manufacturing processes and continuous manufacturing processes are the two extremes of this matrix. Project-based manufacturing processes are suitable for complex and highly customized processes, as the products are manufactured based on the individual needs of customers. In project-based processes, each end product is treated as a project having unique features, requirements, and start and finish dates. On the other extreme, continuous processes are used to produce one product type in large volumes. Due to operational repetitiveness, continuous processes are highly standardized and are mostly operated with automated machines. The flow of products in a continuous process is continuous, meaning the product individual units are not recognizable. Pharmaceutical companies are an excellent example of companies which use continuous type processes.

When product units are distinct and manufacturing involves large volumes of a limited number of product types, mass production processes are the suitable option. The typical example of a mass production process is the auto manufacturing industry in which a single car model is manufactured in high volumes. Different cars do not have significant differences and all follow the same set of operations in sequence. To keep the production volume high and use economy of scale, mass manufacturing processes rely on connected

flow lines with a low degree of complexity. The production layout in a mass production process is a sequential flow line.

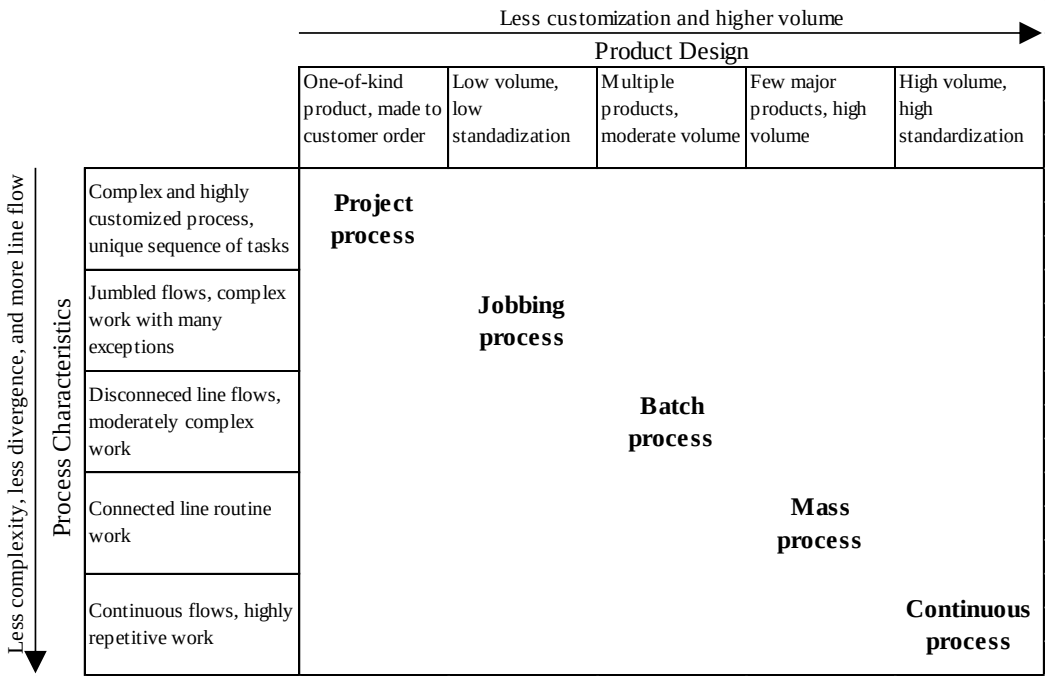


Figure 2- 1 Process Model Matrix (Greasley, 2006)

Jobbing and batch manufacturing processes borrow their specification from project and mass processes. A jobbing manufacturing process is more similar to a project process. In a jobbing process, a wide range of product types are manufactured with different sets of operations. Product units may leave a production unit to another unit to complete their operations. In a batch process, the number of product types is smaller, but the production volume of each product type is larger compared to that of jobbing manufacturing.

According to the above explanation, the traditional home construction industry (on-site home building) is based on project processes. Each house has unique features (design, square feet area, prices, and material quality) and its construction can be defined as a project with specific start and end dates. Unlike traditional construction methods, industrialized construction offers the benefits of mass production (lower costs, shorter manufacturing time, higher production volume) to the construction industry through

introducing prefabricated and modularized housing and deployment of automated operations inside home building factories.

With the transition from on-site home building to industrialized construction, the construction industry can apply useful production management and control tools developed in manufacturing processes to improve productivity through increasing production volume and decreasing cost and delivery time.

2.4.2. Lean Production

Lean production originated from manufacturing management practices in mass production systems, most notably the Toyota Production System (TPS), the Japanese manufacturing industry. Lean production tools and procedures improve mass production systems through using resources more efficiently and reducing all types of production waste (Groover, 2001).

Lean production is "an approach to manufacturing the right product in the right quantity through instant material supply while minimizing wastes and maintaining flexibility to adapt to varying production requirements" (Ikovenko, 2004). The ultimate goal of lean implementation is waste reduction, and if possible waste elimination, in manufacturing processes.

The lean concept has two major components: lean philosophy and lean techniques. While lean philosophy has general and universal principles to design manufacturing processes, lean techniques introduce specific tools which are used in world class mass production systems to manage and control production flow. Lean production inherited some of these techniques from the auto industry; however, its applications are currently implemented in a number of other sectors. (Yu, 2010)

Depending on the industry and the application, lean applies different tools and techniques, including value stream mapping (VSM), 5S, just-in-time (JIT), Kanban, line balancing, and zero-defect to smooth work flow through steadily removing unevenness and waste. Some of these techniques will be explained in Section 2.4.3.

Liker (2004) introduces seven lean principles which improve manufacturing processes:

1. Establish a continuous flow to expose problems: produce only at the time and in the exact amount needed (JIT)

2. Use a pull system to avoid overproduction: the upstream processes start manufacturing if a demand arises from the downstream processes (Kanban)
3. Level the production: the throughput of the entire production line is determined by the capacity of the slowest station (line balancing)
4. Get quality right the first time: solving quality problems at the upstream, even by stopping the process frequently, saves incurred time and cost at the downstream (Poka Yuke or zero defects)
5. Standardize tasks and processes: consistent performance in terms of production time and quality is in reach if everyone does the same work the same way
6. Make things visual: preparing a working environment and guidelines to determine whether the process is normal or deviating from the standard as soon as possible (5S)
7. Use only technology that serves the process: process reliability, consistency and predictability of the system should take precedence over advanced technology

Lean manufacturing aims to improve the deficiencies of mass production and to remove the distinction between jobbing, batch, and mass production processes through identifying and removing production wastes, designing the production process based on continuous flow, and emphasizing high productivity and flexibility (Yu, 2010).

Waste is anything that not only contributes no value to the production system, but also increases production time and cost. Womack and Jones (1996) address seven wastes in the lean concept:

1. **Transport**: unnecessary movement of materials and in-process components or finished products as a result of poor manufacturing layout which increases the risk of lost or damaged product, as well as process delays.
2. **Inventory**: high inventory of raw materials, work-in-process, or finished products which increase storage and transportation costs.
3. **Motion**: any redundant movement of workers performed during an operation which results in overtime production and increases the risk of accident and injury for workers.
4. **Waiting**: the time that workers, machines, or products wait between operations or during an operation for material, tools, or a production component from the previous station.

5. **Over-processing**: unnecessary excess work done on a product which does not add value to the product.
6. **Over-production**: producing more components or products earlier than the time that the customer orders. Over-production can lead to excess inventory and more required storage space, ultimately increasing costs and generating other types of wastes.
7. **Defects**: producing any defective components or products that cause rework or replacement in the next stations. Defects waste time and effort and decrease productivity due to interrupting the integrity of the process flow.

2.4.3. Lean Tools and Techniques

There are different lean tools and techniques for continuous improvement and waste elimination. Depending on the type of industry, product, improvement objective, and application, some tools may appear more suitable compared to others. The most well-known tools include 5S, Kanban, JIT, zero-defect, value stream mapping, line balancing, and scheduling.

Considering the transition from traditional construction to industrialized construction, a number of these tools can be used in home building factories in which different panels are built through several operations and then moved to the site for assembly. In the next few sections of this dissertation, three of these tools which will be used later are discussed: value stream management, line balancing and sequencing techniques.

2.4.3.1. Value Stream Management

Value stream management (VSM) is one of the most common lean tools used in a variety of systems (from manufacturing systems to service systems) that provides better understanding of a manufacturing process and is an essential step for process improvement. It is considered the starting point in planning lean initiatives and linking them based on systematic data collection and analysis (Tapping, et al., 2002).

The main component in VSM is value stream mapping which maps the material and information flow in the current system (current map) in order to analyze the whole process and identify possible problems and hidden wastes. The value stream mapping technique graphically maps flow of materials and information in all steps of production needed to transform raw material into finished products. Before one can discuss removing

wastes in a process, value-added and non-value added activities need to be identified with the help of value stream mapping.

Mapping material and information helps managers identify problems and possible wastes, potential bottlenecks, and excessive work in process (WIP). Waste elimination can reduce production lead time and as a result enables the company to meet customer demand. Value stream mapping also provides a true picture of how operations are running. Value stream mapping provides better understanding of the manufacturing process for the entire company from top managers to floor supervisors and workers (Tapping, et al., 2002).

After identifying which operations are value-added, value stream mapping is used to find the points in the process where time is wasted by showing cycle times and actual elapsed times of different operations. The ultimate objective is to reduce or remove the waste in those process points. The current map analysis and findings will be used to create with an improved map.

VSM views the system as a whole process instead of individual tasks, and helps the organization focus on process components which generate value in order to implement lean improvements. The advantages of VSM, as explained by Rother and Shook (2003), are:

- Visualization of material and information flow provides a clear understanding of the process
- Process mapping and quantitative performance measurements reveal hidden wastes in the process
- VSM maps the required steps in lean transformation from the current situation to an improved future situation

Although the implementations steps of VSM may vary depending on industry type, corporate culture, and production technology, Tapping et al. (2002) have introduced the following eight steps for VSM implementation:

1. **Commit to lean**: Lean expected results are only achievable with the commitment of all people in all levels of the company. Lean implementation is not the responsibility of one person. The commitment should start from the top manager and involve the entire company.

2. **Choose the value stream**: A value stream is the whole process that transforms raw material to finished products through a series of operations. It tracks the product unit in a company task-by-task and station-by-station. Since each company typically manufactures different ranges of products, with different characteristics (dimensions and designs) and processes, the product units with the highest production volume are considered to be a target for value stream improvement.
3. **Learn about lean**: Before mapping the current state, a good understanding of lean concepts is necessary. A training plan should familiarize people with the key lean concepts in order to make an effective plan for the future state.
4. **Map the current state**: Current state mapping starts with time data collection from the factory. The time data represent the situation of the current manufacturing processes using special value stream mapping icons and communication arrows. The scope of value stream mapping differs based on its goal. It can be studied from the time an order is placed until the cash for that product is received, or from the time raw material is received to when finished goods are delivered to a customer.

   Value stream mapping can also be used as a tool for improving the whole supply chain performance, according to Arbulu and Tommelein (2002). They used process flow within the design, procurement and fabrication levels of power plants.
5. **Identify lean metrics:** Key performance indicators (KPI) provide a tool for identifying weak areas, planning for improvement actions, checking results, and making proper corrective actions. KPI not only provide performance measures for a specific operation but also measure the performance of the entire value stream. The most common lean metrics include inventory turns, cycle time, lead time, delivery time, equipment effectiveness, production volume, and value added time (VAT).
6. **Map the future state**: The future state map design is based on the analysis of the current map. The analysis results are used to design a waste-free and more efficient map for the future. There are three stages involved in mapping the future state: a) customer demand stage (set ordering time and production volume to meet delivery times considering the lead times), b) flow stage (develop a

continuous flow), and c) leveling stage (level the use of stations to reduce production wastes and idle times).

7. **Create a continuous improvement plan**: A continuous improvement plan is a detailed plan that helps achieve sustainable improvement of the value stream. A comprehensive plan is required to achieve a successful lean transformation. It determines the completion time of the improvement activities in each of the demand, flow and leveling stages, the lean techniques and tools required, and the person or team responsible for each plan.
8. **Implement improvement plans**: Improvement activities must involve all company personnel in improving the value stream. It is difficult for people to accept changes: however, if a detailed improvement plan is provided and effectively communicated, they will feel more inclined to assist with the transition. Therefore, communicating with people at all company levels is a key point in shifting to lean.

Yu et al. (2009) used VSM in construction to identify areas accumulated with waste and hidden problems. Construction operations were mapped and the required data were collected to calculate the key performance indices. Adopting lean principles to homebuilding processes and using proper lean tools and techniques were major challenges for developing the future state map. Creating a stable production flow was the target of lean implementation in the studied company.

Wang et al. (2009) implemented VSM in the production flow of pipe spool fabrication. The challenge they faced was the high variability and uncertainty in spool fabrication due to the wide range of models.

Despite the benefits of value stream mapping, Hines and Rich (1997) have addressed several problems in using value stream mapping:

- Value stream mapping cannot show all wastes, such as energy waste and human effort waste
- Without information flow, the advantages of value stream mapping are limited
- Some collected data are subjective and are not shown on the map despite potentially having valuable information
- Focusing solely on task mapping will prevent a high level understanding of the whole process, which is required to prioritize improvement plans

- Incomplete process mapping can lead to incorrect improvement implementation and failure to create a better future state

2.4.3.2. Line Balancing

In a manufacturing system, semi-finished products pass through several production line workstations. Different operations are performed at each station to convert semi-finished products to finished products at the end of the line. Each operation may include several tasks or activities. Line balancing develops a smooth production flow by equalizing different station utilizations. Balanced utilization across different work stations reduces the idle time of fast stations through equalizing the work content of work stations and speeding up the slow stations. Line balancing improves productivity and line throughput and reduces cycle time through minimizing the waiting and idle times of stations (Abu Hammad, 2003). In addition, production costs including resource related costs (labor cost or machinery cost), operational costs, and inventory costs, are minimized as a result of cycle time reduction (Monden, 1998).

However, according to Abu Hammad (2003), achieving a perfect balanced line is impossible because of the following reasons:

1. Technical constraints in task ordering (due to a preceding relationship, some tasks cannot be grouped together)
2. Performing some tasks together may cause operational conflicts due to task incompatibility, such as painting and sanding
3. Variability in task durations due to different product specifications and properties

Variability in product design and its effect on system productivity result in researchers and production managers having to find more innovative ways to balance the line and remove bottlenecks from system.

Combining optimization and simulation models provides useful tools to allocate workload in order to convert an unbalanced line into a balanced one. Deterministic parameter assumptions, such as no machinery breakdowns or a predictable schedule in optimization models, provide deterministic outputs. These outputs provide inputs to the simulation model which can then consider more uncertainty in the process parameters (Mahmoodi, et al., 2007). According to Scholl (1999), optimization models of line balancing should be used wisely to address real implications of industrial problems.

Merging activities and merging stations are two suggested line balancing procedures (Soman, 2000). Scholl (1999) explains these procedures in five sequential steps: (1) Define the required tasks, (2) identify the precedence relationship between tasks, (3) combine tasks according to the job specifications and precedence relationship in work stations, (4) calculate the work load of each stations, and (5) move the tasks in the boundaries of the slow work stations to the previous or next stations to balance the work load profile.

In general, line balancing can be improved through two approaches. The first approach is to allocate a task to another station, considering the technical constraints, so that the working mean time at each station is close to equal. The second approach is to increase resources at some bottleneck stations, and thus reduce task times at those stations, so that the working mean time at each station is close to equal.

2.4.3.3. Job Sequencing

The objective of job sequencing is to maximize station utilization by determining the appropriate order of different products entering the production line. Job sequencing is especially important when the product units experience different task times in a station due to their specific design specifications. Job sequencing aims to decrease the buffer time between stations and reduce system inventory (Abu Hammad, 2003). Stations may experience idle time in two cases: (1) the station has finished its work but since the previous station has not finished its operation, there is no work for the current station, and (2) the station has finished its work but cannot handle the product to the next station as the next station is busy with another operation.

A sequencing procedure can be used along with a line balancing optimization model and a simulation model to reduce average cycle time and increase productivity of the system. Sequencing is particularly significant in the situation that work stations are bombarded with loaded jobs, especially lengthy jobs. Sequencing can decrease the cost of jobs waiting as well as the cost of idle work stations (Inman, 2012).

A sequencing procedure works based on a priority rule to order the sequence of jobs so that a continuous work flow with minimum interruptions and idle time is achieved. Priority rules work based on information about job processing times (including setup and processing times) and job due dates. A number of popular priority rules addressed by Vollmann et al. (2005) are listed below:

- **Random (R)**: Choosing jobs with equal probability randomly.
- **Shortest processing time (SPT)**: The first job in line has the shortest processing time.
- **Longest processing time (LPT)**: The first job to be completed has the longest processing time.
- **First-come-first-served (FCFS):** The priority is with the first job arrived
- **Earliest due date (EDD)**: The first job has the earliest due date. This rule works well in shops that are evaluated by job lateness.
- **Critical ratio (CR)**: To achieve this ration, one must divide the required completion date by the required processing time. The jobs with lower CR enter the line first.
- **Least work remaining (LWR)**: The job with the least amount of processing time remained to finish is first in the production schedule. This rule is an extension of the SPT rule.
- **Fewest operations remaining (FOR)**: Job priority is based on jobs that have fewest numbers of remaining operations to be performed. This rule is another extension of the SPT rule.
- **Slack time (ST)**: Slack time can be measured by subtracting total set up time and processing time from the job's remaining time until due date. Jobs with the smallest slack time are completed sooner. This rule is an extension of the EDD rule.
- **Slack time per operation (STO)**: The smallest value of dividing slack time by the number of required operations specifies the highest job priority. This rule is an extension of the ST rule.
- **Next queue (NQ)**: NQ goal is to maximize machine utilization. It works based on evaluating the succeeding queue. The job that goes to the smallest queue will be performed first.
- **Least setup (LSU)**: This rule minimizes the setup time on the machine as well as maximizing utilization. First jobs are those that minimize the setup time of the machine.

This thesis will compare some of the above priority rules to sequence the panels of a house entering the wall line process in Chapter 5.

Chapter 3

Current State study: Work and Time Studies, Current Process Map

3.1. Overview

In this chapter, we review the first phase of the proposed process flow improvement methodology of Figure 1-1: current state study (Figure 3-1). This chapter presents the steps to map the current state of the floor and wall panel production lines of the case study, Landmark Homes Company. The first phase of the proposed methodology includes three main steps: (1) Work study, (2) time study, and (3) current value stream mapping. The aim of the first phase is to understand the features and specifications of the current situation in the floor and wall panel production lines by collecting work and time related data and then mapping the operations, along with a time data summary, in a value stream map. The current value stream map reveals facts about the operational situation of the production lines. At the end of this chapter, the limitations of the value stream mapping are discussed. These limitations hinder its full applicability to our case study and the associated specific complexities.

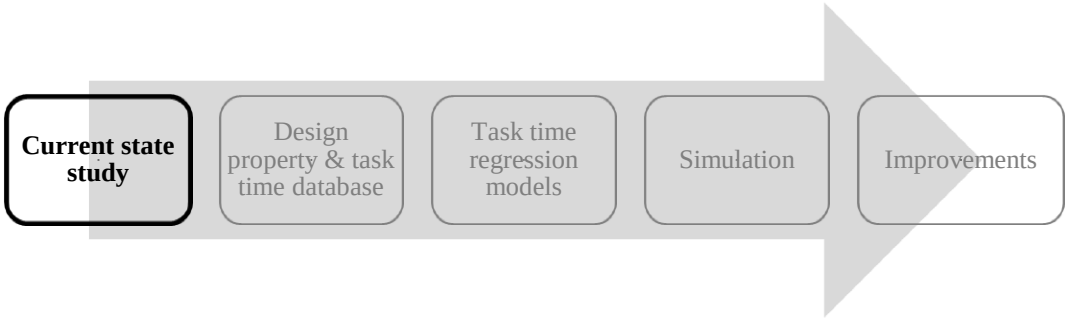


Figure 3- 1 Phase 1: Current State Study

3.2. Work Study

Work study is a technique based on direct observation of all influencing factors involved in an operation in order to understand the operational components, design a standard way of performing the operation, and set target performance measures. In manufacturing systems (like the industrialized home building process in the case study of this dissertation), work study is the first step in analyzing the current state of the system in order to identify possible improvement opportunities.

The floor and wall line layouts of Landmark Homes Company are shown in Figure 3-2. The stations of the floor and wall lines are marked by "F" and "W" in the plant layout, respectively. After several visits to the floor and wall line stations and becoming familiar with the processes at each station, the researcher recorded the specifications of jobs being completed at each station and then divided these jobs into tasks. Breaking down the jobs into tasks enables the researcher to identify detailed work specifications for further use in the time study and data analysis stages. The following recommendations in Kanawaty (1992) and Barnes (1968) were considered when dividing jobs into tasks:

- Identify breakpoints (the starting and finishing points of each task)
- Avoid too short or too long task times
- Separate manual tasks from machine tasks
- Separate occasional tasks (tasks which do not occur in every cycle) from regular tasks
- Separate constant tasks from variable tasks: the net time of a constant task remains almost fixed in different cycles. However, variable tasks have different net times based on panel characteristics (e.g. dimensions, drawing specifications).

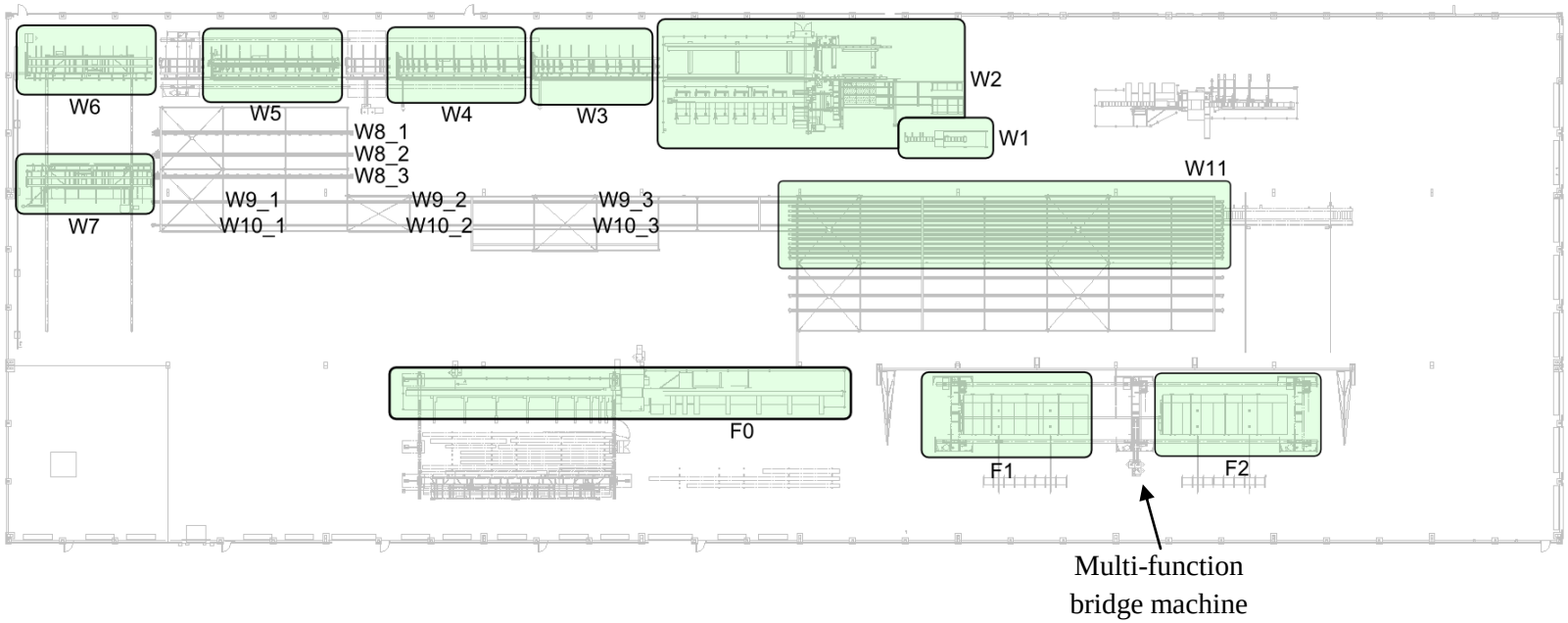


Figure 3- 2 Landmark Floor and Wall Lines Layout

3.2.1 Floor Line

There are two pin tables (F1 and F2 in Figure 3-2) in the floor panel manufacturing line working in parallel. All jobs required to build a floor panel are completed on the pin tables. Panels are stationary in this line. Required components are cut and processed via the WBZ cutting machine (F0 in Figure 3-2) and are conveyed to the pin tables by a conveyer. As shown in Figure 3-2, there is one multi-function bridge machine between the tables to support the operations of both tables. Each pin table requires two workforces to work on a panel. After a panel is completed, it is moved to the temporary storage table and waits to be placed in sequence in a trailer. Seven activities are performed in sequence on the pin tables to build a floor panel. The next paragraphs explain these activities in operational order.

- **Activity F-1: Preparation**

Two workers move wood components from the WBZ processing machine (F0) to one of the pin tables using a conveyer cart, and clean any tools or debris remaining on the pin table from previous work. Then a worker checks the panel drawings and loads the panel file into the multi-function bridge machine to set the pins on the pin table.

- **Activity F-2: Panel set-up**

The workers place proper joists and joist hangers on the pin table, according to the panel drawings and nail the joist hangers to the specified joists, or joists to the rim boards or beams. Then, they glue and nail the outer joists to joist hangers in order to secure all components.

- **Activity F-3: Prefixing OSB[2] (by multi-function bridge machine)**

One worker loads the panel design file (called WUP file) in the multi-function bridge machine. The machine moves over the panel and glues all edges of joists, rim boards, and beams for increased tightness. One worker supervises the job during the machine work.

- **Activity F-4: Fixing OSBs**

Before applying sheathing on top of the floor panel, workers drill four holes for later crane moving. One worker brings sheathing (OSB) to the pin table via the vacuum lifter, and places it on the floor panel, according to the panel drawings. Then, the other worker secures sheathing on the panel by the pneumatic nail gun.

[2] Oriented Strand Board

- **Activity F-5: Finish panel (by the multi-function bridge machine)**

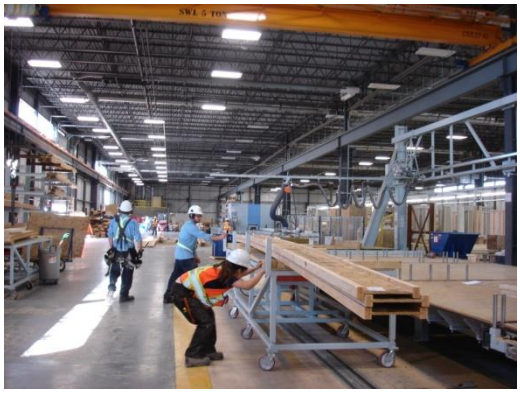
After the drawing file is loaded, tasks in this station are automatically completed by the multi-function bridge machine. The machine moves over the panel and nails or staples the sheathing material (parallel nailing with two nail guns) to the panel. Then, it routes four holes on the sheathing so that the panel can later be lifted by an overhead crane. At the end, it trims and cuts extra edges of sheathing.

- **Activity F-6: Set up for moving the finished panel**

One worker brings the overhead crane while the other worker collects waste parts and labels the panel. Then, both workers connect metal chains to straps around the four holes on the sheathing thus securing the panel to the chains.

- **Activity F-7: Transporting finished panel**

Both workers move the panel to the temporary storage table before shipment to the trailer.



Activity F-1: Preparation

Activity F-2: Panel set-up

Activity F-3: Prefixing OSB

Activity F-4: Fixing OSBs

Activity F-5: Finish panel

Activity F-7: Transporting finished panel

Table 3- **1** lists the tasks of each of the floor line operations described above.

Table 3- 1 Floor Line Activities

Operation	Activity
F-1 Preparation	1.1 Move wood components near the pin table 1.2 Clean the floor table from previous work 1.3 Check the drawing and load the file 1.4 Set the machine
F-2 Setting up a panel, adjustment and inspection	2.1 Bring the required number of joist hangers from the shelf 2.2 Put proper joists and joist hangers on the floor table 2.3 Secure the joist hangers to specified joist 2.4 Glue and nail outer joists to joist hangers 2.5 Nail the joists to the rim boards or beams 2.6 Cut small blocks and transport them to the floor table 2.7 Glue and nail web fillers or squash blocks on joists for more supports 2.8 Apply insulation material on one side of a panel 2.9 Nail insulation blocks to the joists, rim boards, or beam
F-3 Prefixing OSBs (by multi-function bridge	3.1 Glue all edges of joists, rim boards, bracings and beams

machine)	
F-4 Securing OSBs	4.1 Drill four holes for the straps on joists 4.2 Bring OSBs to the floor table via a vacuum lifter 4.3 Nail and secure OSBs to joists, rim boards, bracings and beams
F-5 Finishing the panel (by multi-function bridge machine)	5.1 Set the machine 5.2 Staple sheathings to the joist, rim boards and/or beams 5.3 Route four holes on the sheathing for lifting the panel 5.4 Trim the exterior edges of rim boards 5.5 Route openings and floor edges
F-6 Setting up the finished panel to move	6.1 Collect waste parts 6.2 Put straps around four holes on the sheathing 6.3 Label on the panel 6.4 Transport overhead crane and connect metal chains to straps
F-7 Transporting the finished panel	7.1 Move the panel to the temporary storage table

3.2.2 Wall Line

The wall line has a U-shape layout, as shown in Figure 3-2, with material and equipment stacks close to the stations. In the wall line, from station W1 to W6, each station function as a feeder station for the next station (series stations not parallel). The panel handlings between stations W1 to W6 are done by a roller conveyor and between stations W7 to W9_3/W10_3 are by temporary wheels under wall panels on the ground rails. This system of handling panels is efficient since it moves the panel vertically wherever possible, stations W9_1/W10_1 to the end of the wall line, and it occupies less space and provides faster panel movement. At the end of the line, wall panels are moved to a trailer via a crane. Material handling (such as wood parts, sheathings, and temporary wheels) is done by conveyor carts, vacuum lifters and forklifts. Wall line stations are described in the following paragraphs[3].

- **Station W1: Sub-components (module table)**

[3] The Landmark Group of Builders Health and Safety Program, Safe Work Procedure 2011

This station provides components for station W2 (framing station). Station W1 consists of two substations: (1) the nailing component machine, and (2) the rough opening table. The nailing component machine builds the cripples, two plies, and beam support studs for station W2. Also, at the back of station W1, there is an inventory stud stack, which provides a fully-automated stud assembly system that positions the required studs onto the roller conveyer to the framing station W2. In front of the nailing machine and stud stacks, on the rough opening table, all the interior and exterior door openings, window openings, header of garage doors and single tall walls (any walls over 3200 mm height and/or less than 1800 mm length) are built. Two workforces work in the station, one of which operates the nailing component machine.

- **Station W2: Framing table**

In this station, the wall studs, top and bottom plates and pre-assembled modules are assembled to build wall frames. At first, the only operator of the station loads the WUP file into the framing machine and then inserts the top and bottom plates into the clamp system by using in-feed rollers. Supplied studs and pre-assembled modules from the sub-Component station (station W1) are fed into the machine by the operator for nailing. Then, the machine makes all panel adjustments, such as width adjustment, tightens plates automatically based on the panel properties in the WUP file, and starts the nailing operation. Finished Panels are labeled and moved to the out-feed table to wait for station W3.

- **Station W3: Transportation table**

In station W3, multiple interior and exterior panel walls (if the panel consists of multiple walls) are separated. After separation, the exterior walls, long interior walls, and garage door wall panels are labeled by a worker and moved to the next station. Since interior walls need no sheathing or sprayed foam insulation, short interior walls move off the line and pack together for shipment to the trailer. Prior to shipment, a worker removes reinforcement strips at the openings of short interior walls and inserts poly wrap (as a moisture barrier) on the top plate side of the interior wall panel (only 2nd floor interior walls). Long interior walls and other types of panels (such as exterior walls and garage door panels) need I-bolts (as hangers) installation to move easily on the rail stations, which can be installed at this station or the next, depending on station availability. After this preparation, long interior walls are ready to move forward in the line until they ship to the trailer. The required workforce for this station is two workers.

- **Station W4: Sheathing table**

In this station, workers position sheathing materials (OSB or drywall according to the drawing) on wall frames through using a vacuum lifter and secure sheathing with an air spike nail gun. An operator sets the machine pins to straighten and square the frame prior to placing sheathing. If I-bolts installation has not already been completed in the previous station, it is completed in this station before moving the panel to the next station. Usually two or three workers work in this station.

- **Station W5: Nailing/ Routing**

After the drawing file (WUP file) is loaded, tasks in this station are automatically completed by the multi-function bridge machine. The machine moves over the panel and nails or staples the sheathing material (parallel nailing with two nail guns) to the panel, and/or routes window and door openings. An operator supervises the job and moves the panel to the next station. Some panels need exterior fireguard drywall on their sheathing material. In this case, workers position and nail the fireguard drywall manually, and then if the panel has openings, they are routed by the multi-function bridge machine. If a panel requires fireguard installation, one or two workers from stations W3 or W4 handle the job.

- **Stations W6 and W7: Butterfly table ("feeder" and "receiver" tables)**

The butterfly table composed of two main parts: the feeder table and receiver table. They work together to transfer and rotate the panel. First, the feeder table receives the panel from the multi-function bridge table and tilts it up to vertical. Then, the Receiver table moves toward the feeder table vertically and receives the panel during the rotation. After receiving the panel, the Receiver table moves it to the next station, either to the spray foam booth (station W8), or down the line to the wall magazine (station W9_1 or W10_1). One operator supervises the operations of the Butterfly table.

Station W8: Spray foam insulation booth

All panels, except interior wall panels and multiplex home panels, need spray insulation. This station consists of three sub-station rails (W8_1, W8_2, and W8_3). Depending on the workload, two to four workers are assigned to these sub-stations. After moving the panel from the Butterfly table, workers install stud covers and ensure that the spray guns are clean before spraying. Usually all spacing between studs should be sprayed except openings and the cut zone area. After the foam insulation has been sprayed, the foam

insulation is checked for required thickness. At the end, workers clean the over spray on stud covers and panel with scrapers and air gun and then move the panel out to the Receiver table (Station W7) to pass it to the next station.

- **Station W9_1/W10_1: Buffer (long rail to wall magazine)**

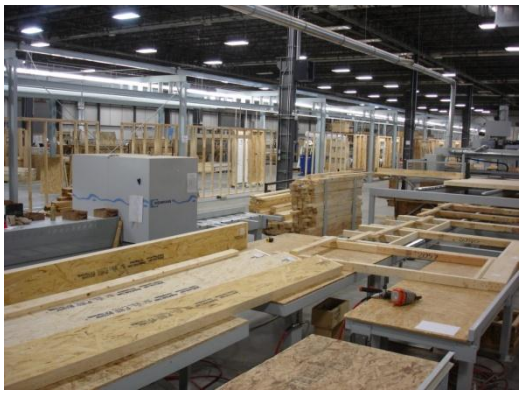
Station W9_1/W10_1 acts as a buffer and no actual operation is done on the panels in this station. After receiving panels from station W6 (panels without foam insulation) or station W8 (panels with foam insulation), the Butterfly table moves the panels to either station W9_1 or W10_1. Long interior wall panels, exterior wall panels without door/window openings and garage door panels usually move to rail W9-1 and after passing the Wall Magazine, move directly to the trailer. Exterior wall panels with door/window openings usually move to rail W10-1 for further operation.

- **Station W9_2/W10_2: Window/door installation**

Exterior wall panels with door or window openings are fitted with guard wrap and shims are installed on the window's bottom edge. Workers then check the drawing to find a proper window or door and take move it into position manually or via vacuum lifter. This station has two or three workers. Usually one worker holds the window in position and the other worker secures it with the pneumatic air gun. At the end, the workers tape all window edges. Door installation follows the same procedure as window installation.

- **Station W9_3/W10_3: Window/door cover installation**

In this station, a worker inserts temporary covers on both sides of each window and door to protect them from any breakage. Workers from the previous station are responsible for finishing the job in this station as well. Following this step, the panel is ready for shipment to the trailer.



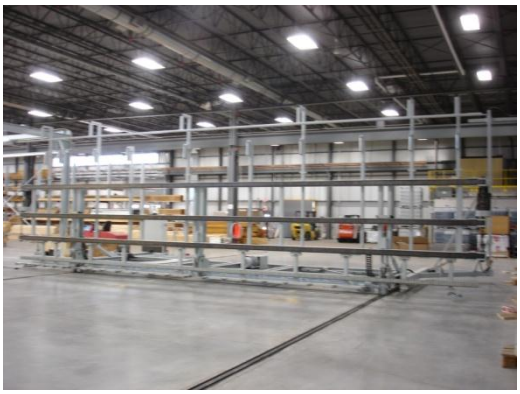
Station W1: Sub-components (module table)

Station W2: Framing table

Station W3: Transportation table

Station W4: Sheathing table

Station W5: Nailing/ Routing


Stations W6 and W7: Butterfly table

Station W8: Spray foam insulation booth

Station W9_1/W10_1: Buffer

StationW9_2/W10_2:Window/door installation

Table 3- **2** lists the tasks of each of the wall line stations described above.

Table 3- 2 Wall Line Activities

Station	Activity
Station W1: Sub-components /module table	1.1 Move wood parts on the table 1.2 Build window/door opening, single tall wall, header of garage door 1.3 Put reinforcement strips at opening
Station W2: Framing table	2.1 Prepare for a new panel 2.2 Load top & bottom plates 2.3 Assemble wall panel 2.4 Label panel and move it out
Station W3: Transportation table	3.1 Receive panel 3.2 Remove reinforcing strips at openings 3.3 Label walls (interior wall only) 3.4 Drill holes + install I-bolts (long interior walls and other types of panels) 3.5 Install interior insulation (Poly) (2nd floor interior walls only) 3.6 Separate 40' wall panel into multiple walls 3.7 Take wall panels off the line (short interior wall only) 3.8 Move panel to the next station

Station W4: Sheathing table	4.1 Receive panel 4.2 Check drawing for sheathing type and size 4.3 Position sheathing material (OSB or Drywall) + drill holes+ install I-bolts 4.4 Label the panel and move it out
Station W5: Stapling/ Routing	5.1 Receive panel 5.2 Load panel file 5.3 Staple sheathing 5.4 Route openings and wall edges 5.5 Position exterior fireguard drywall 5.6 Fasten exterior fireguard drywall 5.7 Route openings and wall edges - exterior fireguard drywall/rigid insulation
Station W6: Butterfly table (Feeder table)	6.1 Receive panel 6.2 Tilt panel up to vertical 6.3 Transfer panel to Receiver table
Station W7: Butterfly table	7.1 Receive panel 7.2 Travel to destination (W8, W9_1, or W10_1) 7.3 Move panel to rail
Station W8: Spray foam insulation booth	8.1 Move wall panel into the station 8.2 Install stud covers 8.3 Spray foam insulation 8.4 Clean spray gun 8.5 Check required thickness and clean over spray & stud covers 8.6 Move panel out to tilting table 8.7 Clean site
Station W9_1/ W10_1: Buffer	9_1.1 Move panel into the station 9_1.2 Move panel out of the station
Station 9_2: Install Windows/Doors	9_2.1 Move wall panel into the station 9_2.2 Check framing for openings (exterior wall only) 9_2.3 Staple guard wrap (exterior wall only) + install shims

	9_2.4 Take window/door to position (exterior wall only) 9_2.5 Install window/door (exterior wall only) 9_2.6 Move panel out of the station
Station 9_3: Install window/door covers	9_3.1 Move wall panel into the station 9_3.2 Find proper window/door cover 9_3.3 Install window/door cover 9_3.4 Move panel out of the station

3.3. Time Study

After the whole process was broken down into tasks, processing time data were collected for all tasks at each station. The author performed the time study in the floor line in August 2011 for floor panels and October-November 2011 for wall panels. Due to a high variety product mix, and in order to capture variability in the process, random sample of time periods were selected for the time study to cover a wide range of house and panel models.

For the floor line, the data for 40 production cycles were collected. For the wall line, due to a higher variety in product mix, 50 production cycles in each station were monitored for time data collection. No historical time data was available in the company before this study. I followed the instructions below which were recommended in related time study text books (Kanawaty, 1992) (Barnes, 1968):

- I was positioned in a location in which I did not distract workers or interfere with their movements.
- Time was recorded when an operator worked at a normal working pace (not in a position of being nervous or tired); otherwise, a rating factor was considered to standardize the timing.
- The recorded data was based on the work of qualified workers with enough training to complete the job with a satisfactory level of quality, quantity, and safety.
- Different weekday and working hours were selected for the time study to cover variety in the product mix.
- Any piece of information which affected the task times was recorded (like machine breakdowns and idle times).

The processing times were measured in minutes using a stop-watch and the cumulative timing approach. In this method, the stop-watch starts recording time at the start of the first task of the first cycle and is stopped when the cycle ends (completion of the last task). Times were recorded in a time sheet similar to the time sheet in Figure 3- 3.

Cycle							
Activity No.	Activity description	WT		ST	Net time	Description	Cycle properties:
		Start time	Finish time				
1	Preparation						Date: Time on: Time off: Panel No.: Job No.: Elapsed time: Net time: Break time:
2	Set up a panel (nailing and gluing joists), Adjustment and Inspection						
3	Gluing for prefixing OSBs (by multi-function bridge)						
4	Fixing OSBs						
5	Finish panel (by multi-function bridge)						
6	Set up for moving the finished panel						
7	Transporting finished panel						

Figure 3- 3 Sample Time Study Sheet

At the end of each task, the cumulative time is recorded in column "WT" (Watch Time). The task time of each task is calculated by subtracting "Start time" from "Finish time" and is recorded in column "ST" (Subtracted Time). The subtracted time shows the total time spent to finish a task and may include idle and delay times. The "Net time" column shows the net processing time spent for the actual operation of each task (net time < subtracted time). The net time excludes idle and delay times from the subtracted time. The net times are used later for data analysis. The "Description" column shows additional information like the number of workers, delay and idle times, machine breakdowns and line stoppage. The "Cycle properties" column contains information specific to the floor (or wall) panel studied in the cycle, such as job (house) number, panel number, the date, start and finish time of building that panel ("Time on" and "Time off"), as well as "Elapsed time," "Net time," and "Break time." The "Elapsed time" is extracted through subtracting the starting time ("Time on") from the finishing time of the cycle ("Time off").

For some cycles with an unusual number of workers, the task times were normalized later based on the usual number of workers required to complete that task and recorded information of the net time and the number of workers working in that cycle. In summary, the following time data can be extracted from the time sheets:

- Task subtracted time = task finish time – task start time
- Task net time = subtracted time – delay time – idle time

- Elapsed time of a cycle = finish time of the last task – start time of the first task
- Panel inter-arrival time in a station = start time of the first task of the current cycle – start time of the first task of the previous cycle
- Transfer time from one station to the next station = start time of the first task of the next station – The end time of the last task of the previous station

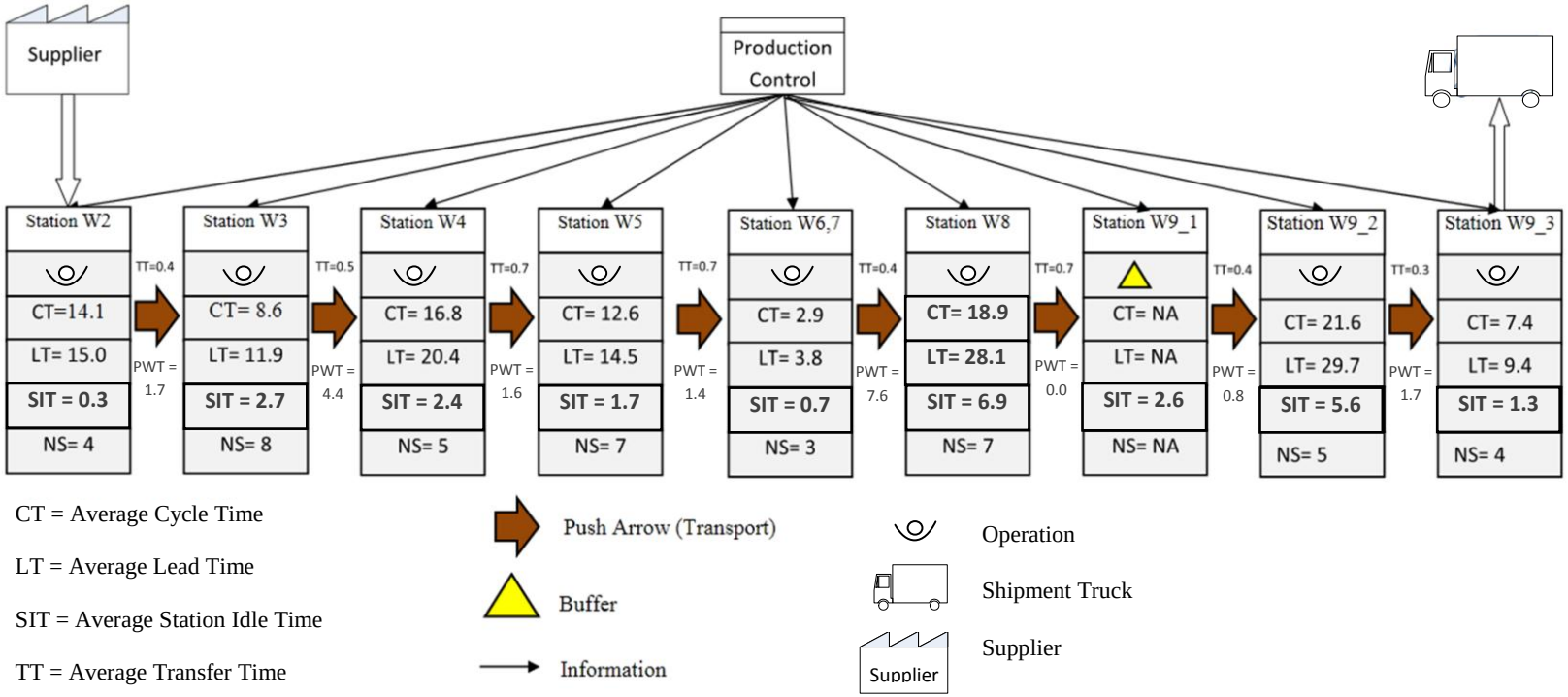
3.4. Current Process Map

The current situation (as of February 2012) of the floor and wall lines is mapped in value stream maps in Figures 3- 4 and 3- 5. For several reasons which will be discussed in later paragraphs (some of which were discussed in chapter 1), the value stream mapping tool cannot explain the details and complexities of the floor and wall lines. However, the tool provides a very high level analysis of the processes and summarizes station performance measures in average values. A value stream map based on average values may provide hints about possible process bottlenecks but there is no guarantee that those values precisely represent the current state.

In Figures 3- 4 and 3- 5 maps, each box represents a station (an operation in the floor line). These maps contain the following notations:

- CT: station cycle time which is equal to the average net task times of the studied cycles in all stations except station W8. Station W8 has three parallel sub stations, and so the net task time and cycle time differ.
- LT: station lead time (average elapsed times of the studied cycles)
- SIT: station idle time (the time a station waits for the next panel) (average station idle times of the studied cycles)
- PWT: panel waiting time (the time that a panel waits until the next station becomes available) (average over all panels studied)
- TT: between stations transfer time (average panel transfer times between two consecutive stations)[4]
- NS: number of activities in a station

[4] The VSM of the floor line does not include transfer times as in the floor line; the panel is stationary and different activities are performed in one station.



CT = Average Cycle Time

LT = Average Lead Time

SIT = Average Station Idle Time

TT = Average Transfer Time

PWT = Average Panel Waiting Time

NS = Number of Activities

Figure 3- 4 VSM for the Wall Line

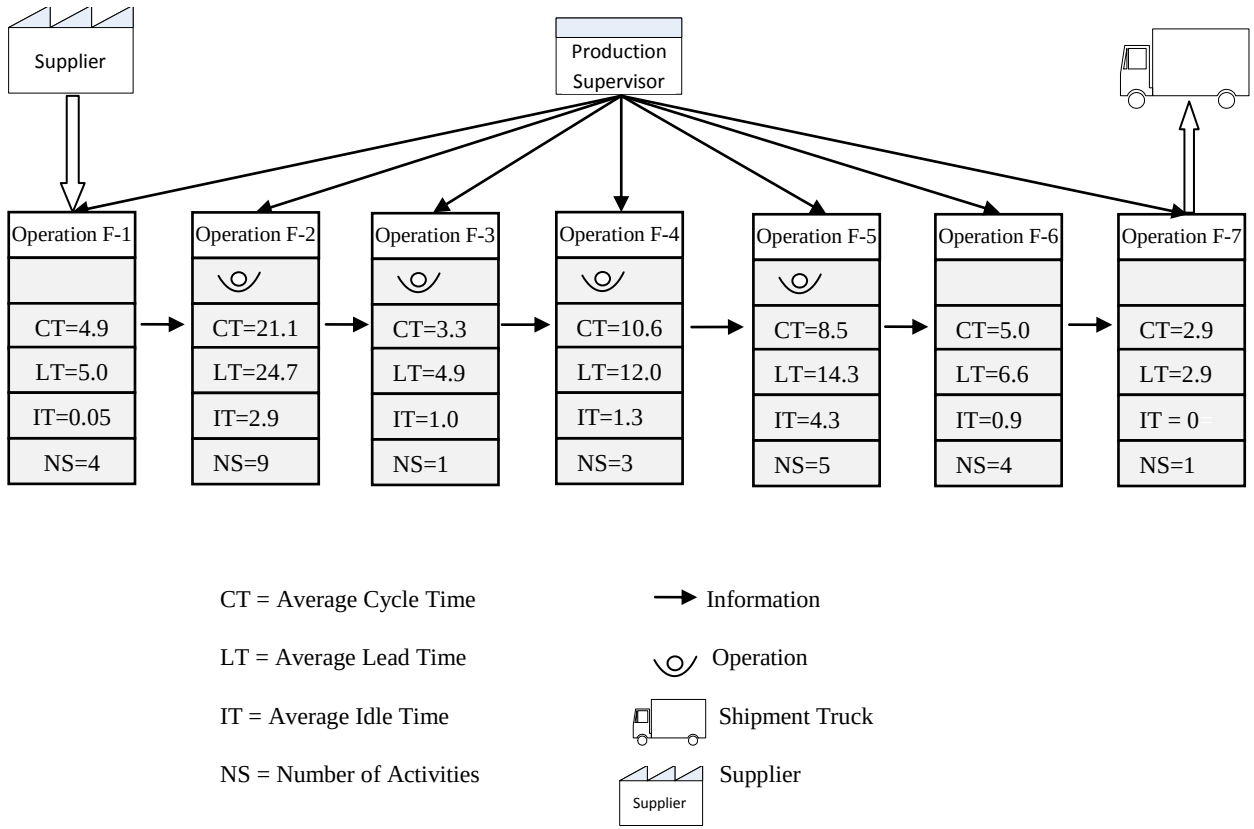


Figure 3- 5 VSM for the Floor Line

Based on information provided in the value stream maps and also the author's observations, several problems can be recognized in the wall line:

- Panel waiting times are longer before station W8 due to its longer cycle time when compared to previous stations (W5, 6, and 7).
- The line bottleneck seems to exist at station W8 and W9_2 as they have the longest cycle times.
- Although station W8 is a possible bottleneck, it also has the longest idle time, because the last operation conducted on short and long interior wall panels was completed in station W3.
- Rework is another form of waste observed during data collection. Usually panels are checked for errors using drawings at stations W7 and W9-2. In the case of any missing I-bolts or hangers, the responsible worker completes the installations at station W7 instead of station W3. Similarly, if any defect is identified at station W9_2, the workers fix it at this station, which increases processing time. These shortcomings can be resolved by providing further training sessions for new workers to minimize rework.

3.5. Issues with Value Stream Mapping

Although the VSM is an easy to learn tool which provides a high level analysis of the process and provides hints about wastes in the production line, it cannot represent the dynamic state of complex production systems with high customization and product variability (Wang, et al., 2009). There are two different methods of selecting a value stream (Tapping, et al., 2002): (1) product-quantity (PQ) analysis, and (2) product-routing (PR) analysis. The PQ method works based on the Pareto rule (80 percent of the total production volume is from 20 percent of the product types) and chooses a product type (or a limited set of product types) which accounts for 80% of the total production based on the production of the past months. In the PQ method the products with higher volume are the first target of value stream analysis.

But in systems with a low-volume and high-variety product mix, the Pareto rule rarely holds as each product has a low share in the total production volume. The PR method is an option in a case which groups the products with identical (or similar) process routes in one family and considers the product family with the highest aggregated production volume as the target of value stream analysis.

In the case of the floor and wall lines in Landmark Homes Company, neither of the PQ and PR methods fit with the specifications of the production process. Landmark Homes Company produces a wide range of houses with different sizes and designs. Furthermore, each house includes 35-60 wall panels of different sizes, each of which requires different operations based on the house design. The combination of house models and different panels in each house makes each panel (as the product unit in the value stream) unique.

As a result, each panel processing time is different at each activity and varies based on panel specifications. Although all panels pass through the whole process similarly (with the exception of interior walls), unique panel specifications (different house models, different panel sizes, and different panel specifications) cause a high variability between panel processing times in a station. The high variability also exists in a station's individual task times. As an example, for the 50 studied cycles for activity W8.3, the range (maximum task time – minimum task time) of the task times is 42.5 minutes (47.58 – 5.08).

The high task time variability makes the point estimates (such as the average of station times) an inaccurate representation of the actual station processing time. Also, due to high product variety and heterogeneity of the panels in the sample of studied panels, fitting statistical distributions for task times is not practical without a larger sample size.

To address the mentioned shortcomings, this thesis combines the collected time data with key design specifications of different panels in a data base and constructs regression models to estimate task times. The regression models estimate the task time of a panel given its panel design properties values. The panel design properties affecting task times and the regression models will be discussed in the next chapter. These regression models will be used in a simulation model in Chapter 5. Using the simulation model, and referring to the next month's production plan, the manager will be able to view actual problems (close to reality) of the line and subsequently, make appropriate decisions to resolve them.

Chapter 4

Statistical Analysis of Task Times

4.1.Overview

This chapter covers phases 2 and 3 of the proposed process flow improvement methodology of Figure 1- 1: “Design property and task time data base” and “Task time regression models” (Figure 4- 1). As discussed in the previous chapter, the detailed analysis of the process improvement opportunities in the floor and wall lines requires almost an exact estimation of the task times for different panels. As the house types and design properties of each panel are unique, relying on average task times or statistical distributions may result in misleading recommendations. Phases 2 and 3 perform statistical analysis of the task times through setting regression models to estimate task times of a panel based on its unique design specifications. These regression models will be used in Chapter 5 in the simulation model of the wall line.

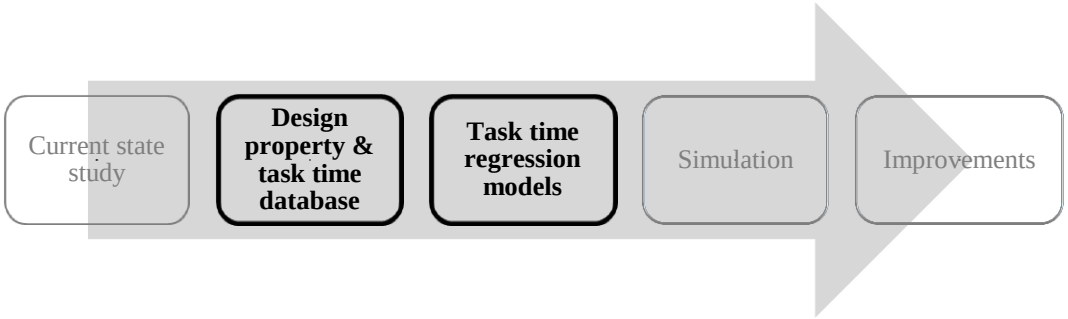


Figure 4- 1 Phases 2 & 3: Statistical Analysis of the Task Times

The results of Phase 2 is a database which includes design property values which affect the task times of panels studied in the time study and the collected task times for those panels. This database is used in Phase 3 to construct regression models for each task time based in the design properties.

4.2.Design Property & Task Time Database

This phase includes two main steps: (1) identifying panel design properties affecting task times, and (2) creating the database for design properties and task times. In the first step, design properties affecting the time of each activity are identified. Then, in the second step, identified design property values are extracted from the drawing files for the houses and panels for which the task times were recorded in the time study. The recorded task times and extracted information for the design properties are used to construct the database for statistical analysis.

4.2.1. Design Properties Affecting Activity Task Times

Stations activities are divided into two categories based on the variability observed in their task times: (1) activities with low variability in task times (CV[5] < 0.5), and (2) activities with high variability in task times (CV > 0.5) (Shaaban and Hudson, 2010). Some activities, such as loading a file into a machine at station W5, have almost constant duration or small variability in their task times in different cycles. The task times of these kinds of activities do not change significantly with house model and drawing specifications. In this case, the average task time is a good estimator of the actual task

[5] CV: Coefficient of variation is a measure which shows the extent of variability in task time with respect to the average task time, CV = standard deviation / mean.

times. Activities with low variable times for the floor and wall lines are listed in Table 4-1 and Table 4- 2, respectively.

Table 4- 1 Tasks with Low Variable Times (Floor Line)

Activity	Average Task Time (min.)
F-1	Avg (T_{F-1}) = 4.90
F-6	Avg (T_{F-6}) = 5.04
F-7	Avg (T_{F-7}) = 2.91

Table 4- 2 Activities with Low Variable Times (Wall Line)

Activity	Average Task Time (min.)
W1.1	Avg ($T_{W1.1}$) = 0.94
W1.2	Avg ($T_{W1.2-Window}$) = 4.75, Avg ($T_{W1.2-Interior\ Door}$) = 4.09, Avg ($T_{W1.2-Exterior\ Door}$) = 5.60, Avg ($T_{W1.2-Single\ Tall\ Wall}$) = 26.73, Avg ($T_{W1.2-Header\ of\ Garage\ Door}$) = 1.34
W1.3	Avg ($T_{W1.3}$) = 0.64
W2.1	Avg ($T_{W2.1-Garage\ Door}$) = 1.12, Avg ($T_{W2.1}$) = 1.89
W2.2	Avg ($T_{W2.2-Garage\ Door}$) = 1.22, Avg ($T_{W2.2}$) = 1.85
W2.4	Avg ($T_{W2.4-Garage\ Door}$) = 0.21, Avg ($T_{W2.4}$) = 0.21
W3.1	Avg ($T_{W3.1}$) = 0.47
W3.5	Avg ($T_{W3.5}$) = 1.73
W3.8	Avg ($T_{W3.8}$) = 0.28
W4.1	Avg ($T_{W4.1}$) = 0.55
W4.2	Avg ($T_{W4.2}$) = 0.92
W4.4	Avg ($T_{W4.5}$) = 1.00
W5.1	Avg ($T_{W5.1}$) = 0.81
W5.2	Avg ($T_{W5.2}$) = 1.96
W6.1	Avg ($T_{W6.1}$) = 0.5
W6.2	Avg ($T_{W6.2}$) = 0.5
W6.3	Avg ($T_{W6.3}$) = 0.35
W7.1	Avg ($T_{W7.1}$) = 0.5
W7.2	Avg ($T_{W7.2}$) = 0.5
W7.3	Avg ($T_{W7.3}$) = 0.35
W8.1	Avg ($T_{W8.1}$) = 0.47

W8.6	Avg ($T_{W8.6}$) = 0.35
W8.7	Avg ($T_{W8.7}$) = 8.92
W9-1.1	Avg ($T_{W9_1.1}$) = 0.75
W9-1.2	Avg ($T_{W9_1.2}$) = 0.35
W9-2.1	Avg ($T_{W9_2.1}$) = 0.55
W9-2.2	Avg ($T_{W9_2.2}$) = 1.65
W9-2.3	Avg ($T_{W9_2.3-Window}$) = 6.01, Avg ($T_{W9_2.3-Door}$) = 4.21
W9-2.4	Avg ($T_{W9_2.4-Window}$) = 1.48, Avg ($T_{W9_2.4-Door}$) = 6.01
W9-2.5	Avg ($T_{W9_2.5-Window}$) = 5.99, Avg ($T_{W9_2.5-Door}$) = 16.59
W9-2.6	Avg ($T_{W9_2.6}$) = 0.38
W9-3.1	Avg ($T_{W9_3.1}$) = 0.30
W9-3.2	Avg ($T_{W9_3.2}$) = 2.88
W9-3.3	Avg ($T_{W9_3.3-Window}$) = 4.53, Avg ($T_{W9_3.3-Door}$) = 7.03
W9-3.4	Avg ($T_{W9_3.4}$) = 1.89

The processing time of tasks with highly variable task times (CV > 0.5) are affected considerably by the design properties of panels. For these activities, possible panel design properties which affect task times were identified through directly observing the floor and wall lines, checking drawing files (CAD and WUP files), and interviewing line managers and the company's senior researcher (see Table 4- 3 and Table 4- 4 for a complete list of panel design properties affecting times of the floor and wall line tasks).

Table 4- 3 Possible Panel Design Properties Affecting Floor Line Task Times

Activity	Possible design Properties
F-2 Setting up a panel, adjusting and inspecting	• Number of joists • Number of rimboards • Number of beams (LSL, LVL) • Number of bracings • Number of double joists • Number of joist hangers • Total number of blocks (blockings+ squashed blocks+ Web Filler/web stiffness)
F-3 Prefixing OSBs (via multi-function bridge machine)	• Total glue length
F-4 Fixing OSBs	• Number of complete OSBs • Number of small OSBs
F-5 Finishing the panel (via multi-function bridge machine)	• Panel's perimeter • Total joist length

	• Total beam and rimboard length

Table 4- 4 Possible Panel Design Properties Affecting Wall Line Task Times

Activity	Possible design Properties
W2.3 Assemble wall panel	• Number of studs • Number of L-studs • Number of double studs and triple studs • Number of window openings • Number of door openings • Total number of openings
W3.2 Remove reinforcing strips at openings	• Number of openings
W3.3 Label walls	• Number of walls • Number of cut zones
W3.4 Drill holes +install I-bolts	• Number of I-bolts • Number of drill holes
W3.6 Separate 40' wall panel to multiple walls	• Number of short interior walls • Number of cut zones
W3.7 Take wall panels off the line	• Number of short interior walls
W4.3 Position sheathing material	• Number of sheathing
W5.3 Staple Sheathing	• Number of nails • Number of travel nails
W5.4 Route openings and wall edges	• Length of outline cut-out • Length of opening cut-out • Number of router travels
W5.5 Install exterior fireguard drywall	• Number of sheathing
W5.6 Fasten exterior fireguard drywall	• Number of screws • Number of screw travels
W5.7 Route openings and wall edges - exterior fireguard drywall	• Length of outline cut-out • Length of opening cut-out • Number of router travels
W8.2 Install stud covers	• Number of studs • Number of L-studs • Number of double studs and triple studs • Number of cut zones
W8.3 Spray foam insulation	• Number of studs • Number of multiple studs • Number of cut zones • Number of openings • Cut zone area • Opening area

W8.4 Clean spray gun	• Number of studs • Number of L-studs • Number of double studs and triple studs • Number of openings • Number of cut zones • Panel length
W8.5 Check required thickness and clean over spray & stud covers	• Number of studs • Number of L-studs • Number of double studs and triple studs • Number of openings • Number of cut zones
W9-2.2 Check framing for openings	• Number of openings
W9-2.3 Staple guard wrap	• Number of openings • Door opening perimeter • Window opening perimeter
W9-2.4 Take window/door to position	• Number of windows • Number of doors
W9-2.5 Install window/door	• Number of windows • Number of doors
W9-3.3 Install window/door cover	• Number of doors • Number of windows

4.2.2. "Panel Design Properties and Task Times" Database

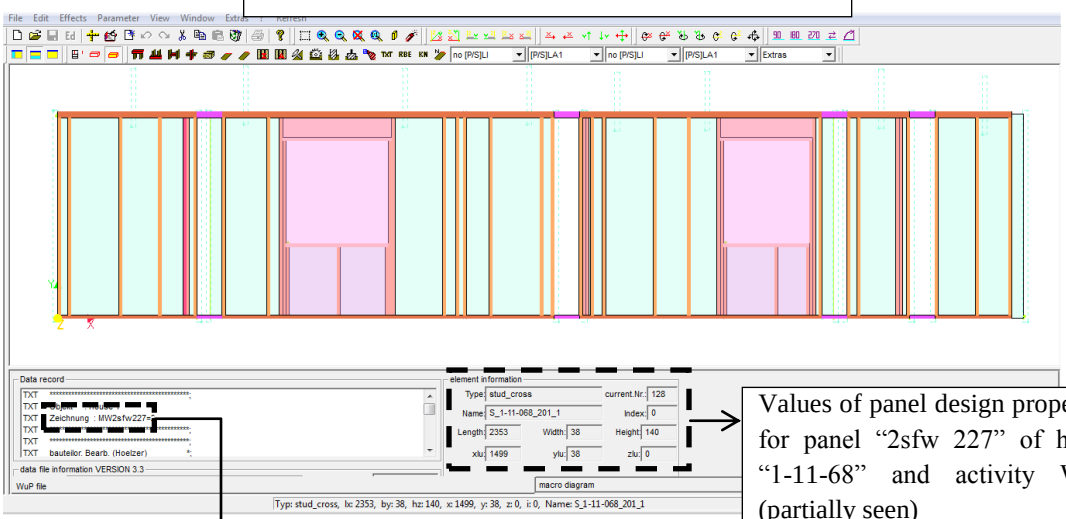
In order to implement statistical analysis on task times, a database is generated through extracting the values of the panel design properties (listed in Table 4- 3 and Table 4- 4) for panels that were considered in the time study. The values of the possible design properties affecting task times were extracted from the WUP drawing files of the panels. This database includes:

- Task times of all activities in the floor and wall lines for the time studied panels (50 task times for each activity)
- Values of the panel design properties extracted from the WUP files for each activity and each panel considered in the time study

Figure 4- 2 partially presents how the "panel design properties and task times" database for activity W8.3 (as an example) is constructed. For each of the activities with high variable task times (listed in Table 4- 3 andTable 4- **4**), a database similar to the data base of Figure 4- 2 was prepared considering the specific panel design properties which affect the task time of each activity. In the next phase, database is used to run regression models

to identify and validate the statistically significant design properties. The statistically significant panel design properties are included in the regression models to estimate task times.

WUP file for panel “2sfw 227” of house “1-11-68”



Values of panel design properties for panel “2sfw 227” of house “1-11-68” and activity W8.3 (partially seen)

Time study

Database for activity W8.3

Cycle #	House #	Panel #	Task time (min)	# of studs	# of multiple studs	# of cut zones	# of openings	Cut zone area (m2)	Opening area (m2)
1	1-11-068	2sfw 227	47.58	25	4	4	2	0.54	2.85
2	1-11-068	2sfw 229	38.65	19	2	2	1	0.54	0.89
3	1-11-068	2sfw 231	6.58	4	1	0	1	0.00	1.93
4	1-11-068	2sfw 230	34.50	22	0	1	2	0.54	1.55
5	1-11-068	1mfw 140	22.51	15	3	2	3	0.61	3.36
6	1-11-068	1mfw 138	15.42	12	1	3	3	0.71	1.92
…	…	…	…	…	…	…	…	…	…
49	2-11-717	1mfw 119	17.66	24	5	4	0	0.53	0
50	1-11-136	2sfw 234	33.5	14	0	2	2	0.59	4.43

Figure 4- 2 “Panel Design Properties and Task Times” Database for Activity W8.3

4.3. Task Time Regression Models

In this section, a regression model is formulated for each activity (with high variable task times) to explain the effects of panel design properties (listed in Table 4- 3 and Table 4- 4) on that activity’s task time. The task time of an activity is considered the dependent variable and the panel design properties affecting task times of that activity are

independent variables in the regression model the activity's task time. The SmartReg Excel add-in is used to perform regression analysis based on the "Panel Design Properties and Task Times" data base constructed for each activity explained in Section 4.2.2 (Figure 4- 2). The regression model of an activity can later be used to predict the task time of a panel for that activity through knowing the specific design information about that panel. In this thesis, task time regression models will be used in the simulation model of the production line to determine the task times of a panel for different activities by extracting the values of the design properties from the panel WUP file and replacing them in the regression models. Activity W8.3 is chosen as an example to illustrate the material in this section. This phase includes two steps:

1. Constructing full regression models: A "full regression model" of the task time of an activity is a model which considers all possible panel design properties for that activity (listed in Table 4- 3 and Table 4- 4) as independent variables. The regression models are formulated based on the information gathered in the task time and design property database. As an example, the SmartReg output for the regression model of the task time of activity W8.3 is shown in Figure 4- 3 where panel design properties x_S, x_{MS}, x_O, x_C, x_{OA}, and x_{CA} denote number of studs, number of multiple studs, number of openings, number of cut zones, opening (doors and windows) area (m^2), and cut zone area (m^2), respectively. The adjusted coefficient of determination (adjusted R^2) of 0.79 shows that 79% of the variation in the task time of activity W8.3 is explained by variation in the value of the six panel design properties. Based on the output, the full regression model for task time of activity W8.3 ($T_{W8.3}$) is formulated as,

$$T_{W8.3} = 2.06\, x_S + 1.14\, x_{MS} + 4.97\, x_O - 3.62\, x_C + 0.86\, x_{OA} - 8.5\, x_{CA} - 5.51. \quad (4.1)$$

To interpret equation (4.1), the coefficients for x_S, x_{MS}, and x_O show that one more stud, multiple stud, and opening (window or door) in a panel have separate effects on increasing average panel task time for activity W8.3 by 2.06, 1.14 and 4.97 minutes, respectively. The coefficient for x_C is negative which implies that as the number of cut zones in a panel increases by one, the panel task time for activity W8.3 decreases by 3.62 minutes on average, as the required amount of spray work is reduced. For the same reason, the task time decreases with the cut zone area by 8.5 minutes per square meter.

Finally, the coefficient for x_{OA} suggest that each extra square meter of opening area (windows and doors area) increases the task time by 0.86 minute.

Regression Statistics									
Multiple R	0.917								
R Square	0.841								
Adjusted R Square	0.791								
Standard Error	6.295								
Observations	50								
ANOVA									
	df	SS	MS	F	Significance F				
Regression	6	3986.349	664.392	37.96	1.13761E-06				
Residual	43	752.910	17.50						
Total	49	4739.259							
	Coefficients	Standard Error	t Stat	P-value	95% LL	95% UL	VIF	Q	P-value (Q)
Intercept	-5.51	3.904	-1.412	0.174	-13.680	2.660			
XS	2.06	0.416	4.937	0.000	1.184	2.927	4.865	1.977	0.048
XMS	1.14	1.074	1.061	0.302	-1.109	3.388	1.896	1.117	0.264
XO	4.97	2.305	2.157	0.044	0.148	9.798	4.647	0.207	0.836
XC	-3.62	1.914	-1.866	0.034	-7.630	0.381	3.757	1.748	0.080
XOA (m2)	0.86	1.008	0.855	0.403	-1.247	2.971	7.101	0.345	0.730
XCA (m2)	-8.50	13.198	-0.644	0.527	-36.120	19.126	9.159	0.731	0.465

Figure 4- 3 Full Regression Model for Activity W8.3 Task Time

In a regression model, the individual t-tests for each independent variable (each of the design properties) determines whether the independent variable has statistically significant effect on the dependent variable (task time). SmartReg provides information about the t-tests and the related P-values (in columns “t Stat” and “P-value”). If the P-value of the t-test for an independent variable is greater than the significance level (α), the independent variable does not have significant effect on explaining the dependent variable, suggesting that removing the independent variable from the model does not have negative impact on the exploratory power of the model. In this thesis, the significance level of 0.05 (α = 0.05) is considered for the regression models as it is the common value used in statistical analysis.

The p-values for the individual t-tests of the regression Model (4.1) show that panel design properties x_{MS} (number of multiple studs), x_{OA} (opening area), and x_{CA} (cut zone area) are not statistically significant at the significance level of 0.05 (α = 0.05) as the p-values for their t-tests (0.302, 0.403, and 0.527, respectively) are greater than 0.05. In the

final regression models, the insignificant design properties are removed and new regression models are formulated based on the significant panel design properties.

2. Constructing final regression models: After obtaining the full regression model results for the task time of an activity, the "Backward Elimination" method is applied to remove those panel design properties which do not explain task time variability. The resulting end model is called the "reduced" model. The reduced model includes a subset of the panel design properties of the full regression which are statistically significant. There are several reasons to use the reduced model instead of the full model of the activity task time (Faraway, 2005):

- The reduced model explains the relation between panel design properties and task time in the simplest form through removing redundant properties from the independent variables. For example, when predicting the task time of activity W8.3, both x_O (number of openings) and x_{OA} (opening area) may provide the same information, suggesting one might be redundant.
- Unnecessary independent variables inaccurately estimate the effect of other independent variables on the dependent variable. A smaller model can achieve more precise estimates for the necessary independent variables.
- Too many independent variables trying to explain the same type of effect in a regression model leads to collinearity. Collinearity occurs when there is a correlation between the independent variables. When a model experiences collinearity, the independent variables' coefficients are not reliable and might be misleading. Using the previous example, there is significant correlation between x_O (number of openings) and x_{OA} (opening area) which may cause collinearity in the model if both are considered.
- Analysis of regression models with more independent variables (design properties) are more time consuming as it requires more work to extract data from the WUP files. Validating regression models with a greater number of independent variables is not easy. Reduced models save time.

The Backward Elimination method starts with all independent variables in the regression model and then removes the independent variables with a highest t-test P-value greater than the significance level (α). Next, it refits the model and removes the remaining least

significant independent variables with P-value > α. With this iterative algorithm, all of the insignificant independent variables will be removed.

Figure 4- 4 shows the SmartReg output of the Backward Elimination method for the regression model of activity W8.3's task time. The output includes six models and reports the P-value for the partial F-tests ("P(Partial F)" column). Each row presents the results of the elimination procedure. For example, the row "XCA (m2)" includes the P-values of the t-tests (P(XS), P(XO), P(XC), P(XMS), P(XOA (m2)), and P(XCA (m2))) of the full regression model through including all the panel design properties. These P-values are the same as the ones under the "P-value" column of Figure 4- 3. As shown, the P-value for "XCA (m2)" is the largest P-value in the first row suggesting that it contributes least among the panel design properties to explaining the task time of activity W8.3. The "P(Partial F)" column shows whether removing the design property of each row has a significant negative effect on the reduced model of that row. If the P-value for the partial F-test is greater than the significance level (α), removing the design property of that row does not cause any problem for the regression model. The design properties are removed from the model until a P-value of smaller than α is achieved for one of the models. So, based on the below output, the Backward Elimination method recommends removing panel design properties x_{MS} (number of multiple studs), x_{OA} (opening area), and x_{CA} (cut zone area) from the full model and keeping properties x_S (number of studs), x_O(number of openings), and x_C (number of cut zones) in the final regression model.

Backward Stepwise Regression

Variable	R Squared	P(Partial F)	P(Intercept)	P(XS)	P(XO)	P(XC)	P(XMS)	P(XOA (m2))	P(XCA (m2))
XCA (m2)	0.841	0.527	0.174	0.000	0.044	0.034	0.302	0.403	0.527
XOA (m2)	0.838	0.551	0.217	0.000	0.049	0.034	0.328	0.551	
XMS	0.835	0.346	0.266	0.000	0.000	0.036	0.346		
XC	0.827	0.044	0.290	0.000	0.000	0.044			
XO	0.791	0.003	0.936	0.000	0.003				
XS	0.689	0.000	0.641	0.000					

P-value for the partial F-tests > α

P-value for the partial F-tests < α

Figure 4- 4 Backward Elimination Method Result for Regression Model of Activity W8-3

Figure 4- 5 presents the result for the final regression model for activity W8.3's task time including panel design properties x_S (number of studs), x_O(number of openings), and x_C (number of cut zones). The adjusted coefficient of determination (adjusted R2) of 0.804, which has increased from the full model, shows that 80% of the task time variation of activity W8.3 is explained by variation in the value of the three panel design properties.

Regression Statistics	
Multiple R	0.910
R Square	0.827
Adjusted R Square	0.804
Standard Error	6.098
Observations	50

ANOVA

	df	SS	MS	F	Significance F
Regression	3	3921.087	1307.029	73.51	1.44072E-08
Residual	46	818.172	17.78		
Total	49	4739.259			

	Coefficients	Standard Error	t Stat	P-value	95% LL	95% UL	VIF	Q	P-value (Q)
Intercept	-3.02	2.785	-1.085	0.290	-8.799	2.754			
XS	1.95	0.261	7.480	0.000	1.411	2.494	2.039	1.901	0.057
XO	5.38	1.285	4.190	0.000	2.720	8.050	1.539	0.014	0.989
XC	-3.42	1.595	-2.142	0.044	-6.724	-0.108	2.782	1.193	0.233

Figure 4- 5 Final Regression Model for Activity W8.3 Task Time

Based on the output, the final regression model for the task time of activity W8.3 ($T_{W8.3}$) is formulated as,

$$T_{W8.3} = 1.95\, x_S + 5.38\, x_O - 3.42\, x_C - 3.02. \tag{4.2}$$

In equation (4.2), the coefficients for x_S show that one more stud in a panel increases the task time of activity W8.3 by 1.95 minutes on average. The average task time increases by 5.38 minutes for one more window or door opening (x_O). However, the task time decreases by 3.42 minutes as the number of cut zones (x_C) increase by one, as the required amount of spray work is reduced. Figure 4- 6 summarizes the steps explained in the previous pages to find the final regression model for the task time of activity W8.3. The final regression models for the task times of all floor and wall lines activities (the ones with highly variables task times) are presented in Table 4- 5 and Table 4- 6, respectively.

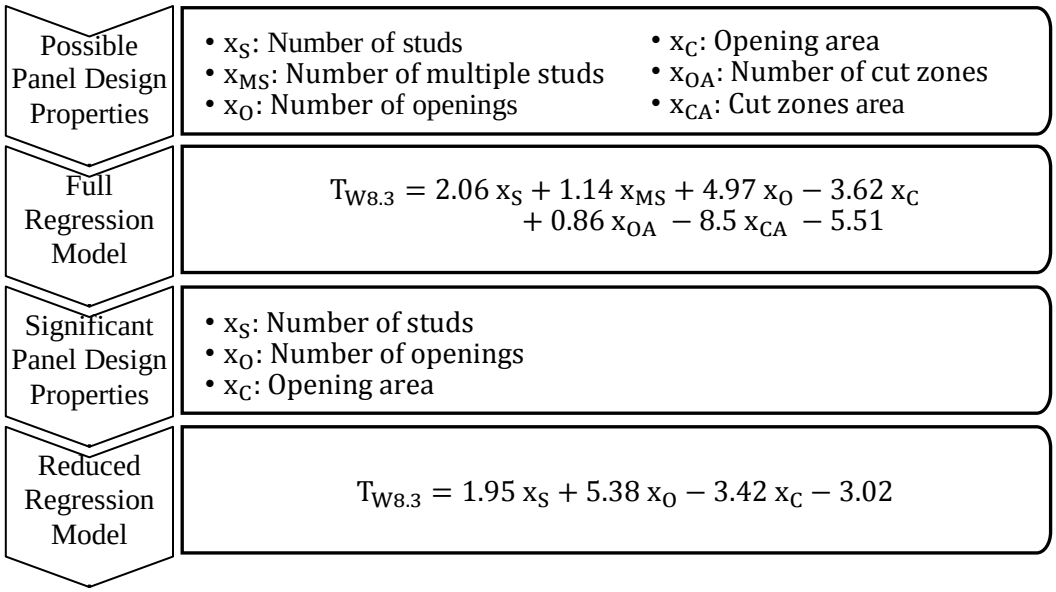


Figure 4- 6 Steps to Derive Final Regression Models for Activity Task Times (example, Activity W8.3)

Table 4- 5 Regression Models for Activities with High Variable Task Times (Floor Line)

Activity	Task Time Regression Models
F-2	$T_{F2} = -3.89\, X_J + 2.59\, X_R - 7.31$ X_J = Number of joists, X_R = Number of rimboards
F-3	$T_{F3} = 0.01\, X_{LG} + 1.12$ X_{LG} = Total glue length
F-4	$T_{F4} = 0.14\, X_{FSh} + 0.51\, X_{PSh} + 7.28$ X_{FSh} = Number of full sheathing, X_{PSh} = Number of partial sheathing
F-5	$T_{F5} = 0.07\, X_{PP} - 0.0048\, X_{LJ} + 1.018\, X_{B\&RL} + 3.47$ X_{PP} = Perimeter of panel, X_{LJ} = Total joists length, $X_{B\&RL}$ = Total beam and rimboard length

Table 4- 6 Regression Models for Activities with High Variable Task Times (Wall Line)

Activity	Task Time Regression Models
W2.3	$T_{W2.3} = 0.22\, x_S + 1.11\, x_{MS} + 1.92\, x_O + 1.92$ x_S: Number of studs, x_{MS}: Number of multiple studs (L-studs, double studs, triple studs), x_O: Number of openings
W3.2	$T_{W3.2} = 0.34\, x_O + 0.08$ x_O: Number of openings
W3.3	$T_{W3.3} = 0.56\, x_W + 0.43$ x_W: Total number of walls
W3.4	$T_{W3.4} = 0.82\, x_H + 0.11$ x_H: Number of drill holes
W3.6	$T_{W3.6} = 0.94\, x_C + 0.69$ x_C: Number of cut zones
W3.7	$T_{W3.4} = 0.36\, x_{Int.W} + 1.01$ $x_{Int.W}$: Number of short interior walls
W4.3	$T_{W4.3} = 1.03\, x_{SH} + 3.31$ x_{SH}: Number of sheathing (full and partial)
W5.3	$T_{W5,3} = 0.08\, x_N + 2.44$ x_N: Number of (100) nails
W5.4	$T_{W5,4} = 3e-05\, x_{OL} + 3e-05\, x_{OpL} + 0.025\, x_T + 0.09$ x_{OL}: Outline length (mm), x_{OpL}: Opening length (mm), x_{RT}: Number of router travel
W5.5	$T_{W5.5} = 1.03\, x_{SH} + 3.31$ x_{SH}: Number of sheathing
W5.6	$T_{W5,6} = 0.10\, x_S + 2.29$ x_S: Number of (100) screws
W5.7	$T_{W5,7} = 3e-05\, x_{OL} + 3e-05\, x_{OpL} + 0.025\, x_T + 0.09$ x_{OL}: Outline length (mm), x_{OpL}: Opening length (mm), x_{RT}: Number of router travel
W8.2	$T_{W8.2} = 0.02\, x_S + 1.11$ x_S: Number of studs
W8.3	$T_{W8.3} = 1.98\, x_S + 5.83\, x_O - 3.42\, x_C - 3.02$ x_S: Number of studs, x_O: Number of openings, x_C: Number of cut zones
W8.4	$T_{W8.4} = 0.24\, x_{PL} + 1.19$ x_{PL}: Panel length (meter)
W8.5	$T_{W8.5} = 0.58\, x_{S\&MS} + 3.45$ $x_{S\&MS}$: Total number of studs and multiple studs (L-studs, double studs, triple studs)

The following assumptions of linear models were checked and validated for the derived regression models (Winston & Albright, 2009):

1. **Outliers:** An outlier is a data point (a task time) that is unusual in comparison with the other data points (task times). In other words, an outlier task time does not fit the pattern of other task times. The presence of one or more outliers in the task time data increases the error of the task time regression models. So, the presence of possible outliers was checked for the task times collected in the time study. The possible reasons for an outlier need to be investigated. The outlier time data was removed from the task time data set if the reason was related to error in collecting times, unusual line stoppages, and unusual process interruptions. The method of identifying outliers in the Excel regression output is to check the values in column "Standard Residuals" of the "Residual OUTPUT" table of the regression results. For the regression model of Activity W8.3 task time, the residual output table is shown partially in Figure 4- 7 for the first 10 collected time data. If the value of the standard residual for a task time is less than -2 or greater than +2, the task time is considered a possible outlier. In Figure 4- 7, there is no sign for an outlier task time data for the first 10 observations.

RESIDUAL OUTPUT

Observation	Predicted TW8.3 (min)	Residuals	Standard Residuals
1	42.611	4.973	0.906
2	30.869	7.781	1.418
3	9.344	-2.760	-0.503
4	45.062	-10.562	-1.925
5	36.994	-1.484	-0.270
6	27.526	4.890	0.891
7	40.396	2.934	0.535
8	9.763	-1.680	-0.306
9	10.932	-2.265	-0.413
10	10.932	-1.765	-0.322
…	…	…	…

Figure 4- 7 Checking Possible Outliers in Task Time Data

2. **Collinearity:** In a regression model, all the independent variables must be independent from each other. If the independent variables (panel design properties) are highly correlated, the regression model suffers Collinearity, meaning that each of

these variables does not have separate influence on the dependent variable (task time of an activity). Collinearity can lead to "wrong" signs for the regression coefficients. The signs of the coefficients for the independent variables can be the opposite of what intuition about the effect of panel design properties might suggest. For example, the resulted regression model of activity W5.3 (staple sheathing) with its two possible design properties, "number of nails" and "number of travel nails"[6], is:

$$T_{W5,3} = 0.09\, x_N - 0.01\, x_{TN} + 2.43$$

x_N: Number of (100) nails

x_{TN}: Number of (100) travel nails

In the above example, the sign for the coefficient of "number of travel nails" is incorrect, since the above equation shows that with an increase in number of travels, the task time decreases. The reason for this wrong sign is the 85% correlation between "number of nails" and "number of travel nails". The correct model must include only one of the variables as:

$$T_{W5,3} = 0.08\, x_N + 2.44$$

The way to check collinearity involves checking the Variance Inflation Factor (VIF) values in the SmartReg output (see Figure 4- 5). If VIF > 5 for one of the independent variables, there is a sign for the presence of collinearity. In the output of Figure 4- 5, the three VIF values for the three panel design properties (independent variables) are 2.039, 1.539, and 2.782 which do not indicate collinearity in Model 4.2.

3. **Linear Relationship:** If the scatterplot of dependent variables (task times) versus independent variables (panel design properties) indicate nonlinear relationships, then the assumed linear relationship will lead to poor task time fits and poor predictions. For each task time, the linear relation between the task time and each of the panel design properties were checked by the visual inspection of plots similar to the plot in Figure 4- 8. Figure 4- 8 depicts the scatter plot of the task time of activity W8.3 versus number of studs (as one of the panel design properties affecting the task time of activity W8.3). The plot does not show any violation of the linear relationship

[6] The number of travels that the nail gun of the multi-function bridge machine needs to travel over the panel to nail. Every one hundred travels are considered one unit.

assumption. None of the task times for activities in table 4-5 and 4-6 required nonlinear regression models.

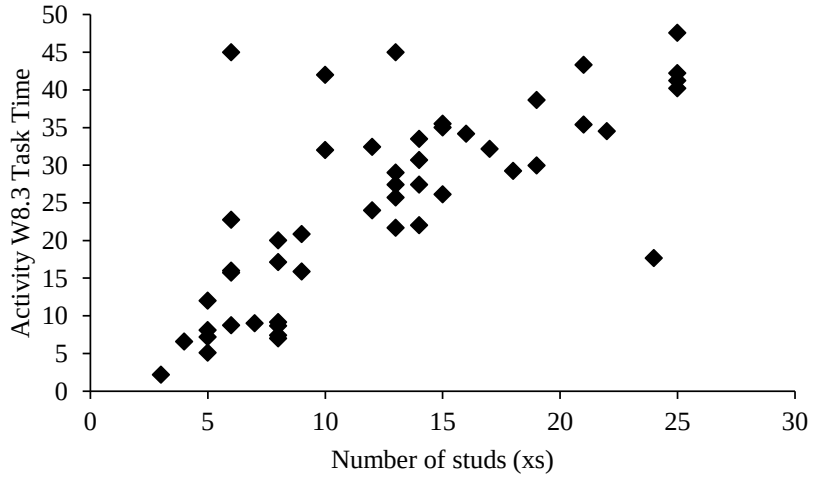


Figure 4- 8 Scatter Plot of Activity W8.3 Task Times versus Number of Studs

4.4. Uncertainty in Task Times

The regression lines do not consider uncertainty in the task times, meaning that for two identical panels (the same panel design properties) the regression model of an activity predicts the same task times. This result is far from reality, as in the real situation, task times are affected by other factors, such as worker performance, line stoppages, and machine breakdowns. To consider the uncertainty in the task times, the "residuals" of each regression model were used.

The difference between the actual data point and the regression model's prediction for that data point is called the "residual". For example, assuming that the regression model of W8.3 includes only one design property, the difference between points A and B in Figure 4- 9 is the residual for task time of activity W8.3 recorded in Cycle 18. When there is more than one design property, the same concept holds, although it cannot be presented graphically. For each regression model, SmartReg provides residuals of each data point as shown in Figure 4- 7. For each regression model in Table 4- 6, the distribution of the residuals was approximated through Triangular distribution, using @Risk Excel add-in, and added to the regression model. Then the uncertainty in task times was incorporated into the regression models. It is important to note that the distribution of the residuals in a linear regression model follows a normal distribution.

However, since normal distribution is unlimited and there is a possibility of obtaining negative task times, this thesis approximated the distribution of the residuals through triangular distribution. Table 4- 7 shows the final regression models incorporating task time uncertainties.

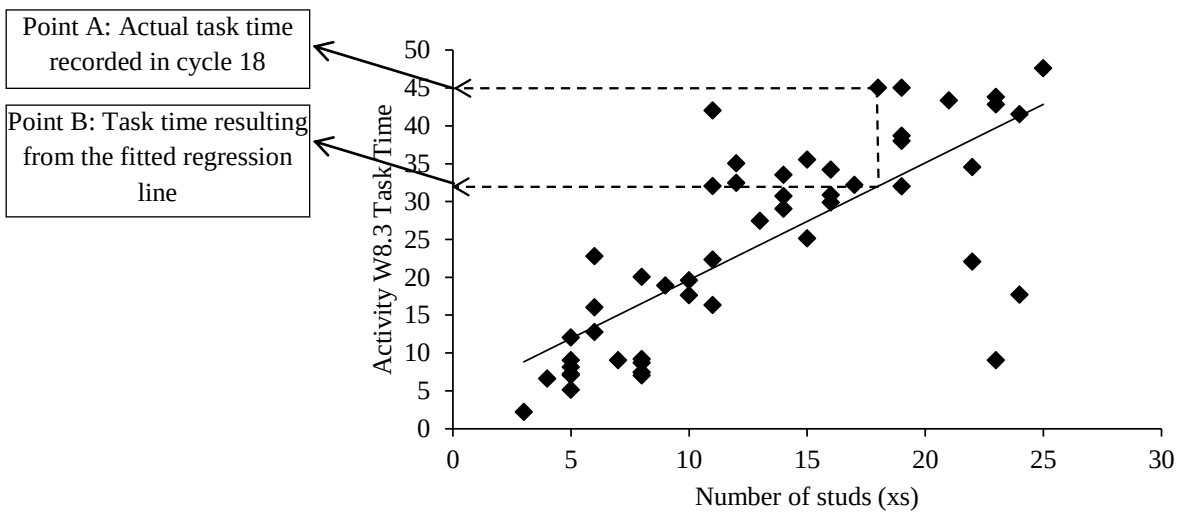


Figure 4- 9 Residual of a Data Point

Table 4- 7 Regression Models Considering Task Time Uncertainty

Activity	Task Time Regression Models
W2.3	$T_{W2.3} = 0.22\, x_S + 1.11\, x_{MS} + 1.92\, x_O + 1.92 + Tri.Dist\ (-3.2, -2.2, 3.5)$ x_S: Number of studs, x_{MS}: Number of multiple studs (L-studs, double studs, triple studs), x_O: Number of openings
W3.2	$T_{W3.2} = 0.34\, x_O + 0.08 + Tri.Dist\ (-1.5, 0.1, 1.9)$ x_O: Number of openings
W3.3	$T_{W3.3} = 0.56\, x_W + 0.43 + Tri.Dist\ (-1.8, -0.5, 3.7)$ x_W: Total number of walls
W3.4	$T_{W3.4} = 0.82\, x_H + 0.11 + Tri.Dist\ (-2.3, -0.1, 4.2)$ x_H: Number of drill holes
W3.6	$T_{W3.6} = 0.94\, x_C + 0.69 + Tri.Dist\ (-1.2, -0.4, 2.8)$ x_C: Number of cut zones
W3.7	$T_{W3.4} = 0.36\, x_{Int.W} + 1.01 + Tri.Dist\ (-2.9, -1.1, 3.7)$

	$x_{Int.W}$: Number of short interior walls
W4.3	$T_{W4.3} = 1.03\, x_{SH} + 3.31 + Tri.Dist\ (-4.4,0.1,3.7)$ x_{SH}: Number of sheathing (full and partial)
W5.3	$T_{W5,3} = 0.08\, x_N + 2.44 + Tri.Dist\ (-0.5,0.2,0.6)$ x_N: Number of (100) nails
W5.4	$T_{W5,4} = 3e-05\, x_{OL} + 3e-05\, x_{OpL} + 0.025\, x_T + 0.09 + Tri.Dist\ (-0.2,0.4,0.9)$ x_{OL}: Outline length (mm), x_{OpL}: Opening length (mm), x_{RT}: Number of router travel
W5.5	$T_{W5.5} = 1.03\, x_{SH} + 3.31 + Tri.Dist\ (-1.2,0.5,1)$ x_{SH}: Number of sheathing
W5.6	$T_{W5,6} = 0.10\, x_S + 2.29 + Tri.Dist\ (-0.8,-0.1,0.4)$ x_S: Number of (100) screws
W5.7	$T_{W5,7} = 3e-05\, x_{OL} + 3e-05\, x_{OpL} + 0.025\, x_T + 0.09 + Tri.Dist\ (-0.6,0.1,0.3)$ x_{OL}: Outline length (mm), x_{OpL}: Opening length (mm), x_{RT}: Number of router travel
W8.2	$T_{W8.2} = 0.02\, x_S + 1.11 + Tri.Dist\ (-0.8,-0.8,2.2)$ x_S: Number of studs
W8.3	$T_{W8.3} = 1.98\, x_S + 5.83\, x_O - 3.42\, x_C - 3.02 + Tri.Dist\ (-8.4,3.2,5.3)$ x_S: Number of studs, x_O: Number of openings, x_C: Number of cut zones
W8.4	$T_{W8.4} = 0.24\, x_{PL} + 1.19 + Tri.Dist\ (-1.6,1.2,3.3)$ x_{PL}: Panel length (meter)
W8.5	$T_{W8.5} = 0.58\, x_{S\&MS} + 3.45 + Tri.Dist\ (-1.2,0.8,2.1)$ $x_{S\&MS}$: Total number of studs and multiple studs (L-studs, double studs, triple studs)

Chapter 5

Process Flow Improvement Using Simulation

5.1.Overview

In this section, phases 4 and 5 of the proposed methodology are explained (Figure 5- 1). In phase 4, the PrefabSim simulation software, developed by National Research Council of Canada (NRC) exclusively for the wall lines of Landmark Homes Co., is presented and validated against actual data. The task times as input in the software are determined by the regression formulas derived in Chapter 4. In phase 5, the bottlenecks of the wall line are identified and improvement plans are proposed to increase the throughput of the line by decreasing station waiting and idle times and reducing the average house completion time. Different improvement plans are compared to the current system state in the simulation model. The end results show that the proposed improvement plans can reduce the completion time of a house by 16%.

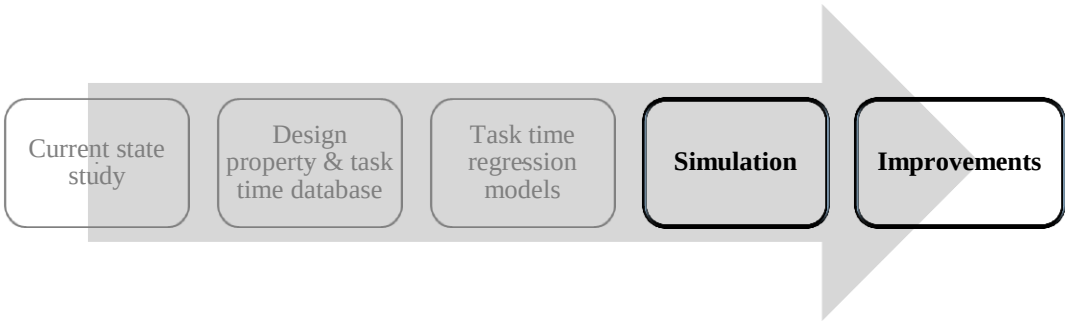


Figure 5- 1 Phases 4 & 5: Simulation and Process Flow Improvements

5.2.Simulation Model Development

Simulation models are useful in verifying and validating wall line improvements prior to actual implementation. The Landmark Shop Floor Simulation Program (PrefabSim) is developed by the National Research Council of Canada (NRC) to simulate the production flow of floor and wall panels in the Landmark Homes Company. This program calculates an individual task time for every panel it passes through using task time formulations described in Chapter 4 considering the configuration information of panel design specifications. The following section briefly explains different components of this program.

5.2.1. Input

The required inputs for the simulation software include: (1) panel type, (2) panel design properties, (3) task time formulas, and (4) the sequence of panels entering the production line. Each individual panel type has its own process flow with a corresponding task list and task times in each station. The design properties of each panel of a house (derived in Chapter 4) are extracted from the house's drawing files (WUP files) and stored in an Excel spreadsheet. Figure 5- 2 shows the panel property file for a sample house. The panel property file is used during the simulation to generate task times according to the specifications of each panel and task time formulas derived in Chapter 4. The task time formulas can be entered as shown in Figure 5- 3.

5.2.2. Presentation and Logic

The default view after running the model is the animation/presentation view Figure 5- 4. Other views, including Animation, Model Logic, Panel Line, Short Rail, Long Rail, and Floor Line, can also be selected. Panels are identified by IDs which are represented as rectangles inside the stations.

This software is developed on the AnyLogic 6 simulation application. The model logic is viewed in the simulation model view as shown in Figure 5- 5. Here, individual objects can be inspected to obtain detailed information on their current state. Panel flows are controlled by the simulation model, configuration database, and panel property files. Panel task times are calculated according to the panel property file (Figure 5- 2) and task time formulas derived in Chapter 4, and are entered in the input screen of Figure 5- 3.

Sequence	HouseID	PanelNumber	PanelType	Length	Height	NumDoors	NumWindows	NumStuds	NumLStuds	NumDrillHoles	NumBlocks	NumCutZones	NumWalls	NumOpenings	NumSheetsFu
1	1-11-068	1mfw138	EXT	10650	2772	2	1	15	1	8	0	3	4	0	
3	1-11-068	2sfw233	INT_L	11346	2467	3	0	22	0	0	0	1	2	0	
4	1-11-068	1mfw139	EXT	12095	2772	1	0	22	4	8	0	1	2	0	
5	1-11-068	1mfw140	EXT	10947	2772	0	2	17	3	7	7	2	3	0	
6	1-11-068	2sfw235	INT_L	11313	2467	3	0	21	0	0	4	2	3	0	
7	1-11-068	2sfw227	EXT	11395	2467	0	2	25	3	8	0	4	5	0	
8	1-11-068	1mfw123	INT	702	2772	0	0	4	0	0	0	0	1	0	
9	1-11-068	2sfw229	EXT	11709	2467	0	1	19	2	8	0	2	3	0	
10	1-11-068	2sfw234	INT_L	11972	2467	3	0	24	0	0	3	5	6	0	
11	1-11-068	2sfw230	EXT	10489	2467	0	1	22	2	5	0	1	2	0	
12	1-11-068	2sfw228	EXT	12175	2467	0	1	20	2	7	0	1	2	0	
13	1-11-068	1mfw141	INT	2197	2772	1	1	2	0	2	0	0	1	0	
14	1-11-068	2sfw231	EXT	3054	2467	0	1	4	0	2	0	0	1	0	
15	1-11-068	1mfw125	INT	702	2772	0	0	4	0	0	0	0	1	0	
16	1-11-068	1mfw143	GAR	1819	2470	0	0	5	0	1	0	0	1	0	
17	1-11-068	1mfw118	INT_L	3267	2772	0	0	10	0	0	5	0	1	0	
18	1-11-068	2sfw232	INT_L	3305	2467	0	0	9	0	2	0	0	1	0	
19	1-11-068	1mfw146	GAR	4267	2788	0	0	7	0	3	0	0	1	0	

Figure 5- 2 Panel Property File

ID	StationId	TaskId	TaskName	Reference	Conditions	Operator	ConstantNum	UnitTime1	TimeFactor1
58	W8_1	10	Move wall panel into the station	8.1		0	0.5		
64	W8_1	15	Install studs covers	8.2		0	1.2		
59	W8_1	20	Spray foam insulation	8.3		0	-3.02	1.95	numStuds
60	W8_1	30	Clean spray gun	8.4	unit: mm	0	1.2	0.00025	length
61	W8_1	40	Check quality and clean over spray	8.5		0	0.5	0.6	numStuds
62	W8_1	50	Move panel out to tilting table	8.6		0	0.3		
63	W8_1	60	Site cleaning (for every three panels)	8.7	should be 9 for every three panels, assign 0 , model it in simulation model	0	0		
65	W8_1	80				0			
66	W8_1	90				0			
67	W8_1	100				0			
68	W8_2	10	Move wall panel into the station	8.1		0	0.5		
74	W8_2	15	Install studs covers	8.15		0	1.2		
69	W8_2	20	Spray foam insulation	8.2		0		1.6	numStuds
70	W8_2	30	Clean spray gun	8.3		0	1.2	0.00025	length
71	W8_2	40	Check quality and clean over spray	8.4		0	0.5	0.6	numStuds

ID:	59	Station Id:	W8_1
Task Id:	20	Task Name:	Spray foam insulatior
Conditions:		Reference:	8.3
Operator:	0	ConstantNum:	-3.02
Unit Time 1:	1.95	Time Factor 1:	numStuds
Unit Time 2:	5.83	Time Factor 2:	numOpenings
Unit Time 3:	-3.42	Time Factor 3:	numCutZones

W8-3 Task Time Regression Formula

Figure 5- 3 Task Time Regression Formulas in The Simulation Software (example, Task Time for Activity W2.3)

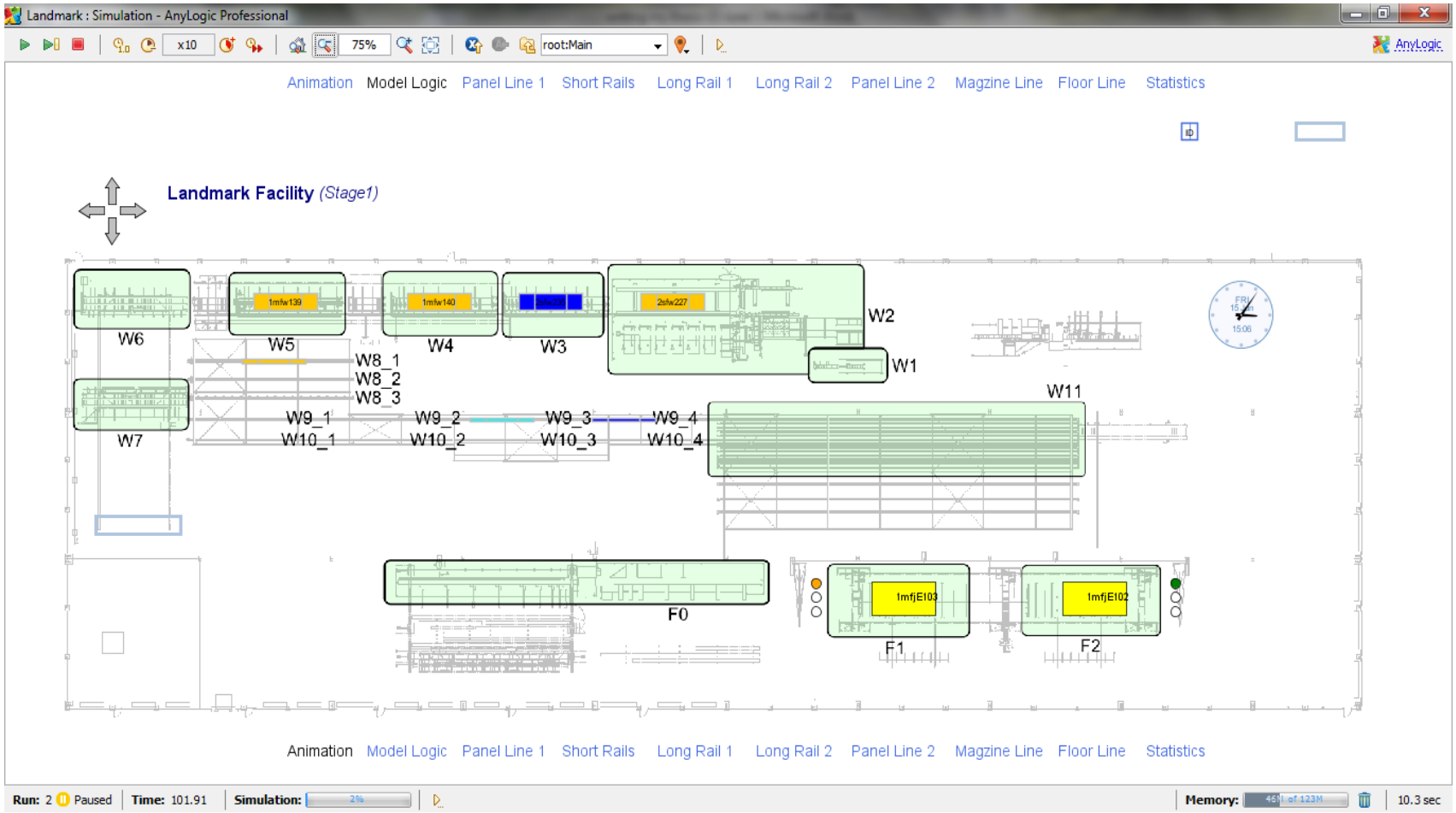


Figure 5- 4 Animation/Presentation View

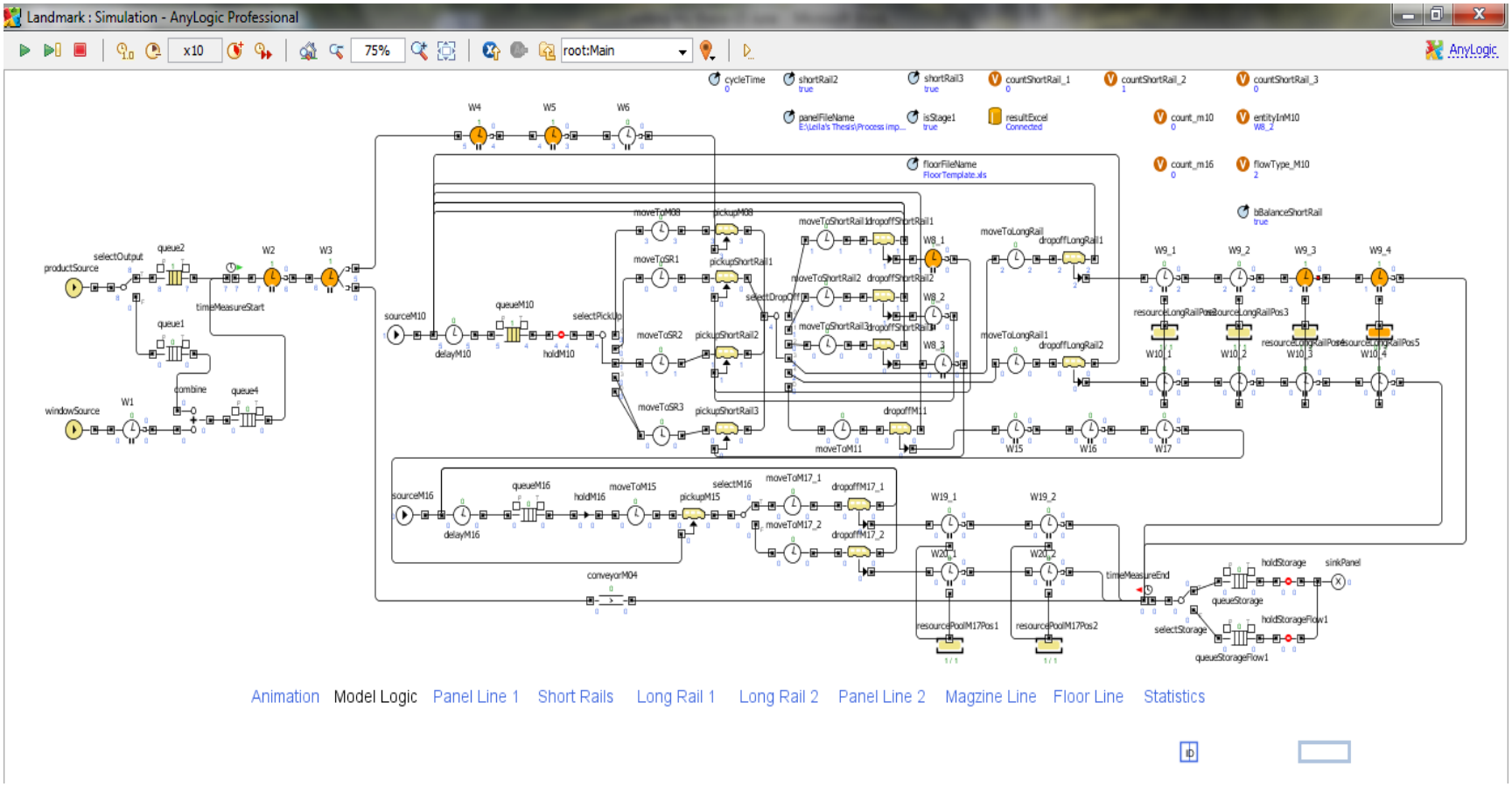


Figure 5- 5 Model Logic View

5.2.3. Output

The statistics view presents several performance measures of each station, such as working time, idle time, stop time, and waiting time during the simulation (Figure 5- 6). Working time is the simulated time (with probability) taken to perform all tasks at this station. Waiting time is the simulated time that the panel waits until the next station becomes available. Idle time is the simulated time for a station waiting for the next panel. Stop time is the simulated time for repair and maintenance. Station utilization is the working time divided by the total working time, waiting time, idle time and stop time. Station utilization is represented in the bracket following the working time.

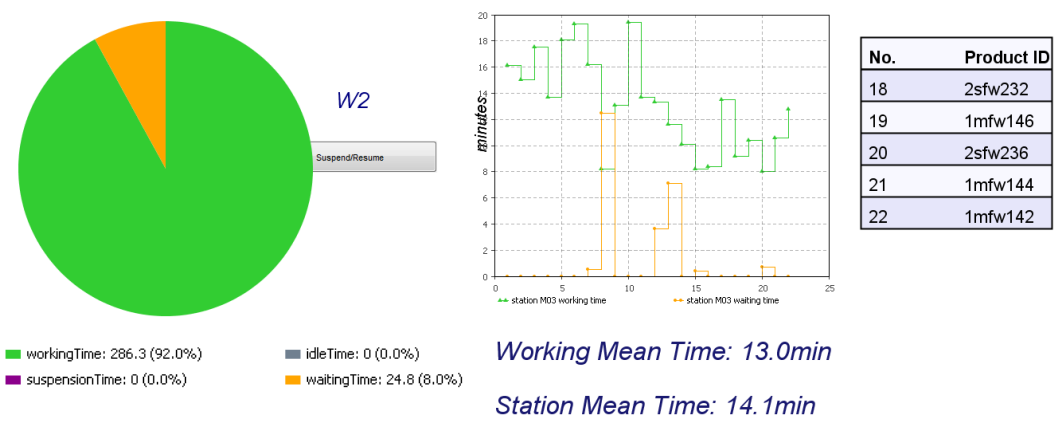


Figure 5- 6 Station Performance Measures

At the end of the simulation, detailed time records for each of the individual panels including product ID, entry time, exit time, number of stations, time in system and cycle time are summarized in a table (Figure 5- 7). The cycle time of a panel (C_p) is calculated by

$$C_p = \frac{F_p - E_p}{NS_p} \tag{5.1}$$

where E_p and F_p are the entry time of the panel to the line and exit time of the panel from the line, respectively, and NS_p is the number of stations the panel passes. Note that $F_p - E_p$ is the total time the panel spends in the line. The average panel cycle time ($\overline{C_p}$) is the average cycle time for all panels included in the simulations and is computed based on equation (5.2) in which NP is the number of total panels. Panel cycle time is one of

the most important performance measures and represents the productivity of the production line.

$$\overline{C_p} = \frac{\sum_p C_p}{NP} \tag{5.2}$$

Average Cycle Time: 11.8min

List of productions (min)

Product ID	Entry Time	Exit Time	Num_Stations	Time in System	Cycle Time
1mfw123	116.3	143.7	2	27.3	13.6
1mfw138	0.0	201.9	12	201.9	16.8
1mfw139	48.6	219.5	12	170.9	14.2
1mfw141	200.1	225.5	2	25.3	12.6
1mfw125	228.9	244.2	2	15.2	7.6
2sfw235	80.3	245.7	10	165.3	16.5
1mfw140	62.3	259.9	12	197.6	16.4
2sfw234	150.1	286.1	10	135.9	13.5
2sfw236	279.0	296.1	2	17.0	8.5
2sfw227	99.6	300.3	12	200.6	16.7
1mfw118	245.9	305.5	10	59.5	5.9
2sfw229	137.0	315.2	12	178.1	14.8
2sfw231	218.8	324.9	12	106.0	8.8
1mfw142	298.3	327.3	2	28.9	14.4
2sfw230	169.5	336.2	12	166.6	13.8
2sfw232	259.4	341.4	10	81.9	8.1
1mfw143	237.5	346.6	12	109.0	9.0
2sfw228	183.2	356.3	12	173.0	14.4
1mfw146	268.6	361.5	12	92.8	7.7
1mfw144	287.7	370.2	12	82.4	6.8

Figure 5- 7 Panel-level Statistics

Other performance indicators collected by the software include:

- Line throughput: total number of produced houses
- Station mean time: station s mean time (MT_s) is calculated based on equation(5.3) below

$$\overline{MT_s} = \frac{\sum_p (WT_{p,s} + DT_{p,s} + IT_{p,s})}{NP_s} \tag{5.3}$$

  Where $WT_{p,s}$ is working time on panel p in station s, $DT_{p,s}$ is the waiting time of station s when passing panel p to station s+1, and $IT_{p,s}$ is the idle time of station s before receiving panel p from station s-1.
- Station utilization: station utilization for station s (U_s) is calculated by the following equation:

$$U_s = \frac{W_s}{W_s + D_s + I_s} \tag{5.4}$$

where W_s , D_s, and I_s are total working time, total waiting time and total idle time of station s, respectively, satisfying the following equations:

$$W_s = \sum_{p=1}^{NP_s} WT_{p,s} \tag{5.5}$$

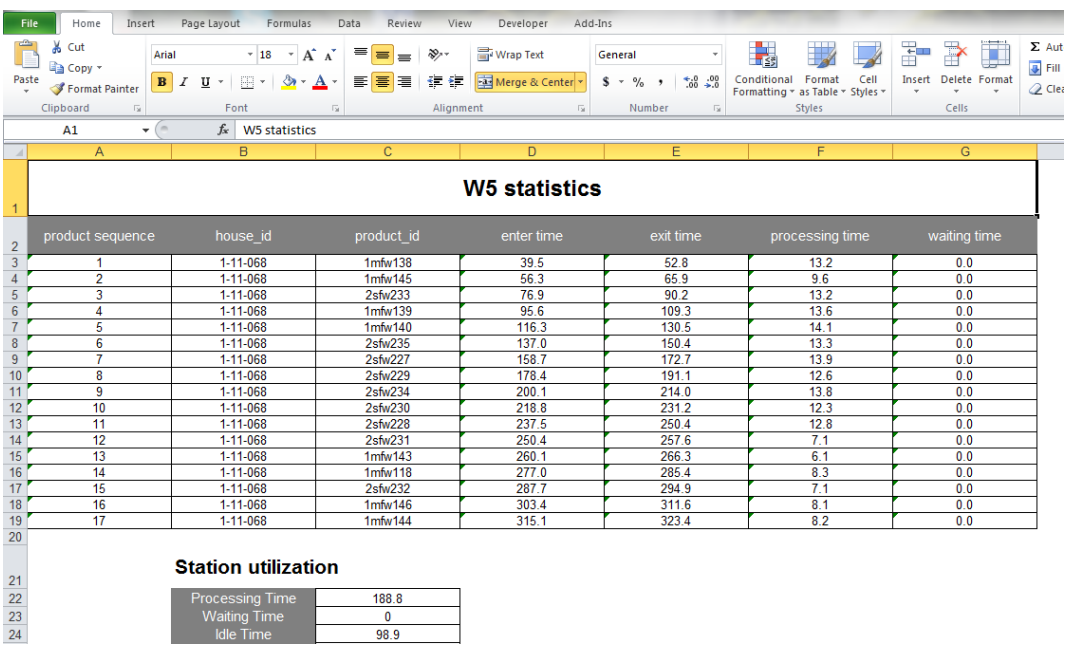
$$D_s = \sum_{p=1}^{NP_s} DT_{p,s} \tag{5.6}$$

$$I_s = \sum_{p=1}^{NP_s} IT_{p,s} \tag{5.7}$$

- Station working mean time: the average working time to process all panels in a station based on equation (5.8). The working mean time can be used as a measure for work contents to conduct "what-if" analysis in line balancing.

$$\overline{WT_s} = \frac{W_s}{NP_s} \tag{5.8}$$

- Task time probability distributions



W5 statistics

product sequence	house_id	product_id	enter time	exit time	processing time	waiting time
1	1-11-068	1mfw138	39.5	52.8	13.2	0.0
2	1-11-068	1mfw145	56.3	65.9	9.6	0.0
3	1-11-068	2sfw233	76.9	90.2	13.2	0.0
4	1-11-068	1mfw139	95.6	109.3	13.6	0.0
5	1-11-068	1mfw140	116.3	130.5	14.1	0.0
6	1-11-068	2sfw235	137.0	150.4	13.3	0.0
7	1-11-068	2sfw227	158.7	172.7	13.9	0.0
8	1-11-068	2sfw229	178.4	191.1	12.6	0.0
9	1-11-068	2sfw234	200.1	214.0	13.8	0.0
10	1-11-068	2sfw230	218.8	231.2	12.3	0.0
11	1-11-068	2sfw228	237.5	250.4	12.8	0.0
12	1-11-068	2sfw231	250.4	257.6	7.1	0.0
13	1-11-068	1mfw143	260.1	266.3	6.1	0.0
14	1-11-068	1mfw118	277.0	285.4	8.3	0.0
15	1-11-068	2sfw232	287.7	294.9	7.1	0.0
16	1-11-068	1mfw146	303.4	311.6	8.1	0.0
17	1-11-068	1mfw144	315.1	323.4	8.2	0.0

Station utilization

Processing Time	188.8
Waiting Time	0
Idle Time	98.9

Figure 5- 8 Station Performance Measures

Simulation Validation

Before improvement plans in the simulation model can be proposed, the validity of the simulation model needs to be checked to ensure that the model elements simulate the wall production line accurately. In this research, the simulation model is validated in two levels: (1) activity task times, and (2) house completion times.

In the first level (activity task times), three wall line activities were selected: W2.3 (assembling wall panel), W4.4 (secure wall sheathing), and W8.3 (spray foam insulation). For these activities, a new set of task times were collected through performing the time study for another 26 cycles. The house numbers and the panel ID numbers were recorded. Then the same houses and panels were run in the simulation software for 30 replications and the average simulated task times for activities W2.3, W4.4, and W8.3 were compared to the actual task times. Figures 5- 9, 5- 10, 5- 11 show the results of the comparison between the actual and simulated task times for the three activities. The correlation coefficients between actual and simulated task times are 91%, 89%, and 90% for activities W2.3, W4.4, and W8.3, respectively. These results show high correlation between the actual and simulated times implying that the task time formulas implemented in the simulation model conform to actual times. To check the accuracy of the simulated times, the pairwise comparison t-test was implemented at the significance level of 0.05 ($\alpha = 0.05$). The pairwise comparison t-test checks if the difference between two datasets (here, actual and simulated task times) is statistically zero. The t-test result verified that the difference between the simulated and actual task times is insignificant which validates the accuracy of the simulation model in the task time level.

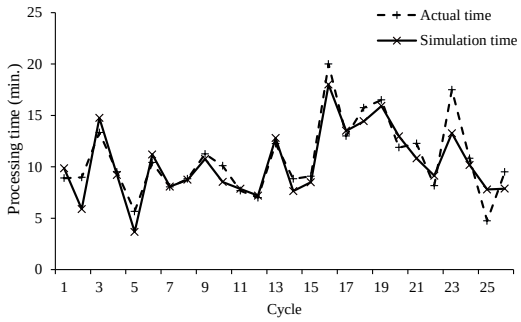


Figure 5- 9 Simulation Validation: Task Time W2.3

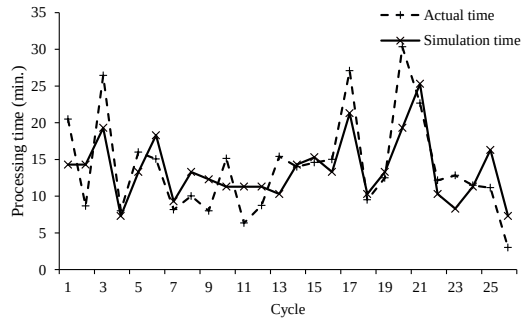


Figure 5- 10 Simulation Validation: Task Time W4.4

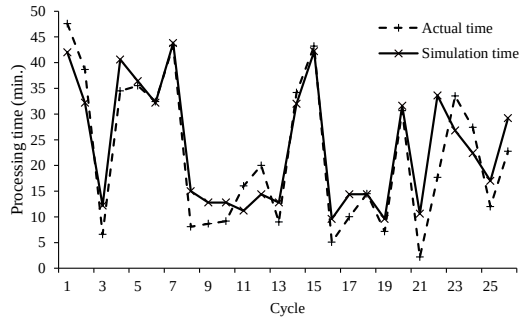


Figure 5- 11 Simulation Validation: Task Time W8.3

In the next level (house completion times), the average house completion times obtained from 30 simulation replications were compared to the actual completion times for 30 houses. The actual completion times for these 30 houses were provided by the wall line manager. The validation approach in this level is different from the approach used to validate task times. After running the simulation model for all houses, the average ($\overline{T}$) and standard deviation (S) of the simulated completion times were calculated for each house. Based on the average and standard deviation, the 95% confidence intervals were computed by equation (5.9) and the lower and upper confidence limits were plotted in Figure 5- 12. In equation (5.9), $Z_{\propto/2}$ is the inverse of the standard normal cumulative distribution at the significance level of $\alpha = 0.05$. Then, the actual completion times were added to the plot. As it can be seen, the actual completion times fall within the confidence interval limits which validate the simulation model.

$$C.I. = \left[\bar{T} - Z_{\propto/2}\frac{S}{\sqrt{30}}, \bar{T} + Z_{\propto/2}\frac{S}{\sqrt{30}}\right] \tag{5.9}$$

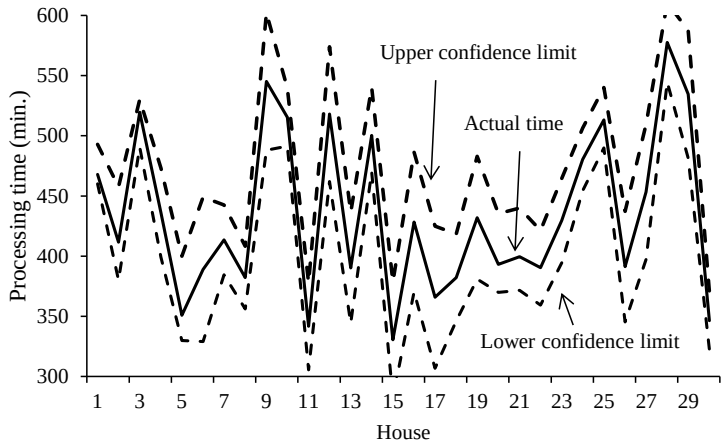


Figure 5- 12 Simulation Validation: Actual Completion Times Vs. 95% Confidence Intervals for Simulated Times

5.3. Process Flow Improvement

In this section, several process flow improvement plans are proposed through focusing on waste elimination, bottleneck identification, line balancing, and panel sequencing in the wall line. The effects of the improvement plans are analyzed using the simulation software of the wall line and comparing performance measures before and after improvements. Section 5.3.1 covers line balancing and Section 5.3.2 covers panel sequencing.

5.3.1. Line Balancing

The background on line balancing was discussed in Section 2.4.3.2. Line balancing develops a smooth production flow by equalizing station utilizations. Balanced utilization across different stations reduces the idle time of the fast stations through equalizing the stations' work content and speeding up the slowest stations (bottlenecks). Line balancing improves productivity and line throughput, and reduces cycle time through minimizing the stations' waiting and idle times. In general, line balancing can be achieved through two approaches. The first approach is to move one or several tasks from the bottleneck stations (the ones which have the longest processing times) to the previous or next stations, considering the technical constraints, so that the working mean times of stations are almost equal. The second approach is to increase resources at some bottleneck stations to reduce their cycle times.

5.3.1.1. Identifying Process Flow Bottlenecks

The first step in line balancing is to identify bottleneck stations. Bottleneck stations are those which work at a slower pace compared to other stations due to either a large work content or lower production rate. The speed of the bottleneck station determines the speed of the entire line. The station before the bottleneck station could be blocked, since the buffer before the bottleneck station may not have enough capacity as work in process between the two stations increases. Consequently, the station after the bottleneck starves, as it needs to wait for the bottleneck station to release station-finished or station-semi-finished products.

To identify potential bottlenecks in the wall line, the manufacturing process of 48 houses was simulated for 30 replications. The selected houses in the experiment sample include recently produced houses with different models and sizes. These 48 houses have a total of 1282 wall panels (NP = 1282). The houses were run in the simulation model in the same sequence as they had been manufactured. Simulation performance measure results are summarized in Table 5- 1.

Table 5- 1 Simulation Results

Stations	W2	W3	W4	W5	W6	W8	W9_1	W9_2	W9_3	W10_1	W10_2	W10_3
Total processing time (min.)	18972	9348.5	13118.4	9893.8	1100.2	6131	498.7	11966.4	7503.8	260.2	4059.4	3721
Total waiting time (min.)	2763.8	4758.2	1331.5	977.8	14425	631	788.6	4919.5	2697.6	5846.4	6669.2	3466.6
Total idle time (min.)	0	7596	7234.6	10774.6	799.2	6934.1	11335.7	4837	11613.6	14863.2	10277.8	13660.8
Working mean time (min.)	14.8	7.2	18.2	13.7	2	50.1	1	25.1	15.7	1	16.5	15.2
Station mean time (min.)	16.9	11	20	15	25.2	59.4	21.6	35.5	21.4	24.9	43.8	29.3
Station utilization	87%	43%	61%	46%	7%	45%	2%	55%	34%	1%	19%	18%
Bottleneck frequency	17	0	6	2	0	1	0	4	0	0	0	0

Understanding the difference between station waiting time and idle time in Table 5-1 is crucial. A station can be forced to be idle for two reasons. (1) Blocking: this scenario occurs when the current station has finished its work but is unable to pass the panel since the next station is busy with the previous panel. As a result, the panel needs to wait in the current station until the next station finishes its previous panel. The panel waiting time in the current station is equal to the idle time of the current station, as the current station

cannot start a new panel before passing the current one to the next station. This type of idle time is called station "waiting time". (2) Starvation: In this case, the opposite scenario occurs. The current station has finished its work but there is no new panel to work on as the previous station has not finished its work. The current station needs to wait until the previous station finishes its work. This type of idle time is called station "idle time". In Table 5- 1:

- Total processing time of a station for a simulation replication is calculated by equation (5.5) when$N_p = 1282$. The row "Total processing time" reports the average of total processing times for 30 simulation replications.
- Total waiting time of a station for a simulation replication is calculated by equation (5.6). Row "Total waiting time" reports the average of total waiting times in each station for 30 simulation replications.
- Total idle time of a station for a simulation replication is calculated by equation (5.7). Row "Total idle time" reports the average of total idle times in each station for 30 simulation replications.
- Working mean is calculated by equation (5.8). Row "Working mean time (min.)" reports the average of the working mean times in each station for 30 simulation replications.
- Station mean is calculated by equation (5.3). Row "Station mean time (min.)" reports the average of the working mean times in each station for 30 simulation replications.
- Station utilization is calculated by equation (5.4). Row "Station utilization" reports the average of the station utilizations for 30 simulation replications.
- Bottleneck frequency counts the number of replications (out of 30 replications) in which a specific station has been identified as the bottleneck (having maximum utilization).

The results indicate that station W2 is the bottleneck of the wall panel line with a utilization of 87%. Since this station is at the beginning of the line, its low throughput decreases both the throughput of the total line and the productivity of all other stations. Out of 30 simulation replications, this station has been identified as the process bottleneck in 17 replications (57% of the replications). After W2, stations W4 and W9-2, with respective utilizations of 61% and 55%, are the busiest line stations. In the next section, we focus on these three stations and investigate possible

improvement plans to make the utilizations of the stations in the line more balanced. Figure 5- 13 compares the station utilizations (presented in Table 5- 1) with the average of all station utilizations (average of the numbers in the utilization row of Table 5- 1. If perfect line balance is achieved, all stations should have nearly equal utilizations of around 35% (the dotted line in Figure 5- 13). Figure 5- 13 shows how the current situation of the flow line is far from the perfectly balanced line. However, it should be noted that achieving the perfectly balanced line is not possible due to the technical constraints regarding task properties and dependency relations between tasks. In the next section, the improvement plans for stations W2, W4, and W9-2 will be developed with the goal of achieving a smoother utilization profile compared to Figure 5- 13.

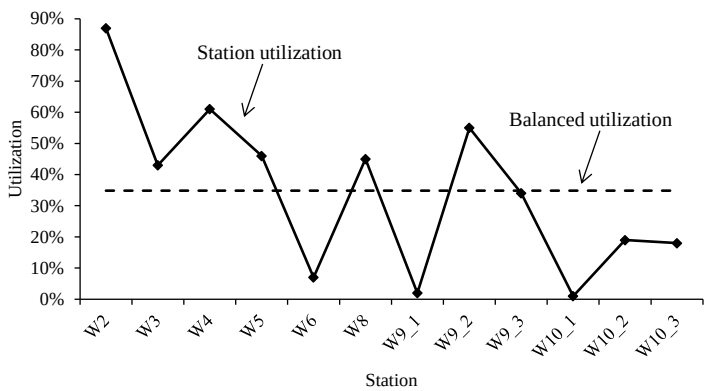


Figure 5- 13 Simulation Result for Station Utilization

5.3.1.2.Process Flow Improvement Plans

In this section, several improvement plans are proposed to improve the throughput of stations W2, W4, and W9-2. These stations are selected for process improvement since they are the bottleneck stations in the wall line. The result of the improvement plans will be evaluated against the current situation in the simulation model. The goal of the plans is to improve the wall line and achieve a more balanced line.

- **Station W2**

This station is first in the line, and therefore feeds the remaining stations. Any improvement in increasing the throughput of this station definitely improves the productivity of the whole line. The productivity of the framing machine limits the

production of station W2, as this station completes the majority of its work using this machine. Consequently, increasing the number of workforces or increasing the service rate of the machine (assuming that controlling the machine speed is not possible) are not viable options to reduce the station's processing time. There are two practical plans to reduce this station's processing time:

Plan 1: Consider longer shifts only for this station. In this case, the machine produces extra panels at the end of the day which can be used by station W3 at the beginning of the next day. Therefore, station W3 can start its work without waiting for station W2 to deliver panels. Currently, this plan cannot be implemented as there is not sufficient inventory space at station W2. The other concern is that the overtime work at this station imposes an increased cost to the company.

Plan 2: The framing machine has the capacity to process panels up to 40 feet in length. Producing longer panels in this station at once (using the total 40 feet length capacity of the framing machine) can increase the throughput of the station as setup times will be removed (Figures 5- 14 and 5- 15). Also, longer panels increase the utilization of the next station (station W3) by reducing the waiting time at this station which leads to more equal station utilizations at stations W2 and W3.

To analyze the result of implementing Plan 2, 14 house pairs were selected. The houses in each pair are of the same model and almost equal in size. The first house of each pair is designed based on shorter panels (current situation) and the second house is designed based on longer panels (close to 40 feet, improved situation). Indeed, the second house has fewer panels in total as shown in Figure 5- 16. Replacing longer panels (up to 40 feet long) has decreased the average number of panels from 29 to 15. The 14 pairs were then run in the simulation model for 30 replications and the processing times of station W2 for the two houses of each pair were plotted in Figure 5- 17. The average processing time for station W2 with shorter panels is 359.98 minutes while the average processing time with longer panels (improved design) is 223.27 minutes which amounts to a 38% reduction in processing time.

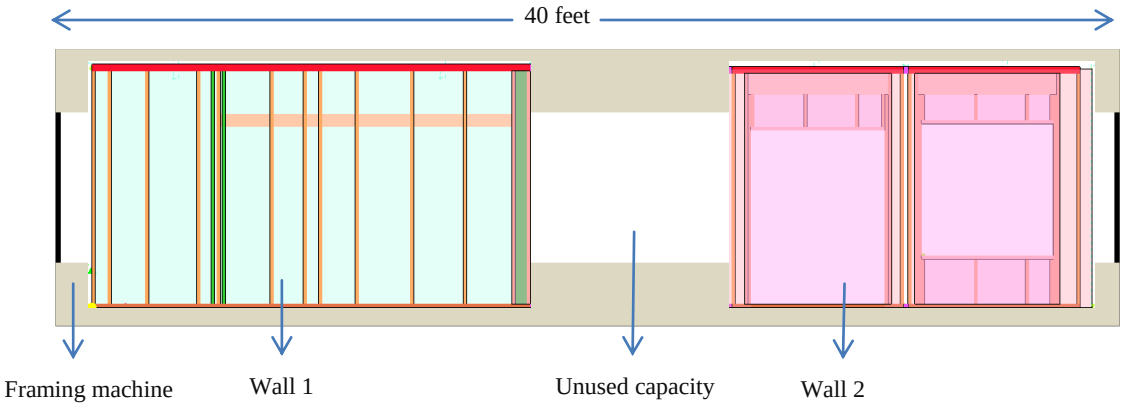


Figure 5- 14 Panel Configuration in the Framing Machine (Previous Design)

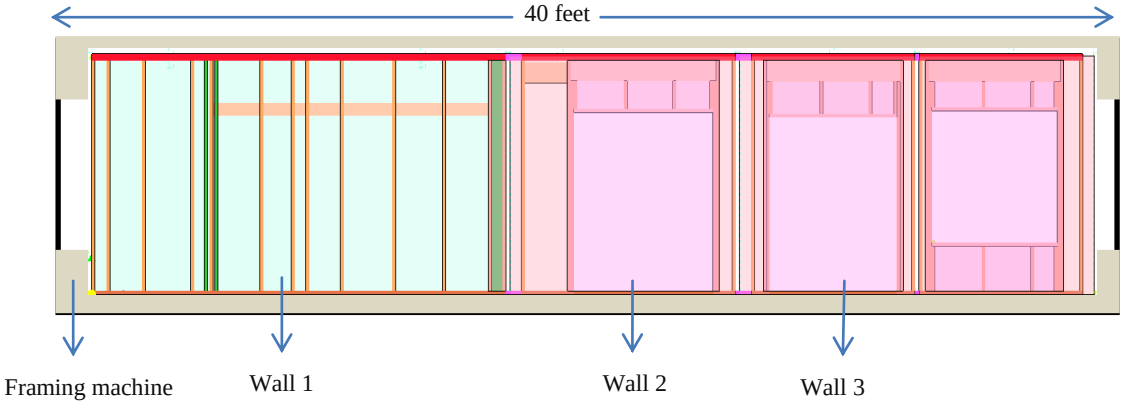


Figure 5- 15 Panel Configuration in the Framing Machine (Improved Design)

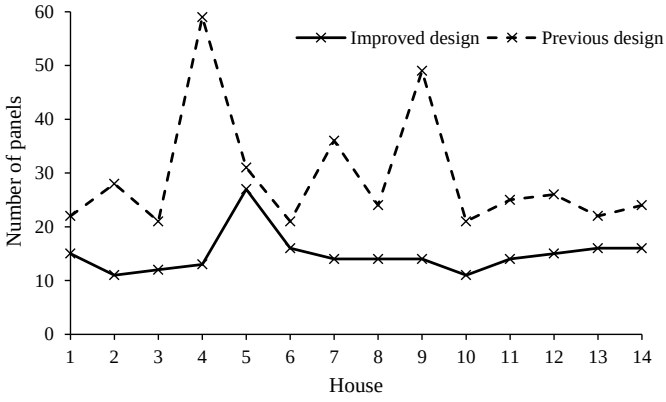


Figure 5- 16 Number of Panels in the Current and Improved Designs

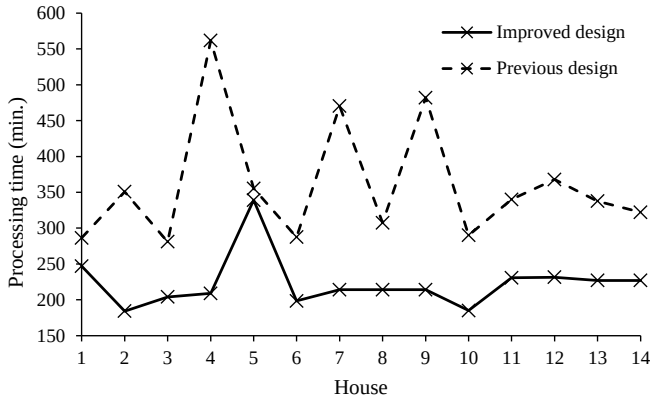


Figure 5- 17 Station W2 Processing Time for the Current and Improved Designs

Figure 5- 18 plots the utilizations of station W2 under the previous design and the improved design. The average station utilization for houses with shorter panels is 91% compared to 82% for houses with longer panels, which amounts to a 9% reduction in station W2 utilization. This improvement helps obtain a more balanced line and increases throughput of station W2. In addition, recently the plant has laminated top and bottom plates for wall frames which eliminate the need for manual plate gluing. Using laminated plates also decreases the process time of task W2.2 from 1.85 minute to 1 minute on average.

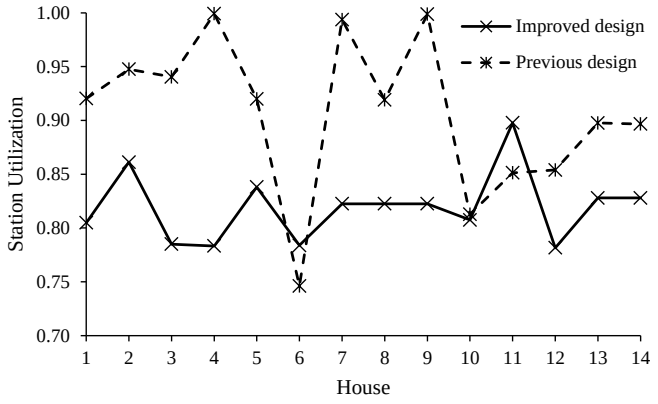


Figure 5- 18 Station W2 Utilization for the Current and Improved Designs

- **Station W4**

Station W4 has currently the second highest utilization and is a potential process bottleneck. In order to balance the line, one option is to reduce processing time in this

station. This station has four tasks. Figure 5- 19 shows the average processing time of these tasks according to the time study. As shown, activity W4.3 constitutes the main component of the total processing time of station W4.

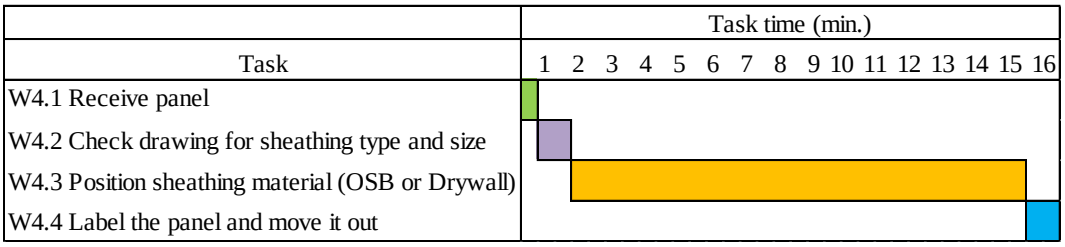


Figure 5- 19 Task Times of Station W4 (with 2 Workers for Task W4.3)

Currently, two workers perform activity W4.3. If a third worker is added to this task, it can be expected that the average task time decreases from 13.48 minutes to 8.98 minutes. The simulation results show 12% improvement (from 81% to 69%) in station W4 utilization after adding a worker to the station.

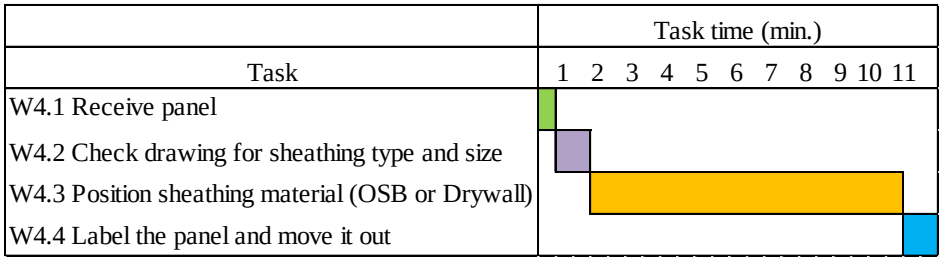


Figure 5- 20 Task Times of Station W4 (with 3 Workers for Task W4.3)

- **Station W9-2**

Based on the time study observation, it is noted that some portion of the working time of this station is spent on rework. If there is a problem in the previous stations' production, the workers at station W9-2 fix the issue before sending panels out of the line. The time spent on rework accounts for almost 10% of the working time in this station. This time can be saved through conducting inspections at the end of each station and ensuring that panels conform to the design properties.

5.3.2. Panel Sequencing

A house includes 20-30 wall panels. These panels enter the production line in sequence. The sequence in which the panels enter the line affects the line's productivity and the production cycle time of a house. The objective of panel sequencing is to maximize

station utilization by determining the appropriate order of different panels entering the wall line.

Currently, each panel has an ID which is used to determine panel sequencing. A panel with a smaller ID number enters the line earlier. In this section, the performance of the following job sequencing methods is compared to the current practice:

- **Random (R):** Panels enter the line in random order.
- **Shortest processing time (SPT):** Panels are sequenced based on their processing times and the panel with the shortest processing time entering the line first. The processing time of each panel is identified through replacing the values of the design properties in the regression lines and then adding up the processing times for the tasks that a panel passes through.
- **Longest processing time (LPT):** Panels are sequenced based on their processing times with the panel with the longest processing time entering the line first. The processing times are determined as explained above.
- **Fewer operations and shortest processing time (FOR+SPT):** Panels are sequenced based on the number of stations they pass through. Panels with fewer stations enter the line first. Then, if the number of stations for two panels is equal, the panel with the shorter processing time enters first.

The performance of these methods was tested by the simulation model to produce 48 houses. The performance measures of interest include: house average completion time, panel average cycle time, station average waiting time, and station average idle time. Table 5- 2 summarizes the performance of the sequencing methods and compares it with current performance. The "ID" column shows the current performance based on sequencing by panel IDs. The average station waiting time and average station idle time for the "ID" column are calculated through obtaining the average of the numbers in the "Total waiting time" and "Total idle time" rows of Table 5- 2.

Table 5- 2 Simulation Results for Panel Sequencing Methods

Sequencing methods	ID	R	SPT	LPT	FOR+SPT
House average completion time	458.9	479.2	444.4	511.0	393.2
Panel average cycle time	15.9	17.3	15.1	18.7	14.0
Stations average waiting time (min.)	8327.2	9080.2	8434.3	9987.1	8102.0
Stations average idle time (min.)	4106.3	4313.8	4077.3	4617.8	3780.8

As Table 5- 2 suggests, the FOR+SPT method outperforms other methods through reducing house average completion time by 14%, panel average cycle time by 12%, station average waiting time by 3%, and average idle time by 8%. Among the sequencing methods, LPT has the worst performance, while the performance of random sequence and SPT are similar to current performance.

5.3.3. Improved Line Performance

In this section, the performance of the wall production line after the proposed improvement plans is compared to current performance. The same 48 houses used in Section 5.3.1.1 to identify bottleneck stations were selected and run in the simulation of the improved line. For activity W4.3 and station W9-2 improvements, the coefficients of the regression lines were changed to capture the improved task times. For example, the original regression model for the task time of W4.3 ($T_{W4.3}$) was:

$$T_{W4.3} = 1.03\, x_{SH} + 3.31.$$

This regression model is based on two workers. After adding a third worker, it is expected that the coefficient of x_{SH} is reduced accordingly and the regression model changes to:

$$T_{W4.3} = 0.67\, x_{SH} + 3.31.$$

Table 5- 3 compares the performance before and after implementing improvement plans. The proposed improvement plans have decreased the average completion time of a house by 15.8%. The average waiting and idle times have also decreased by 17.7% and 18.9%, respectively.

Table 5- 3 Performance Improvement

	Before improvement	After improvement	Improvement (%)
Average completion time of a house	458.9	386.4	15.8
Average station waiting times in production of a house	173.5	142.8	17.7
Average station idle times in production of a house	85.5	69.3	18.9

Chapter 6

Conclusion

6.1. General Conclusion

This thesis describes a methodology for process improvement in panelized home building production lines through increasing productivity and reducing production cycle time based on lean production and simulation tools. The methodology was implemented in a home building manufacturer in Edmonton and several improvement plans were proposed after comparing the studied performance measures to current performance measures. In panelized home building, the panels of a home are produced in a factory and then moved to the construction site for assembly. In other words, homes are the end products of a manufacturing process. The common practice for evaluating improvement plans in a manufacturing process involves fitting statistical distributions for different tasks and developing a simulation model to check the effect of improvement plans on the performance of production systems. However, the challenge in improving a panelized home building manufacturing system is the high customization level in home models and styles which limits the ability to fit distributions for task times and evaluate improvement tools which are originally designed for manufacturing systems with similar products, like lean tools. Home panels as product units have different design properties which lead to highly variant processing times in different production stations for different panels. As a

result, defining task times through fitting statistical distributions in a simulation model of the panelized home building process is not reasonable because the panels' processing times at each station vary significantly based on panel design properties.

In this thesis, the floor and wall panels' manufacturing process was studied through breaking down the operation of each station into activities and performing a time study. In the next step, the panel design properties which affect the processing times of panels in each activity were identified. The activity task times and values for the identified design properties for the time studied panels (extracted from drawing files) were stored in a database which was later used to develop task time regression models for each activity. The regression models are inputs in the simulation model of the floor and wall lines which estimate the task time of each activity based on the specific design properties of a panel. To incorporate uncertainty in task times, triangular distributions were fitted to approximate the difference between the actual task times and the times resulting from regression models. These triangular distributions were added to the task time formulas.

Through simulation experiments, the bottleneck stations of the wall line were recognized. The bottleneck stations were the targets of the proposed improvement plans to balance the utilizations of the line stations. A balanced line provides a smooth production flow through reducing idle and waiting times in stations which leads to higher productivity and line throughput. Another stream of improvement plans are based on panel sequencing, which sets the order of entering panels into the line so that the total station waiting and idle times and average completion time of a house are minimized. The comparison of different job sequencing methods showed that better performance was achieved when panels with fewer required stations and shorter processing times entered the line first. Ultimately, the simulation experiments revealed 16% improvement in average house completion time after implementing all the propose improvement plans.

6.2. Research Contribution

The contributions of this research can be summarized as follows:

- Identifying panel design properties which affect their processing times at different activities of a panelized home building process
- Formulating task times of the activities in a panelized home building process as regression models which include task time of an activity as the dependent variable and the panel design properties as the independent variables.

- Incorporating task time uncertainties in task time regression formulas based on the difference of the actual times from estimated times for each activity
- Improving production line performance through evaluating line balancing and panel sequencing improvement plans in the simulation model of the line which estimates task times of activities according to the developed task time regression formulas and the unique design properties of each panel.

6.3. Research limitation

The scope of this thesis is limited to certain factors including:

- Regression models are assumed to be linear and interaction between independent variables is not considered.
- Simulation model used in this thesis provides some constraints in order to model the system performance. For example, the simulation model accepts triangular distribution to incorporate uncertainties. So, the residuals of the regression models were fitted with triangular distribution although the residuals theoretically follow normal distribution.
- The formulas used in the simulation model are limited to the observation period in the factory. Due to dynamic change of the company production lines, the task processing times are changing and as a result it will affect the regression formulas used to predict task times.

6.4. Future Research

- Possible research on task time estimations in panelized home building is to use clustering methods to categorize panel types according to similar properties and task times. For each cluster, statistical distributions can be fit for task times. The comparison between estimating task times based on regression formulas and estimating task times based on statistical distributions of each cluster can be investigated.
- Another future research area is to investigate the improvement possibility of producing panels of different houses together through considering all panels in panel sequencing.
- At a higher level of analysis, the optimal production mix of the different house types can be determined to maximize company profit considering customer

demand requirements and production capacity, and through incorporating financial analysis.

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