Integrated Lean and Simulation for Productivity Improvement for Windows Manufacturing

by

Yining Wang

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Construction Engineering and Management

Department of Civil and Environmental Engineering

University of Alberta

ABSTRACT

The manufacturing sector is of importance to Canada's economic vitality. However, given the phenomenon of globalization, low trade barriers, and advances in technology, there has been a decline in manufacturing's share of the Canadian economy. Today, Canadian manufacturing companies are striving to grow their businesses and enhance productivity. Lean manufacturing, a systematic method born when Japan was facing a shortage of resources, has benefited the manufacturing industry for decades. Simulation proved to be effective to analyze dynamic processes and statistically justify paybacks; therefore, this research proposes to incorporate lean with simulation.

The purpose of this research is to combine lean manufacturing and simulation tools to improve the productivity of the production line. Specifically, lean manufacturing is used as a starting point from which current state mapping and waste identification are performed, after which a root cause analysis is conducted, and corresponding solutions are proposed. Traditional manufacturers are usually reluctant to implement major changes proposed by lean if they cannot predict whether the gains are significant to cover the cost. In this research, simulation tools are used to statistically re-analyze the payback from the effect of changes to the production line. Since simulation can dynamically mimic the production process, it will also be used to conduct continuous analysis, such as determining where the bottlenecks are and to assist the resource allocation process. The methodology of this research is implemented through a case study with a local window and door manufacturer.

Acknowledgements

First, I would like to express my gratitude and appreciation to my supervisors, Professor Mohamed Al-Hussein and professor Yasser Mohamed, for their mentorship, encouragement and support throughout my M.Sc. Thanks for introducing me to modular construction, giving me the chance to be part of the research team, and introducing me to local manufacturing companies.

My gratitude also goes to the local window and door manufacturing company for giving me the chance to carry out my research. I would like to thank Gabriela, Projects Manager, and Jason, Director of Manufacturing Operations for inspiring me, trusting me, and supporting me. The work experience I gained at there was the foundation of my research. I have had the pleasure to work with amazing people. I learned more on this journey than what I could ever hope to express my gratitude for.

I feel lucky to have my friends by my side on this journey. I want to express my thanks to Ruth, my closest friend who is always there for me. To Yifan, Heather, and Savanah, who bring so much joy to my life. I would like to extend my gratitude to the support and love from my family. A special thanks to my mom, who is my first teacher and my best friend. The values and ideas you've imparted to me since I was a little girl empower me to face the challenges in my life. I wouldn't have gone this far without you.

Table of Contents

List of Tables

List of Figures

Chapter 1 Introduction

1.1 Research Motivation

As one of Canada's most important economic sectors, the manufacturing industry accounts for approximately $174 billion of Canada’s gross domestic product (GDP), which is over 10% of Canada’s total GDP (Government of Canada, 2019). Given the spread of globalization and the low trade barriers, the manufacturing industry is facing growing opportunities as well as tremendous competition. The unprecedented requirements for product customization have increased the volatility of the manufacturing sector (Mourtzis, Doukas, & Bernidaki, 2014). The manufacturing sector is being challenged to coop with the rate of producing innovative products within shorter timeframes. There are new innovative technologies, theories, and idea coming out every single day, and manufacturers are striving to realize the benefits to their businesses and generate more value.

The concept of lean manufacturing was originated by Toyota in Japan after the Second World War, at which time Japanese manufacturers were challenged from a shortage of resources and financial support. To overcome this, corporate leaders in Japan put efforts into developing and refining the manufacturing process to reduce waste and non-value-added activities (Elbert, 2013). The system focuses on identifying the waste and use tools such as just-in-time (JIT), Kanbans, and setup time reduction to reduce or eliminate the wastes (Abdulmalek & Rajgopal, 2007). Through years of application, lean manufacturing has been proven to benefit the manufacturing industry. Manufacturers report improvement in productivity, net income, labour utilization rate, machine utilization rate, and return on investment, as well as decreases in the cycle time and cost (Pavnaskar, Gershenson, & Jambekar, 2003).

In the application of lean concepts, one of the most well-known methods is value stream mapping. Value stream mapping is a visual representation of all manufacturing operations aimed at exposing non-value-added activities in current processes (Patel, Chauhan, & Trivedi, 2014). By using value stream mapping, the goal is to identify the waste and propose methods to eliminate that waste (Rother & Shook, 2003). By using value stream mapping as a tool to apply lean thinking to a case study from a window production line, one goal of this research is to identify and reduce the non-value-added activities in operations to reach a higher production rate.

Although the core methodologies of lean are simple, a tool that can predict if the gains are of a significant magnitude to justify the cost of changes would benefit the implementation of lean. (Abdulmalek & Rajgopal, 2007). In manufacturing companies, the cost of reallocating resources, purchasing new machinery, modifying manufacturing processes etc. are usually high. Lacking justification for future paybacks, the managers are usually reluctant to put lean analysis into practice. In general, one tool that can quantify and visualize the gains in the early planning stage is simulation (Abdulmalek & Rajgopal, 2007). The statistical analysis from simulation tools can enable managers to compare the potential future performance based on the implementation of the lean analysis to the existing system (Detty & Yingling, 2000). In this research, a simulation tool will be used to develop models that can mimic the production process. One of the goals is to determine the payback and use that to justify applying lean manufacturing. However, since value stream mapping is a paper and pencil method, it also has its own limitations. As a static tool, it is unable to capture dynamic behaviour and cannot handle complicated processes or capture uncertainty (Lian & Van Landeghem, 2007). As a result, lean is applied less often in the continuous process sector as compared to discrete industry (Kumar, Singh, & Sharma, 2014). To make up for this disadvantage, simulation models are used to mimic the production flow and analyse the effect of improvement suggestions on productivity.

This research is conducted, tested and validated in collaboration with a local window and door manufacturing company; referred to as WD throughout this dissertation. WD is a window and door manufacturing company with over 40 years of experience focusing on crafting windows and doors. WD has over 10 window production lines, producing windows of different types, such as double sliders, triple sliders, basement windows, casement, awning, fixed windows, picture windows, etc. With over 10 production lines, 3 working shifts, and over 260,000 windows produced per year (data from 2018), WD is one of the largest windows and door manufacturers in western Canada. As competition in the manufacturing industry grows, WD is looking to new theories and technology to expand the business. For this reason, this research begins with conducting time study and operation observation for operations in the plant, then lean manufacturing is employed to identify the opportunities to improve productivity. Simulation, is used to predict the after-effects of changes proposed by the lean analysis to provide managers with more confidence in adopting the changes. Simulation will also be used as a tool for bottleneck identification and line balancing.

1.2 Research Objectives

This research proposes to develop a framework to improve the productivity of manufacturing through the integrated application of lean manufacturing and simulation modelling. The framework will be elaborated upon and examined through a case study with a window and door manufacturing company. This research is built on the following hypothesis that:

Combining lean manufacturing and production simulation can help manufacturing companies to identify waste, find methods to reduce such wastes, and statistically analyse the payback of implementing changes, thereby increasing overall productivity.

Specific research objectives of this research are as follows:

- To identify the waste in the manufacturing process using value stream mapping;
- To conduct root-cause-analysis and propose solutions to issues using lean tools;
- To develop a simulation model to statistically analyse the payback of adopting lean manufacturing changes;
- To determine the best resources allocation scenario using simulation analysis.

1.3 Thesis Organization

This thesis is divided into five chapters. Following the introduction chapter is Chapter 2 (Literature Review), in which the development trend, the current application status, tools and techniques, and the challenges of lean manufacturing and production line simulation will be reviewed. Chapter 3 (Methodology) includes the problem statement, research processes, data collection, and the methods this research uses to solve the existing problems. Chapter 4 (Proposed Methodology Implementation) includes case studies from a local window and door manufacturer. In this chapter, following the background information about the company, this research, which uses actual production numbers, will elaborate on how the proposed methodology can benefit the production.

Chapter 5 (Conclusions and Recommendations for Future Research) summarizes the conclusions and contributions of this research, and also the limitations and recommendations for future studies are included in this chapter.

Chapter 2 Literature Review

2.1 Lean Manufacturing

2.1.1 The development and application of lean

Today, most manufacturers have heard of the term "lean". The idea of lean originated in Japan at Toyota after the Second World War when there was a shortage of human resources, material, and money. The president of Toyota Motor Company, Kiichiro Toyoda, realized their western counterparts were producing at a scale more than 10 times what they were producing (Abdulmalek & Rajgopal, 2007). At the time, corporate leadership decided to make up for this disadvantage by focusing on improving the internal design of production lines, hence they could increase their overall production by improving the efficiency and without necessarily needing massive production (Melton, 2005). Later, the book *The Machine That Changed the World* first compared the Toyota production method to the western mass production system and emphasized the better performance of the former (Melton, 2005). The book popularized Lean Manufacturing worldwide. Today, this system is known as "Toyota Production System" or "lean manufacturing".

The Toyota Production System pioneered by Shigeo Shingo and Taiichi Ohno includes two components: just-in-time (JIT) production system and respect-for-human system (Bhamu & Sangwan, 2014). In 1983, Monden further broadened the JIT concepts and introduced them to the USA. Over the last decades, lean manufacturing went through a series of tremendous changes and improvements through applications (Spear, 2004). The discussion around lean manufacturing can be generally categorized into two views. The first is a philosophical perspective in which the authors focus on building principles and clarifying goals, while the second is a practical perspective in which authors discuss the practices, tools, and techniques that are tangible (Bhamu & Sangwan, 2014). The application of lean follows five steps. Firstly, determine the value of a product from a customer's point of view, and secondly map the value stream and the waste will be identified in this step. The third step is to focus on the flow and try to improve the lead time, and the fourth step is to determine the pull factor. The last step is to continuously work towards perfection (Lean Enterprise Institue, Inc, 2016).

2.1.2 The goal of lean manufacturing

The main goal of lean manufacturing is to satisfy the demand of the customer with the least waste. This means to produce the product with the least resources and cost, and also deliver the product at the time required (Bhamu & Sangwan, 2014). Waste can be in any form and occur as part of any operation at any time, and it can be found in policies, design, and operational procedures (Seth & Gupta, 2005). According to Russell and Taylor (2011), waste is defined as anything more than the minimum amount of resources deemed as essential to add value to the product. There are seven types of waste that result in non-value-added activities, namely defects, overproduction, waiting, transportation, inventory, over processing, and motion (Melton, 2005). According to lean production, the value of a produced is defined as it perceived by the customers and the production flow should be in line with the time the customer needs it (Sundar, Balaji, & Kumar, 2014). Also, in the production process, lean manufacturing focuses on constantly eliminating waste by distinguishing value-added activities from non-value-added activities.

Except for the most commonly accepted goal of lean that is stated above, other goals of lean manufacturing may exist in different areas of research because lean manufacturing has evolved over the last decades (Bhamu & Sangwan, 2014). Some of the most commonly discussed goals in the application of lean are as follows:

- Continuously improve the flow of production (Liker, 2004)
- Minimize the inventory
- Reduce cost
- Reduce lead time
- Perform quantity check in the production processes to reduce rework
- Raise the understandings of the process
- Improve productivity and quality

2.1.3 Lean tools and techniques

Over the past few decades, lean tools have evolved and there are new ones proposed from time to time. The concept of lean includes over 10 different tools and techniques. In the following section, the lean tools and techniques used in this research are reviewed.

I. Value stream mapping (VSM)

As per Jones and Womack (2002), value stream mapping is a process of observing the flows of resources and information, summarizing and analysing them, and then coming up with a future state that performs better. VSM is a tool to map out the entire process flow, and it consists of three steps. The first step is to conduct current state mapping, which is done by following the product from the outbound all the way back to inbound. The production process is recorded using VSM iconography to map the flow of resources and information. The second step is to identify the non-value-added actives, find the root causes, and eliminate the waste. A "future state map" is also created in this stage. The final step is to apply the changes to improve production (Gahagan, 2007). VSM can visually illustrate the inventory, lead time, cycle time, waiting time, and the production flow, thus the bottleneck cycle time can be identified again Takt time (Sundar, Balaji, & Kumar, 2014). The current state mapping can visually represent the internal and external production process of companies, and serve as a start port for systematic analysis of the production process and identification of existing wastes (Yu, 2010). The main goal of VSM is to identify the waste in the production process and take actions to eliminate those wastes (Rohani & Zahraee, 2015).

II. Cellular manufacturing

Cellular manufacturing organizes the operations into groups. Each group should include a few nearby workstations where operations are performed on similar raw materials, machines, and equipment (Hyer & Wemmerlov, 2001). By locating the resources to process similar products close to each other, cellular manufacturing can improve the continuous performance of production lines. After applying cellular manufacturing, companies have reported the improvement of productivity, lead time, quality, space utilization, and cycle time (McLaughlin & Durazo-Cardenas, 2013). To optimize the benefit of the manufacturing system, social systems, such as employee training and job satisfaction assessments, need to keep in pace with the technical systems, which includes workflow sequence design, physical arrangement, etc. (Huber & Brown, 1991). Other line techniques, such as U-line manufacturing, line balancing, and flow manufacturing, can also support the successful implementation of cellular manufacturing (Sundar, Balaji, & Kumar, 2014).

III. Kanban

Kanban is the Japanese word for “signboard”. It is a signal system to ensure the suppliers only supply the materials when the next work centre requests to do so (Melton, 2005). Kanban is a system to ensure just-in-time production. Since all requirements are only pulled when needed, Kanban can solve some of the material flow design problems and inventory level problems. When the demand is uncertain, the Kanban system can manage to provide proper buffers between operations, which is important for a smooth workflow. The Kanban system can support the mixed model production and optimize the inventory level, which can contribute to reducing lead time in product delivery, and increase the utilization rate of resources (labour, machine, etc.) (Sundar, Balaji, & Kumar, 2014).

IV. Employee perception

Employee perception can influence the success of the implementation of a lean transition. The transformations created on the floor when applying lean production are often under hot debate. The implementation of lean usually comes along with changes in operating procedures and resource reallocation. Employees generally have mixed feelings towards it. Employees may suffer from stress and anxiety as they step out of their comfort zones and the methods they are familiar with, which may result in an intensification of work even when the positive benefits of lean production have been shown (Neirotti, 2018). A survey has studied the factors that influence the workers’ belief in whether the lean transformation will be successful, and the factors are organized into two groups, which are critical intrinsic factors (commitment, belief in lean) and external factors (work method, communication) (Losonci, Demeter, & Jenei, 2011). To ensure the optimal outcome of lean, better employee perception can be cultivated through employee training, and awareness can be raised by defining the road map or updating the standard operation procedure (SOP) manuals (Mehta, Mehta, & Mehta, 2012).

V. Takt time

The Takt time is the production rate at which products should be produced to meet customers' demand. The Takt time is usually calculated using effective working time for production divided by the required unit of production (Zahraee, Hashemi, Abdi, Shahpanah, & Rohani, 2014). Takt time plays an important role in manufacturing systems. It represents the consumer's requirement of what is the proper time to start production. Takt time can be used to determine the production speed of machinery and estimating the minimum batch sizes in changeovers (Rohani & Zahraee, 2015).

VI. Line balancing

Line balancing is an important issue to consider in the workflow planning stage. There are many contributing factors causing line imbalance in production. For example, the fluctuation of labour productivity, instability in machine cycle time, rework, and transportation between operations (Sundar, Balaji, & Kumar, 2014). Also, in the mixed model line, changeover may also be a reason for line imbalance because it creates fluctuation in machine cycle time (Sundar, Balaji, & Kumar, 2014). Line balancing is a lean tool used to level production. Line balancing is used to explore the optimum resource allocation at each workstation to reach the fastest cycle time possible. It can also reduce the number of workstations in fixed cycle time by levelling the workload (Masood, 2006). Through line balancing, labour idleness can be reduced and the productivity can be enhanced.

VII. Kaizen

In Japanese, “kai” means “change” and “zen” means “better”. Kaizen is a tool for continuous improvement. Kaizen can be divided into two categories. The first one is the flow kaizen, which focuses on the flow of material and information in the entire production line, while the second one is process kaizen, which solely focuses on the improvement at each single workstation (Misiurek, 2015). Kaizen tools are used to determine the root cause of inefficiency, and also to design a system with zero waste and identify current waste (Sundar, Balaji, & Kumar, 2014).There are three organizational capabilities that are considered the prerequisites of successful implementation of Kaizen. The first one is workers’ initiative to study and improve the work process, the second one is barrier-free cross-functional communication in the company, and the third capability is to discipline workers to ensure they follow the instructions (Chan & Tay, 2018). The goal of Kaizen is to generate more value and eliminate waste. Kaizen is commonly used as a starter for major changes, and the implementation of Kaizen usually starts with data collection.

2.1.4 Challenges

Though many companies have heard about lean and have thought about maximizing their benefits through lean practices, there are still problems holding companies back from adopting lean thinking. The two biggest problems that hinder the application of lean are: 1) some business owners believe their processes are already efficient enough, and 2) the lack of confidence in tangible benefits (Melton, 2005). Although both thoughts can be challenged as there are many proven benefits about lean practices in terms of productivity and supply chain, the viewpoint that business processes are efficient enough is too often a hallucination (Melton, 2004). In terms of applying major changes suggested by lean, it is hard to predict if the gains will be significant enough compared to the cost. The traditional lean application process does not validate the benefits of the future state before implementation, instead, it depends on modifying the system to reach a satisfactory performance through iteration (Marvel & Standridge, 2009). Management's decision of whether to implement lean or not usually relies on trust in lean manufacturing, reports from others, and previous experience (Abdulmalek & Rajgopal, 2007). This is often insufficient to support decision making. Lean researchers have also been exploring the benefits of using other approaches such as system dynamics, simulation, and mathematical and expert system-based approaches (Seth & Gupta, 2005).

2.2 Production Line Simulation

2.2.1 Introduction

The idea of the digital factory is to enhance the manufacturing process by using digital technology, and as a key technology within this concept, simulation has gained great attention in recent years. However, simulation is a very general concept with a lot of branches. This research focuses on using computer simulation to build simulation models and facilitate the improvement of production lines. According to Encyclopedia Britannica (2017):

"Computer simulation, the use of a computer to represent the dynamic responses of one system by the behavior of another system modeled after it. A simulation uses a mathematical description, or model, of a real system in the form of a computer program. This model is composed of equations

that duplicate the functional relationships within the real system. When the program is run, the resulting mathematical dynamics form an analog of the behavior of the real system, with the results presented in the form of data. A simulation can also take the form of a computer-graphics image that represents dynamic processes in an animated sequence."

As per Christopher A. Chung, "Simulation modelling and analysis is the process of creating and experimenting with a computerized mathematical model of a physical system" (Chung, 2014). Simulation models are built based on the characteristics of a real operational system aiming at imitating actual production. The dynamic processes captured in simulation models are able to simulate experiments that are applicable in real production (Bako & Božek, 2016).

In today's manufacturing industry, product development processes are facing unprecedented complexity given the trend of increasing product variation, mass customization, and personalisation (Mourtzis, Doukas, & Bernidaki, 2014). To overcome such a challenge, many researchers have considered using computer simulation. Simulation tools can be used to gain insight into complex production design, and test out new operations and system design before actual implementation, and also for the existing system, simulation analysis can be conducted without disturbing current production (Pegden, Shannon, & Sadowski, 1995).

Specifically speaking, in the early design and planning stage, simulation models can be applied on different phases of the production planning and controlling as it can associate the top-level decisions with the floor operations (Kühn, 2006). Simulation allows the experimentation and validation of systems and configurations design as it comprises the actual data to mirror the physical world in a virtual model, therefore it can explore the optimal resource arrangement of production system even before the actual production processes are built (Rüßmann et al., 2015). Simulation can be used as a complementary tool with VSM to justify the payback in the early exploration and planning stages (Abdulmalek & Rajgopal, 2007). Through the application of simulation, the time to market can be reduced, the error handling time and the production improvement time can be shortened, which brings the time benefit to the entire production process (Kühn, 2006).

In the executive stage, by using simulations, the collaboration between production planning and execution, and the visibility of production processes in supply chain planning can be improved (Kühn, 2006). Simulation models can continuously improve the performance of the current system, and it can be used to test out the what-if scenarios without influencing the current production, as well as explore the optimal resource arrangement of the production system. As shown in Figure 2-1, the role of simulation in system design is that simulation can refine the initial plans.

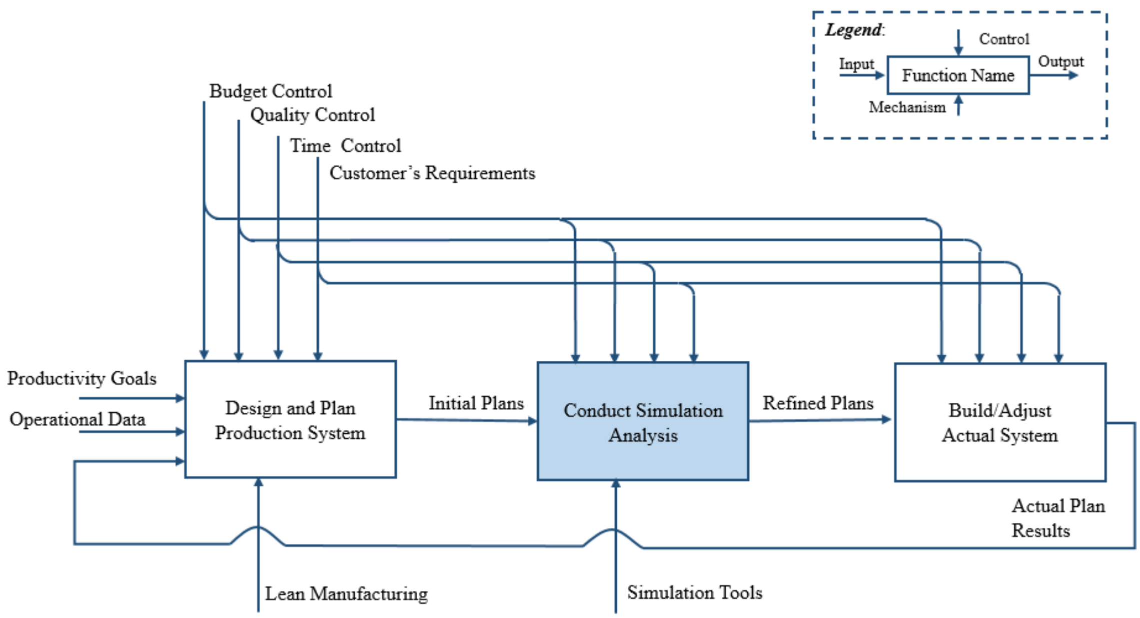


Figure 2-1: Simulation's Role in System Design

2.2.2 Simulation classification and tools

Based on whether the simulation models require time factor as an input, they can be divided into static simulation and dynamic simulation. Dynamic simulation can be further classified into continuous simulation in which the system outputs are continually tracked throughout the time, and discrete simulation in which outputs change only at discrete points in time. Discrete simulation can also be further categorized into time-stepped and event-driven. In time-stepped simulation, the output changes after a fixed time interval, while in event-driven simulation, changes occur when an entity passes through a scheduled event and the duration of each event may be distinctive (Mourtzis, Doukas, & Bernidaki, 2014). Based on the classification criteria mentioned above, the classification of simulation model is given in Figure 2-2.

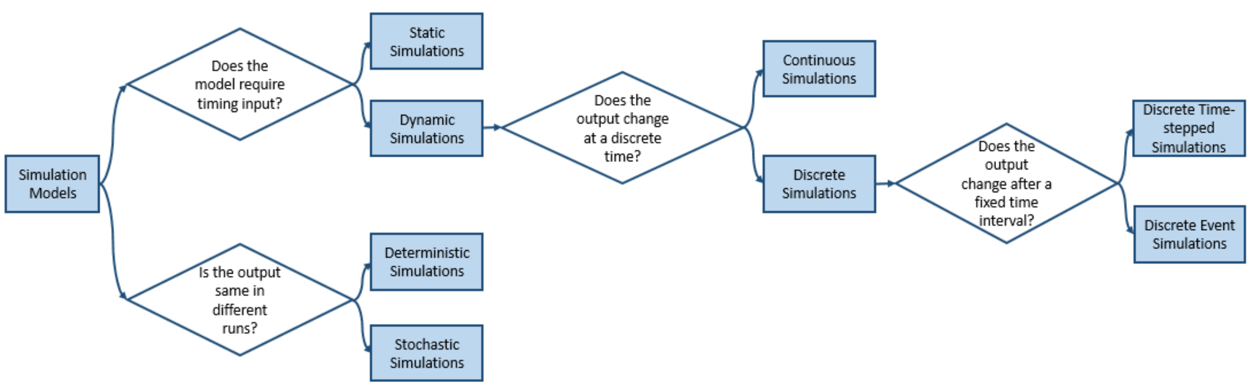


Figure 2-2: Classification of Simulation Models

This research uses discrete event simulation to model production processes as it best reflects the actual production where materials only transform after passing a work centre, and every single operation can be treated as an event in the simulation model. The discrete event simulation software can model any production system that involves a process flow and where system events occur in time sequence (Omogbai & Salonitis, 2016). A typical example is a product flowing through a manufacturing system. The discrete event simulation can improve the performance of production systems through:

- verifying the payback of changes before actual implementation;
- reducing the cost of production line planning;
- detecting and eliminating potential problems before actual production; and,
- testing out the what-if scenarios to reach the best resource allocation.

Currently, there are a few well-known computer simulation software applications such as AnyLogic, Simphony, WITNESS, Plant Simulation, SIMSCRIPT, Automod, SIMUL8, and ARENA. The general principles of all the modeling software are similar and they all have general purpose templates to model processes.

In this research, Simphony is used as the simulation tool to model the manufacturing process. Simphony is a software based in Microsoft Windows modelling environment. Simphony is a platform based on modular and hierarchical concepts that can be used to model manufacturing processes. Besides the general-purpose template, which is a collection of high-level elements that can be used to develop simulation models, Simphony also has collections of modelling elements, called templates, targeted at representing real-life problems, which makes the modelling process quicker and easier (AbouRizk, Hague, & Ekyalimpa, 2016).

2.2.3 Application of simulation

In the current practice, simulation has already been widely used in product design, tracking materials, and production processes, but looking forward, simulation will be more broadly used in plant operations (Rüßmann, et al., 2015). This research is focused on using simulation to improve the productivity of manufacturing procedures. The applications of simulation in manufacturing are reviewed in the following sections.

I. Sequence Optimizations

As initial inputs to the production system, the sequencing and scheduling of job orders have vital importance to the workflow on the factory floor. Different products usually have different production time in the same workstations A favourable job sequence can ensure a smooth production flow with the least amount of worker idleness or over-production throughout the entire shift. Simulation-based sequencing tools can reduce manual effort in scheduling. The state-of-the-art simulator can test out the permutation and combination of job orders and present the best sequencing scenario in a timely manner (Kühn, 2006). Kämpf and Köche (2006) have used simulation to optimize order sequencing and lot size design considering a limited warehouse storage capacity, set-up cost and times, and switching production between different items.

II. Process Simulation

A manufacturing process is defined as using one or more procedures to transform materials into a demanded product (Chryssolouris, 2013). Discrete event simulation tools can be used to mimic the production process. The simulation tools can assist in optimizing material flow, resource utilization, and logistics through statistical analysis of production procedures (Kapp, Löffler, Wiendahl, & Westkämper, 2005). Bako and Božek (2016) have simulated the manufacturing processes of an office equipment manufacturer and provided the company with a visual understanding of current capacity, utilization rate, and material consumption. Omogbai and Salonitis (2016) have used a simulation model to mimic implementing the changes proposed by lean into the current system, and through analysing lean performance values, the research justified and quantified the payback of each change.

III. Dynamic line balancing

Conventional line balancing is performed based on operation cycle time calculation, but discrete event simulation can assist in line balancing from a dynamic perspective. It can evaluate the work-in-process, utilization rate, and buffer sizes in different scenarios, and decide the most balanced production line design. (Kühn, 2006). Mendes et al. (2005) have used discrete event simulation models to statistically verify the line balancing solutions provided by heuristic analysis in a mixed-model PC camera assembly line, and by doing so, the flow time and average utilization rate of different work allocation can be calculated to provide deeper insight into the system. Masood (2006) has used simulation software to demonstrate the increase in machine utilization rate and reduction in cycle time through re-sequencing the existing operations and improving the conditions of tools. Melouk et al. (2013) have developed a simulation model for a steel manufacturing company to experiment with the influence of balancing operation time and capacity, and experimentation suggested a significant reduction in cost through adjusting work-in-process inventory and balancing operations.

2.2.4 Challenges

Although after decades of evolution, simulation has seen great improvement, there are still fields that can be further developed in simulation. Technically speaking, currently, not many commercial simulation tools have integrated cloud-based functionality into their software, which hinders the application of simulation tools on model devices and the interoperability between different partners (Mourtzis, Doukas, & Bernidaki, 2014). Moreover, the libraries in most simulation tools only focus on the basic modelling of manufacturing processes without considering the wide field and complexity of manufacturing (Mourtzis, Doukas, & Bernidaki, 2014). At the same time, the lack of modelling templates in most simulation software applications has made the development and verification of large models very time-consuming (Lee, Kang, Kim, & Do Noh, 2012). Developing high-performance software with powerful functionality at a minimal cost is a problem that still needs to be solved.

Regarding the research studies focused on simulation analysis, very few applications take the lifecycle cost into consideration. Most research studies only focus on the inefficiency of system design and better resource allocation, but the field of lifecycle analysis is still waiting to be explored.

Chapter 3 Methodology

3.1 Window Manufacturing Process Introduction

3.1.1 Window category and components

This research was carried out at the WD company, a window and door manufacturing company that has been in business more than 40 years. The company has three manufacturing facilities, seven branches, and close to 800 dealers throughout Canada. This study concerned the most complicated and biggest production line at WD, which is called the "Apex line". Two series of windows were produced on the production line: the 9950 series, a metal clad PVC window series; and the 9100 series, an acrylic wrap window series. There are four types of units manufactured on the line as shown in Figure 3-1: 1) casement is referred to a window that includes a sash attached to a frame by a hinge on one side, and the sash can swing outwards like a door; 2) awning is referred to a window that includes a sash hinged on the top that can swing outwards; 3) fixed is referred to window that includes a sash that doesn't open; 4)picture is referred to a window that doesn't have a sash. The profile of a picture window is smaller compared to a fixed window, so the glass surface is maximized.

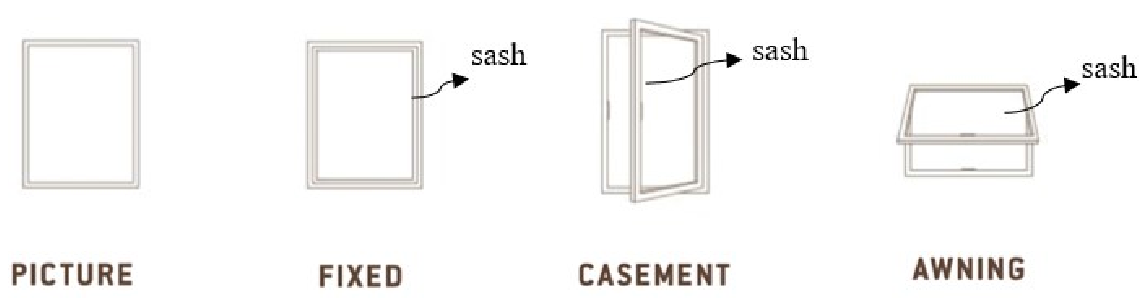


Figure 3-1: Window Catalogue (Window Catalogue, 2017)

Most windows are combination of single units. Up to 16 units can be combined to make one window. Typically, a window with more units takes longer time to make. Some typical window combination examples are given in Figure 3-2. A Window consists of multiple components. The anatomy of a typical window is given in Figure 3-3.

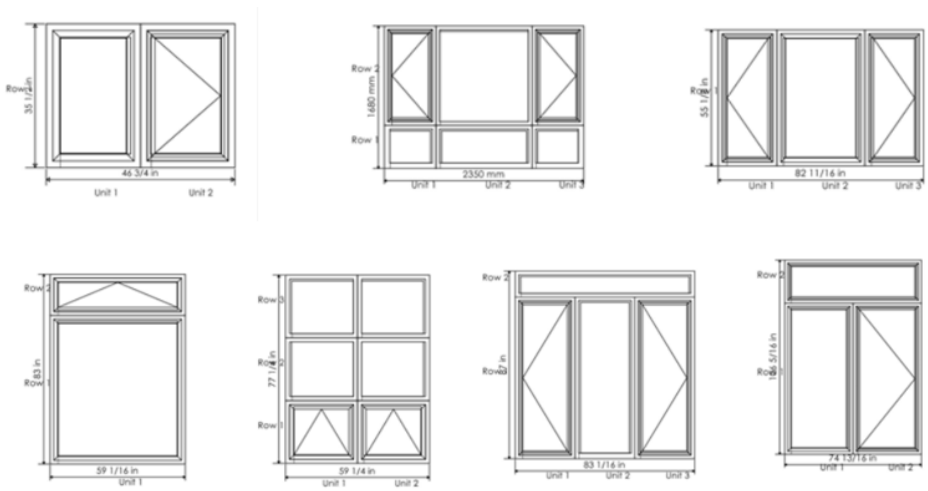


Figure 3-2: Window Combination Examples

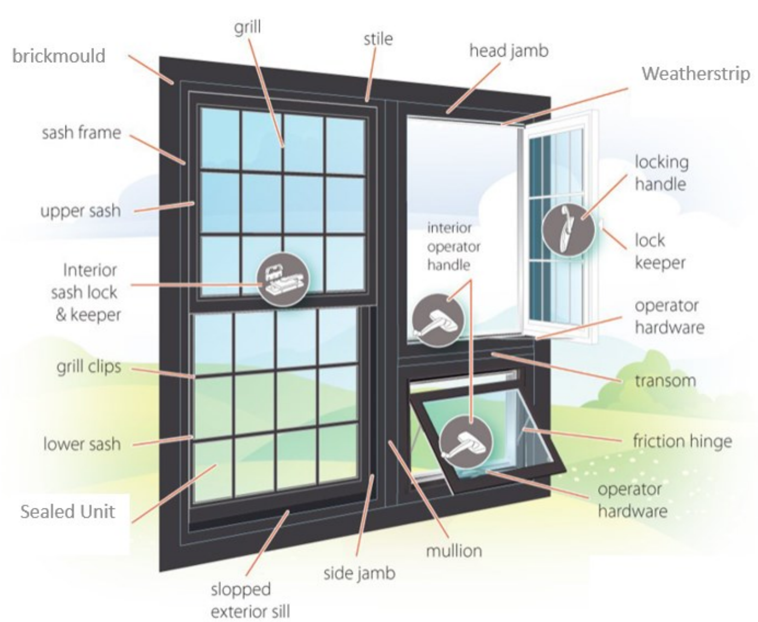


Figure 3-3: Anatomy of a Window (Bayview Windows, 2017)

The windows at DW are made using PVC profiles. The profile that forms a division between window units is referred to as mullion. Figure 3-4 shows the three views of a frame profile sample and Figure 3-5 shows the three views of a mullion profile sample.

Figure 3-4: An Apex Line Frame Profile Sample

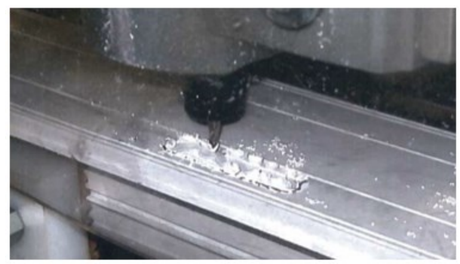
Figure 3-5: An Apex Line Mullion Profile Sample

3.1.2 Window manufacturing operations

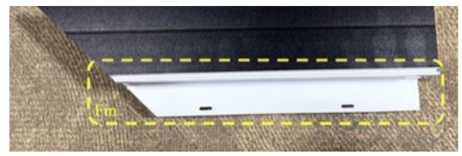
To manufacture a window, there are 29 typical operations as shown in Table 3-1.

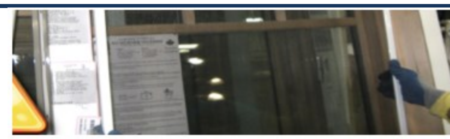
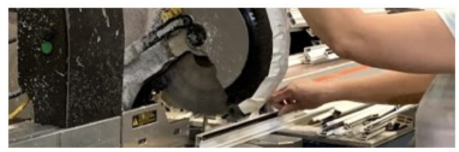
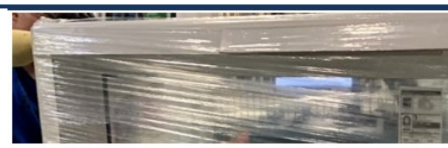
Table 3-1: Window Manufacturing Operations

Operations	***Pictures***

1. Cut and Router Frame Profiles: A worker loads the PVC profiles into the cutting machine. The machine cuts and routers the profiles. A worker unloads profiles, places stickers, and puts it on the cart. Each casement unit has one lock and one operator. Each awning unit has two locks and one operator.	
2. Cut Mullions: A worker picks mullion PVC profiles and loads them to mullion saw. The chop saw cuts PVC mullion profiles. A worker unloads profiles, places stickers, and puts profiles into the arrowhead machine, and finally places them on the table.	
3. Router Lock on Mullion: A worker routers a lock on a mullion manually.	
4. Router Operator on Mullion: A worker routers an operator on a mullion manually. A schematic diagram of cutting and routering is given in Figure 3-6.	
5. Install Reinforcing: If required, a worker installs a reinforcing bar into the mullion/frame profiles.	
6. V-notch: A worker puts the mullion or frame profiles into the V-notch machine and unloads it when the machine finishes. A comparison between before and after V-notch is given in Figure 3-7.	
7. Install Fixed Sash Clips: For fixed units only, a worker installs sash clips around the unit to hold the sash in place.	
8. Weld Mullion to Frame on Single Head Welder: A worker loads a mullion and a frame on the single head welder, welds one side then flips it to the other	

side, then cleans the unit corners by hand while the machine is welding.	
9. Weld Mullion to Frame on Double Head Welder: A worker loads mullions and a frame on the double head welder, welds one side then flips to the other side, then cleans the unit corners by hand while the machine is welding. Figure 3-8 is a schematic diagram shows welding mullion to frame operations.	
10. Weld Mullion to Mullion on Single Head Welder: A worker loads mullions on the single head welder, welds one side then flips them to the other side, then cleans the unit corners by hand while the machine is welding. Figure 3-9 shows the welding mullion to mullion operation.	
11. Weld Frame: A worker loads the frame profiles on the welding machine. The machine melts and joins the corners together. The welding frame operation is shown in Figure 3-10.	
12. Auto Corner Clean: The corner clean machine automatically cleans 6 corners of a single frame and transfers it to the hand clean area.	
13. Manual Corner Clean: A worker manually cleans the residual left from auto corner cleans. A comparison of a joint before and after corner clean is given in Figure 3-11.	

14. Paint Welding Joints: For the frame with colour coating, the colour in the joints is usually peeled off in corner clean, and as a result, a worker needs to paint the welding joints of the frame. The changing of color coating on the corners after corner clean and paint welding joints is giving in Figure 3-12.	
15. Install Gasket/Tape: A worker applies gasket/tape and stickers on the frame.	
16. Cut Fin: If required, a worker cuts four sides of the frame fin off.	
17. Install Brickmould: If required, a worker installs brickmould on the outer side of the frame. If there is no brickmould, a J-clip is installed on the bottom of the frame instead.	
18. Install Frame Hardware: A worker installs track, ramp, operator, snubber, and lock handle on an awning or casement unit.	
19. Install Cladding: For the 9950 series only, a worker installs metal cladding on the outer side of the frame and mullion.	
20. Install Sash: A worker installs one fixed/awing/casement sash on the frame, punches, and screws in nails	
21. Install Jamb Extension: If required, workers install jamb extension and accessories on the inner side of the frame.	

22. Install Cardboard and Shipping Blocks: A worker installs cardboard, shipping blocks and door sweep around the frame.	
23. Install Lumber: For oversized windows, a worker installs lumber strips on the frame.	
24. Glaze Sealed Unit: A worker glazes a sealed unit on the frame and installs glazing stops around the unit.	
25. Install Screen: If required, a worker installs the screen on the unit.	
26. Cut Glazing Stop: A worker gets glazing stop profiles, cuts profiles in a chop saw, and installs glazing gasket and placed them in cart.	
27. Punch Glazing Stop: A worker picks up glazing stops, drills holes, and places them in a cart.	
28. Quality Check and Scan: A worker performs quality checking and scans unit, applies stickers and a new label.	
29. Wrapping: A worker picks a window, wraps, and puts the wrapped window on a cart.	

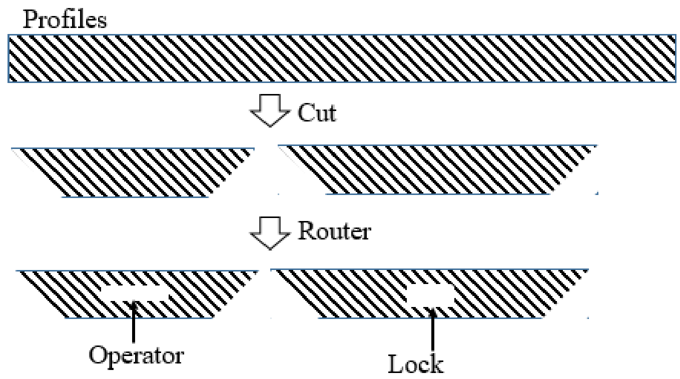


Figure 3-6: Cut and Router Profiles

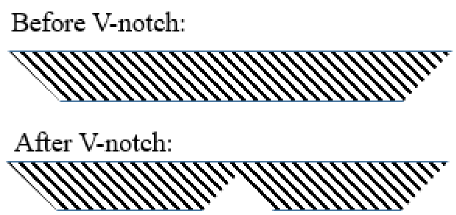


Figure 3-7: V-notch

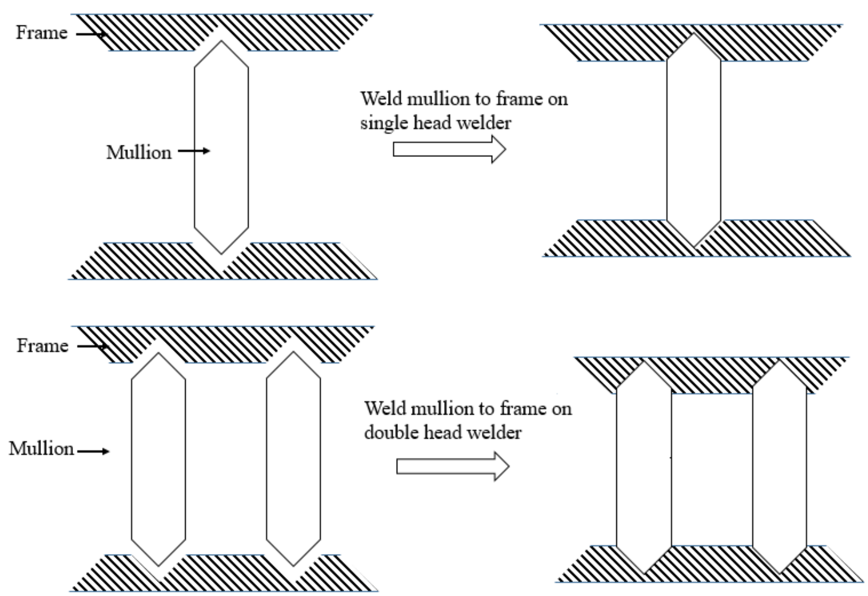


Figure 3-8: Weld Mullion to Frame

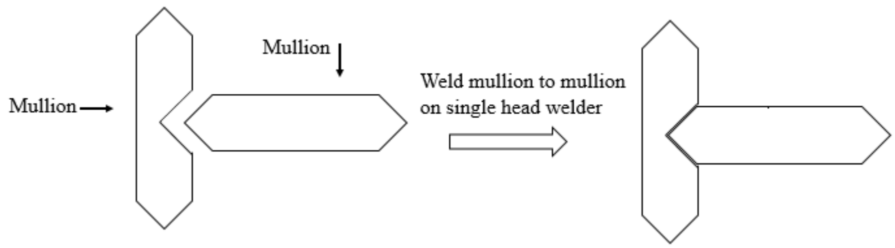


Figure 3-9: Weld Mullion to Mullion

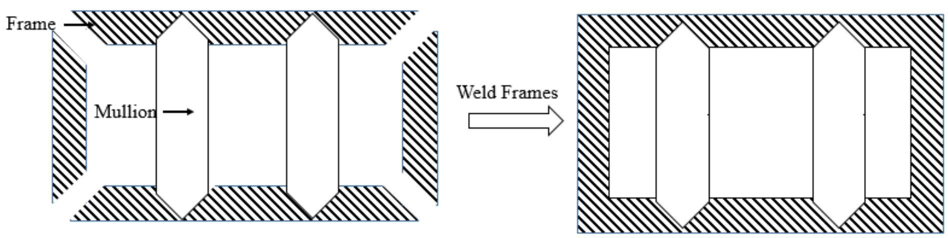


Figure 3-10: Weld Frame

Figure 3-11: Comparison between Before and After Corner Clean

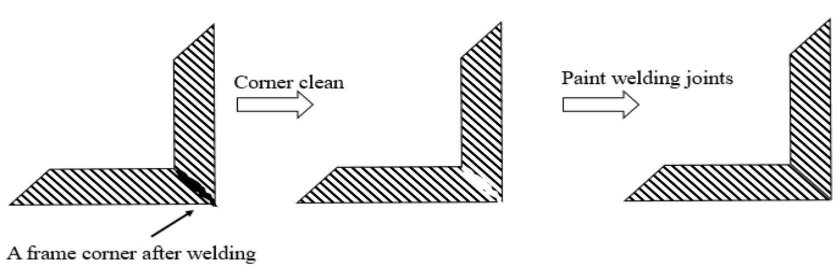


Figure 3-12: Paint Welding Joints

The operational sequence is shown in Figure 3-13.

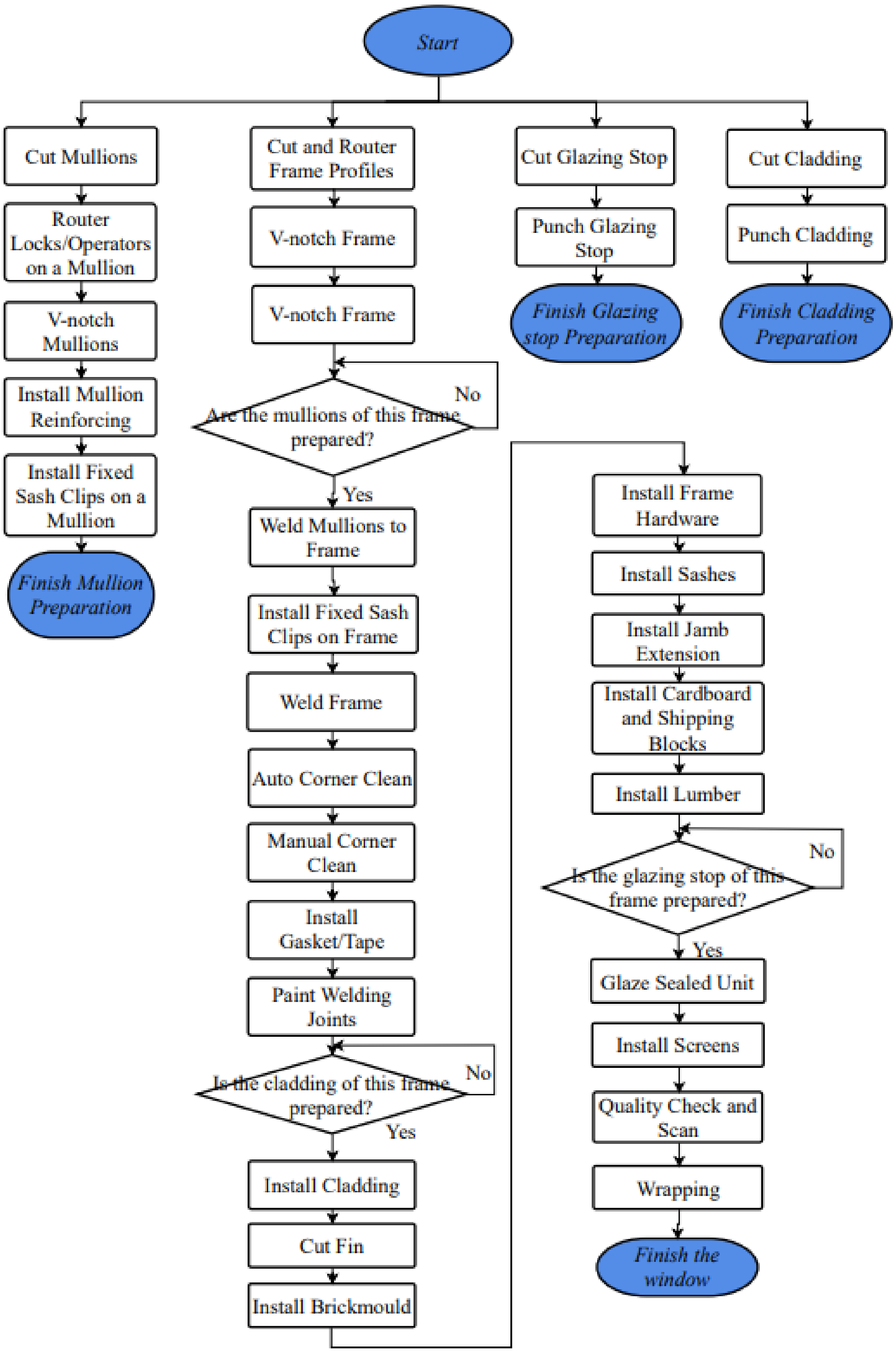


Figure 3-13: Apex Line Flow Chart

3.1.3 Workstations

There are 10 workstations on the Apex line. Within each station, all the workers are able to perform all the operations (multi-taskers). The resources, both workers and machines, are shared between operations within each workstation.

1. The frame cutting station is shown in Figure 3-14. The PVC materials are cut into required lengths. Each frame consists of four pieces of PVC profiles. The routing of the frame operator and lock are also finished inside the machine when the material is cut.

Figure 3-14: Frame Cutting Station

2. The mullion prep and frame welding station is shown in Figure 3-15. The Apex line has an innovative welding technology called V-weld, which means all the mullions and frames are welded together to eliminate water and air leaks. An automatic 6-points welder can

weld up to six points of frame and mullion together, while the rest of the welding points are done manually before loading to the automatic welding machine.

Figure 3-15: Mullion Prep and Frame Welding Station

3. The corner clean station is shown in Figure 3-16. The PVC materials are melted and joined together in welding. Unavoidably, there is melted PVC scraps left on the corners after welding. An automatic corner clean machine can clean the majority of the scrap, and what is left is cleaned by hand.

Figure 3-16: Corner Clean Station

4. The gasket installation station is shown in Figure 3-17. In this workstation, gasket and weatherstrip are installed on the frame. Also, for the windows with colours other than white, the colour coating is ripped off in corners due to cleaning. To paint the colour back on to the corners, an operation called touch-up paint is also performed in this workstation.

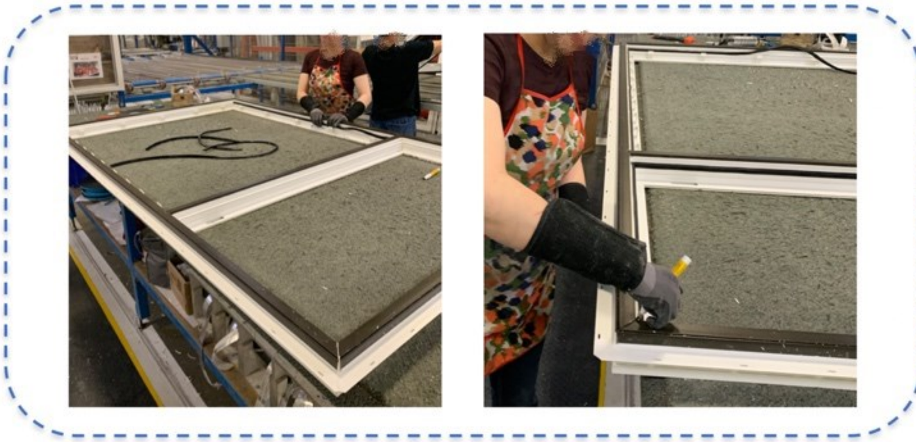


Figure 3-17: Gasket Installation Station

5. The frame hardware installation station is shown in Figure 3-18. The installation of brickmould, sashes, cladding, and hardware on the frame are all performed in this workstation.

Figure 3-18: Frame Hardware Installation Station

6. The final assembly station is shown in Figure 3-19. In the final assembly station, the workers install the jamb extension, cardboard, and shipping blocks on the window.

Figure 3-19: Final Assembly Station

7. The glazing station is shown in Figure 3-20. Windows are glazed in this station, which means this is the station where the glass is installed.

Figure 3-20: Glazing Station

8. The glazing stop preparation station is shown in Figure 3-21. To hold the pieces of glass in place, each sealed unit requires four pieces of glazing stop. All the glazing stops used in the glazing station are cut in this station.

Figure 3-21: Glazing Stop Preparation Station

9. The cladding preparation station is shown in Figure 3-22. The metal clad for the Apex line are cut in this station.

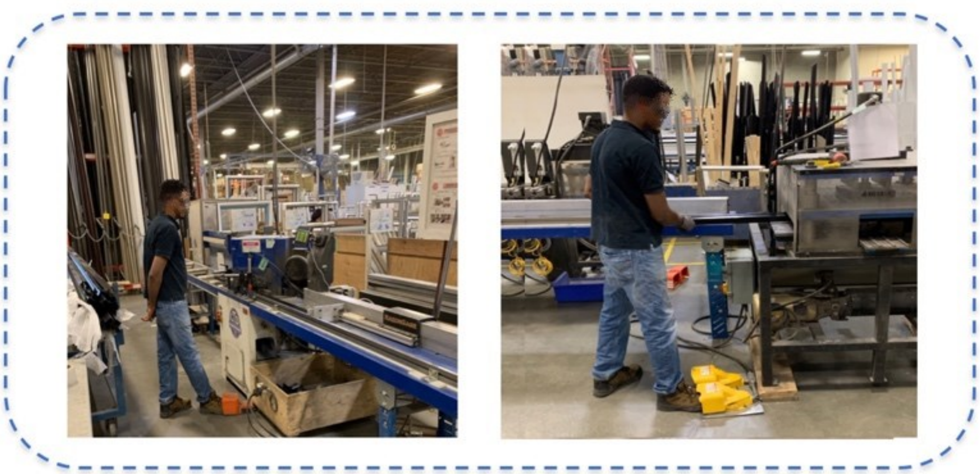


Figure 3-22: Cladding Preparation Station

10. The wrapping and scanning station is shown in Figure 3-23. At the end of the line, quantity checks are performed in this station. Qualified windows are wrapped and transferred to outbound for shipping.

Figure 3-23: Wrapping and Scanning Station

The Apex line is in production every Monday to Friday. There are two operation shifts: the A shift, also known as the day shift, works from 7 am to 3:30 pm; and the B shift, also known as the night shift, works from 4:40 pm to 1 am. Each work shift has a 30-minute unpaid lunch and two 15 minute paid breaks, so the effective working time of each shift is 7.5 hours. All the manual processes stop during the break.

3.2 Methodology Overview

This research presents a method of combining lean manufacturing and simulation tools in production line productivity improvement. This chapter will elaborate on the methodological approaches, the data collection, and the research processes. A framework of integrating lean manufacturing and simulation production line performance will be detailed in this chapter, and in the following chapters, the framework presented will be examined and validated through a case study with a local window and door manufacturing company.

Many manufacturers share the common misconception that their manufacturing process is efficient (Melton, 2005). One reason causing this misconception is that manufacturers are often too familiar with their production lines and all the operating procedures may seem already proper. Therefore, we chose lean manufacturing as one of the key methods to perform a productivity enhancement analysis because lean manufacturing allows to review the entire manufacturing process. As mentioned in the previous chapters, using lean manufacturing tools such as value stream mapping and employee perception, manufacturers can identify the waste in current processes and find the root cause. Other lean tools such as Kanban system and Kaizen can also be used to eliminate the waste. As discussed in Chapter 2, previous studies and applications have proven lean's ability to minimize inventory, reduce cycle time, and improve productivity and quality.

However, in practice, it has been observed that manufacturing companies are generally reluctant to apply the major changes proposed by lean analysis (Abdulmalek & Rajgopal, 2007). The considerate cost and energy of adding new machinery and moving cumbersome machines around the plant are inherent reasons that make it difficult to implement changes proposed by lean. At the same time, the payback of implementing changes is also uncertain since the lean method can't quantitatively calculate the benefits. To solve such a problem, the changes proposed by lean are categorized into four types, don't do, strategic, quick hits, and gems respectively, using a value graph. The classification depends on two factors, the effort required to eliminate the waste and the benefit obtained by removing the waste. The layout of a value graph is given in Figure 3-24 (Prashar, 2014).

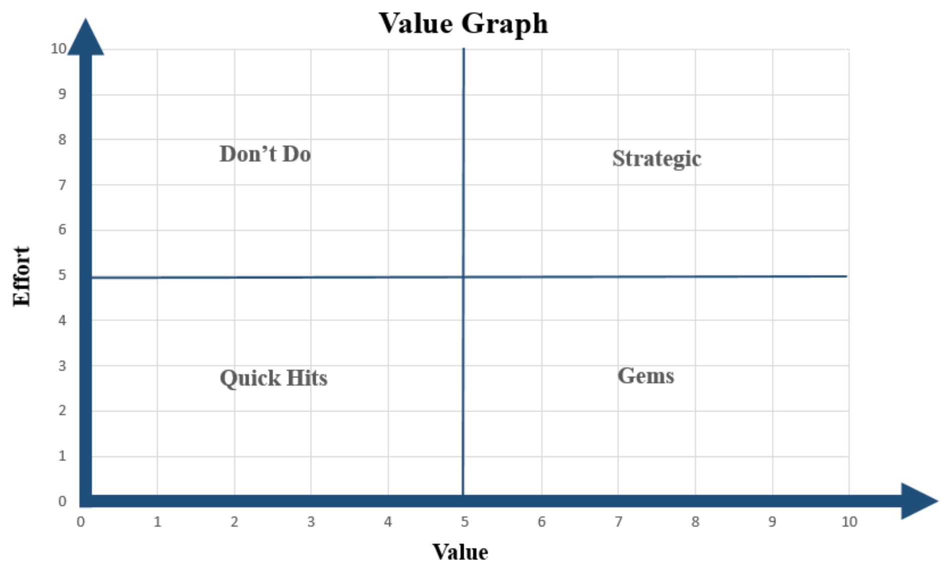


Figure 3-24: Value Graph

For those strategic changes that require high effort but also have high benefit returned, simulation analysis is performed. This research uses discrete event simulation because it best reflects the features of production lines where materials transform after passing a workstation. Simulation tools enable us to mimic the dynamic work process and present the workflow in a more tangible way. It can statistically analyse the payback of implementing changes, which can support decision making. Furthermore, simulation will be used to identify the bottleneck in production and also test out the best resource allocation scenario that can balance the production flow.

In conclusion, by integrating simulation tools and lean manufacturing, not only can we identify the waste on the production lines and propose changes accordingly, but we can also statistically analyse the gains of implementing changes before actual production.

3.3 Research Processes

To achieve the research objectives, this research will follow the methodology shown in Figure 3-25.A time study will be performed on Apex line at the WD manufacturing facility. For every single operation, multiple time data are collected are raw data, and the time study procedure is detailed in section 3.4.1. Also, in this stage, a process study is performed, in which operational sequence and resource layout are studied. The order information and actual productivity are also recorded. Using lean manufacturing techniques, value stream mapping in particular, the waste in the production process is identified. This research includes the root cause analysis of existing non-value-added procedures and corresponding solutions are proposed. Proposed solutions will be categorized into four kinds using "value graph". The changes requiring high efforts but also having high benefits are called "strategic". Before implementing strategic changes, future analysis in simulation is needed. Simulation models of the Apex line is built based on data from the time study and the process study. The models are validated using actual production numbers and current resource allocation. Simulated production rate (sealed unit/man-hour) are compared to the actual production rate to verify the accuracy of the model. The last stage is the simulation analysis; Simulation models are used to mimic the production under strategic changes. The strategic changes with the highest payback are selected. After implementing changes, simulation is used to identify the bottleneck in production and propose the best resource allocation scenario.

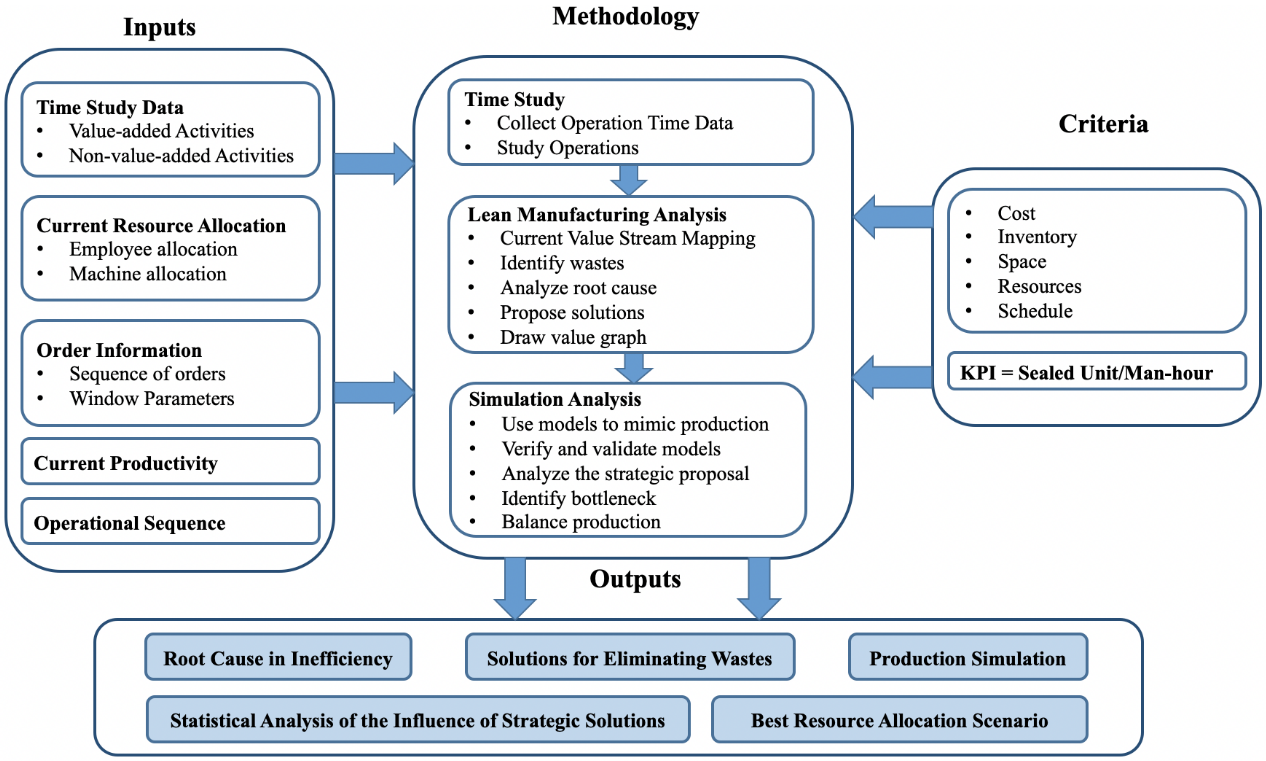


Figure 3-25: Research Process

3.4 Data Collection

3.4.1 Time study

Time study is a process that tracks the start to finish time of each operation. The quantitative data collected can be used to perform future analyses, planning, and improvement. As discussed in section 3.1.2, there are 29 operations on the Apex line as listed in section 3.1.2. For the same operation, the operation time can differ based on the variances below:

- The type of each unit
- The combination of units
- The size of window
- The type of components

- The material of components
- The colour of the window

To reflect the variances of operation time listed above, a spreadsheet with the columns as listed in Table 3-2 is created to capture all value-added operation activities.

Table 3-2: Value-added Activities Spreadsheet

Column Name	***Description***
Series	The series number of the production line
Workstation	The station in which the operation takes place
Operation	The name of the operation
Size Range	The range of a window's overall size
Time Calculation Unit	Seconds or seconds/mm
Rules	The rules of calculating operation time
Operation Description	Detailed description of operation steps
Observed Time 1	The first time that is observed to complete the operations
Observed Time 2	The second time that is observed to complete the operations
Observed Time 3	The third time that is observed to complete the operations
Average Observed Time	The average of three observed time collected

In addition to value-added activities, there are also non-value-added activities in between operations. These non-value-added activities are called waste according to lean manufacturing. There are seven types of waste on the production line, namely defects, overproduction, waiting, transportation, motion, extra-processing, and inventory. Some of the non-value-added activities happen in between operations, for example, the transportation of a product from one workstation to another. Some non-value-added operations follow a certain frequency, for instance, a cart of profiles is transferred from the cutting to the welding station once the cart is full. Additionally, there is waste that happens in a somewhat random fashion, such as when an employee may spend time finding the right component from a pile of components. The possibility of such waste occurring is recorded. A spreadsheet with the columns listed in Table 3-3 is used to collect non-value-added activities.

Table 3-3: Non-value-added Activities Spreadsheet

Column Name	***Description***
Waste Category	One of the seven types of wastes: defects, overproduction, waiting, transportation, motion, extra-processing, and inventory
Operation Name	Name of the non-value-added operations
Series	The production line on which the non-value-added activity occurs
Description	Detailed description of the non-value-added activity
Observed Time 1	The first non-value-added time collected
Observed Time 2	The second non-value-added time collected
Observed Time 3	The third non-value-added time collected
Average NVAT	The average of three non-value-added time collected
Frequency/Possibility	The frequency or possibility of the non-value-added activity.

To collect accurate quantitative data, the following instructions from the time study guidelines are followed (Kanawaty, 1992):

- The time study person is open and frank with workers about the purpose of the time study.
- The time study person collects the data without distracting the worker or interfering with their normal operations.

- Operation time data are recorded when the operation is performed by a skilled, well-trained worker who is working at a standard working pace.
- The time study person maintains a professional, friendly relationship with workers throughout data collection.
- Operation time for the same operation are collected on different working days and/or times to capture any variance in the operation time.

3.4.2 Current resource layout

The operation resources required in each workstation are recorded in Table 3-4 as input for the lean manufacturing analysis and simulation model.

Table 3-4: Current Resource Layout

Workstation Name	Operations	List the operation names here
	Machines	List the machine name and number here
	Number of Operators	List the number of operators in each shift

3.5 Current state mapping

3.5.1 Value stream mapping

Value stream mapping (VSM) is a tool that came out of lean manufacturing. It is a special type of flow chart that not only includes the material flow, but also the information flow. Value stream mapping focuses on the continuous improvement of the entire manufacturing flow rather than single operations alone. It allows companies to identify the waste on the value stream. Value stream mapping consists of three steps. The first step is to use a variety of unique VSM icons to conduct current state mapping. There are four types of VSM symbols: process symbols, material symbols, information symbols, and general symbols. The symbols used in this research are shown in Table 3-5, Table 3-6, Table 3-7, and Table 3-8, and After mapping the current value stream, the second step is to identify the muda (waste) in the value stream, find the root causes and solutions to eliminate the waste, and create the future state of the value stream. The third and final step is to apply the changes to improve production.

Table 3-5: VSM Process Symbols (Rother & Shook, 2003)

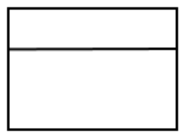
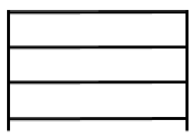
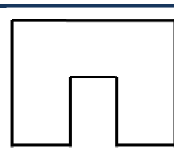
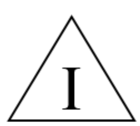
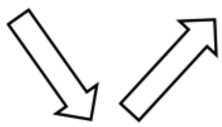
Process Symbols	***Symbol Icons***	***Description***
Supplier/Customer		Represents the supplier when it is placed on the upper left corner and represents the customer when placed on the upper right corner
Process Box		Represents operation through which the material flows. It is usually used to describe an area of material flow
Data Box		Carries out important data and information required for further analysis
Workcell		Represents multiple operations are conducted in the same work station

Table 3-6: VSM Material Symbols (Rother & Shook, 2003)

Material Symbols	***Symbol Icons***	***Description***
Inventory		Represents the inventory between two operations
Shipment		Represents the shipment of materials from the supplier to the factory, and the shipment of material from the factory to customers

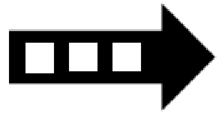
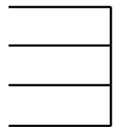
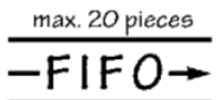
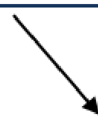
Push Arrow		Represents the flow of material from one operation to another
Supermarket		Represents a Kanban stock point
Withdrawal		Represents the physical removal of shored inventory from supermarkets
FIFO Lane		Represents there is a First-In-First-Out constrain in the process
External Shipment		Shipments using external transport

Table 3-7: VSM Information Symbols (Rother & Shook, 2003)

Information Symbols	***Symbol Icons***	***Description***
Production Control		Represents a central scheduling and controlling department
Manual Info		Represents the flow of information from memos, reports or conversations
Electronic Info		Represents the flow of digital information such as electronic data, online orders, and weekly fax

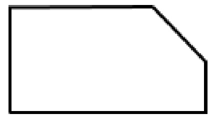
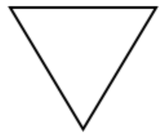
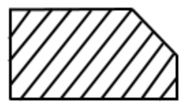
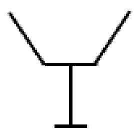
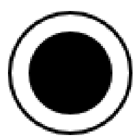
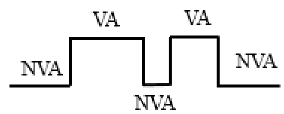
Production Kanban		Triggers the production of a defined number of parts which are required for downstream operations
Signal Kanban		Represents the inventory level in the supermarket drops to a trigger or minimum point and signals the production of parts.
Withdrawal Kanban		Represents the number and type of parts that should be withdrawn from supermarket to a process.
Kanban Post		Represents the location for collecting Kanban signals.
Sequenced Pull		Represents a pull system that instructs subassembly processes to produce a predetermined type and quantity of parts without using a supermarket
Go See		Represents getting information from observation.

Table 3-8: VSM General Symbols (Rother & Shook, 2003)

General Symbols	***Symbol Icons***	***Description***
Kaizen Burst		Highlight the operations in which improvements and kaizen analysis are required to achieve future state of value stream

Operator		Represents the number of operators in an operation
Timeline		Indicates value-added-times and non-value-added-times

3.5.2 Employee perception

As discussed in section 2.1.3, the perception of employees is of vital importance to the successful implementation of lean manufacturing. To benefit from the rich practical experience of workers on the line and also to take into account the concerns of workers, a meeting with all supervisors, team leaders, process analysts, and manufacturing managers is held after the current value stream mapping. Over 20 people attended each meeting, and majority if the attendee had lean trainings and lean certifications. During the meeting, the suggestions and existing waste in the current value stream from the employees' perspective will be presented and discussed.

3.6 Root Cause Analysis and Changes Proposal

The waste on the line can be recognized from different perspectives. To find the root cause of wastes, the 5 Whys technique is used in this research. The 5 Whys technique is the most commonly used strategy in identifying root causes. As a tool in lean manufacturing, by repeatedly asking "Why?" five times with respect to a problem allows us to dig into the problem, be clearer with the nature of the problem, so "five whys" can lead to "one how" (Ohno, 1988).

Once the solution is proposed, the benefits and effort required for each solution are evaluated on a scale from 1 to 10. The benefits and effort required are quantitatively represented by a number.

According to the value graph, it is possible to use two parameters, which are the effort required to eliminate the waste and the benefit obtained by removing the waste, to categorize issues into four types:

- Strategic: The issues under the strategic category require relatively more effort, but the gains after applying the changes are considerable. Solutions to strategic issues often result in major changes in the manufacturing design; hence, more advanced and detailed analysis is required to support decision making.
- Gems: Gems refer to the solutions that require low efforts but have high benefits or short-term paybacks. Gems are the most favorable solutions and should be carried out first.
- Quick Hits: Quick hits usually take low effort. Even though the benefit may not be significant at the current time, solving one quick hit issue may lead to solving other issues. Quick hits may trigger a chain reaction that brings high benefits in the future.
- Do Not Do: At the current time of analysis, the gains in this category are not significant enough to be worth the effort.

In practice, most companies are willing to apply the changes to accomplish "gems" and "quick hits" because these changes require low effort. In most manufacturing companies, the cost of reallocating resources, purchasing new machinery, modifying the manufacturing process, etc. are high. The strategic solutions usually result in major changes in the plant. If there is not enough justification for future paybacks, the managers are usually reluctant to put lean analysis into practice. Typically, further analysis is necessary before implementing strategic changes. In general, one tool that can quantify gains and make gains visible in the early planning stage is simulation. The statistical analysis from simulation tools can enable managers to compare the potential future performance of changes to the existing system. In this research, the solutions that fall into the strategic category all need to go through simulation analysis before implementation to statistically analyze the gains.

3.7 Simulation Analysis

3.7.1 Developing simulation models

This research uses discrete event simulation (DES) to model the window manufacturing processes because it best reflects the actual production in which materials only transform after passing a workstation. Simphony, simulation software developed in the University of Alberta, is used as the tool of modelling. Description of discrete event simulation and Simphony can be found in Section 2.2.2. Developed based on the functional relationship and data of the real system, a simulation model should be able to mimic the dynamic responses and behaviour of the real system. As per AbouRizk et al. (2016), to make sure the simulation result is realistic and fruitful, a schematic given in Figure 3-26 needs to be followed.

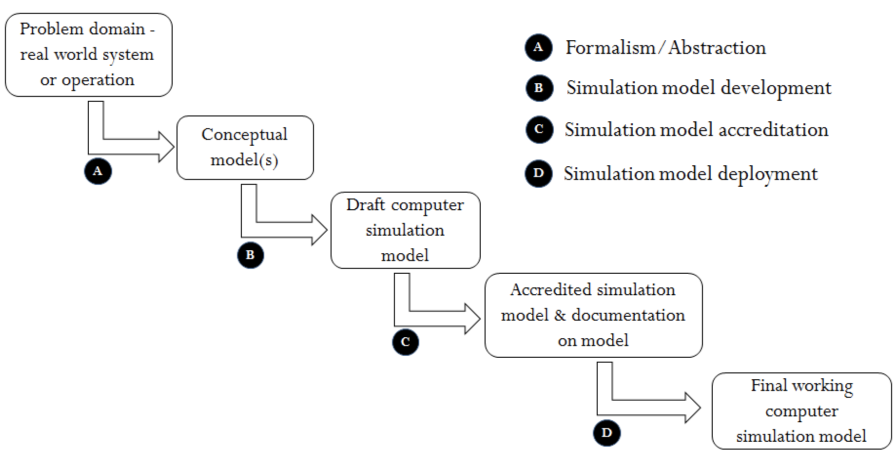
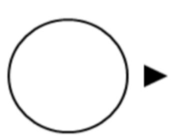


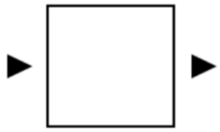
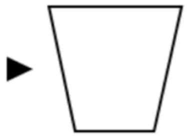
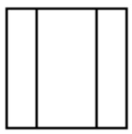
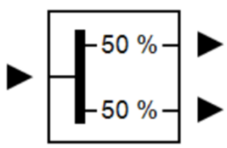
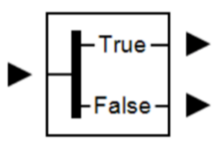
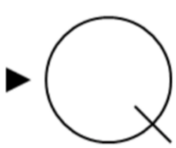
Figure 3-26: A Schematic Layout of a Typical Simulation Model Development Process (AbouRizk, Hague, & Ekyalimpa, 2016)

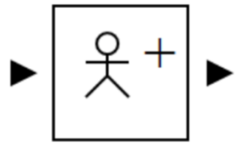
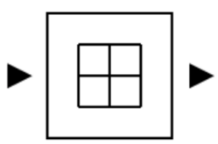
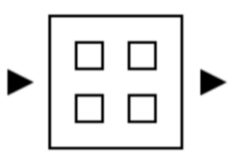
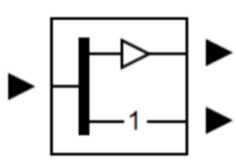
The first step in developing the simulation model is to abstract and identify the problems of the real system, which is designed to test out the impact of changes proposed by the lean analysis and improve the process design of window production lines to reach higher productivity. The main production lines are selected to be the problem domain. The assumptions, inputs, and specifications are defined in the conceptual model stage. Followed by which, the draft computer simulation model is built using the information gained from the time study, the process study, and the resource allocation study as described in section 3.4. The development of the model uses the general template within Simphony. A brief introduction to the modelling elements used to simulate the behaviour of the real system are given in Table 3-9.

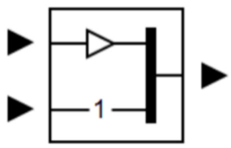
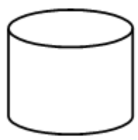
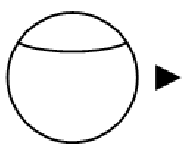
In the simulation model, elements are linked by arrows that direct the flow of entities. Entities, also called the flow units, are flowing through elements. In this research, the entities are window orders. Each entity carries out the information of each window, and it flows from the beginning to the end of the production line. The behaviour of each element is performed when an entity passing through it which mimics the operations that happen step-by-step on the production line.

Table 3-9: *Simulation Model Elements*

Element Name	***Symbol***	***Description***	***Properties***
Create		Introduces entities into the simulation model	1) The number of entities to create. 2) The simulation time at which the first entity will be created. 3) The time interval between entities.

Task		Represents an activity	1) The duration of the task. 2) The number of workers and machines required if it is a constrained task.
Destroy		Removes entities from the simulation model	None
Counter		Tracks the number of entities passing through	None
Composite		Contains elements for sub-models	None
Probabilistic Branch	 	Directs entities to different paths based on the probability	1) The probability for each branch.
Conditional Branch	 	Directs entities to different paths based on the condition	1) True and False conditions (If…then…else decision)
Resource		Define a resource	1) Number of Servers
File		Provide a location where the entities wait for a resource	1) The priority of the file

Capture		Allow an entity to request one or more servers	1) The resources the entity requires 2) The number of servers required 3) The priority of the request 2) The file in which the entities will wait if the request cannot be fulfilled
Release		Allow an entity to cease using one or more servers	1) The resources to be released 4) The number of servers to be released.
Statistics		Defines a custom statistic	2) None
Statistic Collect		Adds an observation record when an entity passes through	1) The statistics to which the record will be collected The value to collect
Batch		Batches a certain number of entities together	1) The quantity of entities per batch 2) The entity whose attributes will be used as the batch attributes (first or last)
Unbatch		Unties the entities batched together	2) The order in which the entities should be unbatched (FIFO or LIFO)
Generate		Creates one or more copies of the entity passing through	1) The number of copies to generate

Consolidate		Destroys one or more copies of the entities passing through	1) The number of copies to destroy
Execute		Executes user-written code when an entity passing through	None
Database		Connects to a database	1) Connects string to a certain database
Database Create		Introduces entities into the simulation model with the attributes set in a database	1) The database from which data are retrieved 2) From which fields in the database will the local attributes of entities get data from 3) The query to retrieve demanded data from a database 4) The start time of each entity

3.7.2 Simulation validation and verification

Simulation models are generated based on the observation and data from the real system, and they should be able to mirror the behaviours of the real system. In this research, simulation models will be used to support the decision-making and test the what-if scenarios. In window manufacturing companies, the cost of reallocating resources, purchasing new machinery, and modifying the manufacturing process is high; therefore, it is imperative to validate and verify the models to make sure they correctly capture the real system it mirrors. The relationship between simulation and reality is shown in Figure 3-27. Simulation models are built on the conceptual model which is origin from reality.

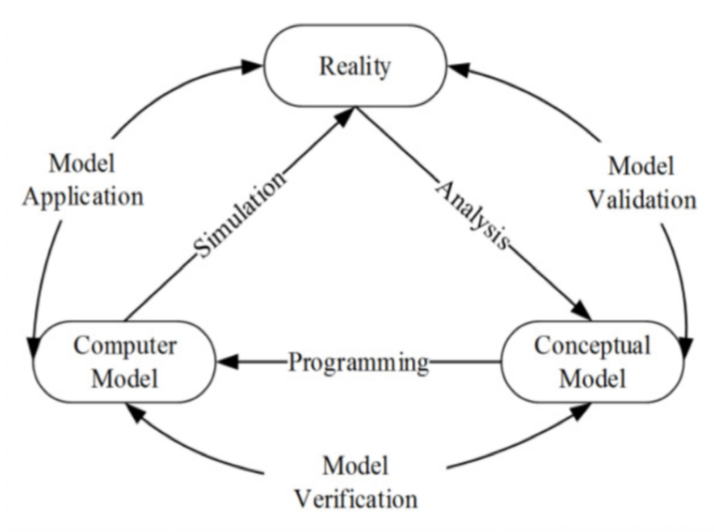


Figure 3-27: Relationship between Simulation and Reality (Bako & Božek, 2016)

In the verification stage, two verifications need to be conducted according to Sargent (2010): 1) specification verification to assure the properties and design on the specific computer system can reflect those in the conceptual models; and 2) implementation verification to ensure the simulation model is a valid implementation of simulation model specifications. To complete the verification, as suggested by AbouRizk et al. (2016), the following errors are checked:

- logical errors
- syntax errors
- data errors
- experimental errors
- bugs within the models

In the validation stage, the validation technique used is historical data validation. The production system of the WD company tracks the order information of windows, the number of workers on the line, and the number of windows produced each shift. The order information of the windows for two production days are selected to be the input of entities in the model. The simulation time is set to be 15 hours, which represents two shifts per day. At the end of the simulation time, the counter element is used to track the total number of sealed units produced. A key performance indicator (KPI), the productivity, is calculated within the model using Equation 3-1. The simulated productivity is compared to the actual productivity to check if the simulation model is close to reality.

$$Productivity\ (sealed\ unit/h) = \frac{Total\ number\ of\ sealed\ units\ produced}{Total\ labour\ hours\ required\ (h)} \qquad (3\text{-}1)$$

Note that it is often very pricey and time-consuming to validate whether the model is absolutely accurate and valid. Instead, a simulation model should be considered valid when enough confidence in its attended application is obtained. The relationship between confidence in a simulation model and model development effort, and corresponding value to a user is represented in Figure 3-28. As shown in the figure, the cost required to achieve high model confidence is extremely high, while at the same time the increased in value is small; therefore, a reasonable confidence goal is of great importance. In this research, the model will be validated using the actual production inputs, and the simulated productivity will be compared to actual productivity to reflect model accuracy.

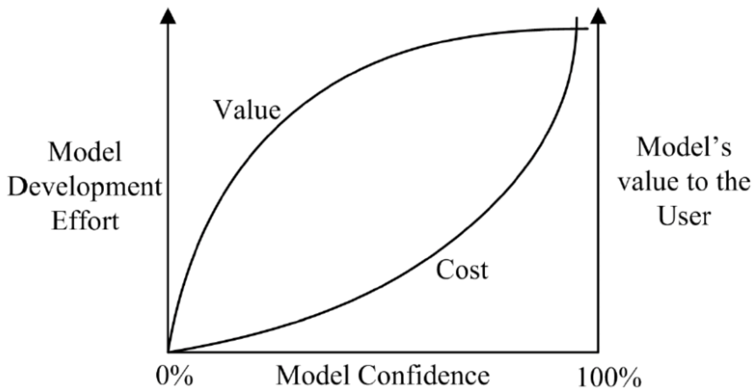


Figure 3-28: Model Confidence (Sargent, 2010)

3.7.3 Proposed changes analysis

As mentioned in Section 3.6, the changes proposed can be categorized into four types: strategic, gems, quick hits, and don't do. The changes that fall into the strategic category often require major changes in the manufacturing processes and/or design, for instance, purchasing new machinery or changing the material design. Those proposed changes are usually discussed at the managerial level. However, one intrinsic feature of the manufacturing sector is that the cost of relocating or purchasing machinery, or doing process modifications is usually high. Without enough justification on the payback, managers are often reluctant to adopt strategic changes. To alleviate this problem, this research will use simulation to statistically analysis the influence of strategic changes.

The input in the simulation models will be modified according to the changes proposed. At the general level, two performance indicators of the proposed changes will be compared to the current production: 1) the number of sealed units produced a day, 2) the productivity of the line. Ideally, a favorable change should not only boost the number of sealed units produced, but it should also be able to increase productivity.

3.7.4 Bottleneck identification

After the simulation is run, the utilization rates of all the resources are calculated. A sample of the resources utilization report is shown in Figure 3-29. This enables us to track the utilization rate of all workers and machines on a certain production day.

Resources

Element Name	Average Utilization	Standard Deviation	Maximum Utilization	Current Utilization	Current Capacity
Final Assembler	27.5%	23.5%	100.0%	20.0%	5.000
Flow Person	NaN	NaN	NaN	0.0%	1.000
Frame Cutter	48.3%	50.0%	100.0%	0.0%	1.000
Frame Cutting Machine	48.3%	50.0%	100.0%	0.0%	1.000
Frame Welding Machine	39.1%	48.8%	100.0%	0.0%	1.000
Frame&Mullion Welder	60.9%	18.0%	100.0%	16.7%	6.000
Gasket Installer	27.0%	29.8%	100.0%	100.0%	2.000
Glazer	29.6%	25.1%	100.0%	75.0%	4.000
Glazing Stop Cutting Machine	49.4%	5.6%	50.0%	50.0%	2.000
Glazing Stop Preparer	100.0%	0.4%	100.0%	100.0%	1.000
Hardware Assembler	56.7%	36.0%	100.0%	66.7%	3.000
Manual Corner Cleaner	31.9%	42.3%	100.0%	100.0%	1.000
Mullion Cutting Machine	88.8%	31.5%	100.0%	0.0%	1.000
Mullion Welding Machine	94.2%	23.4%	100.0%	100.0%	1.000
QC Checker	48.4%	40.4%	100.0%	0.0%	2.000
Single Assembler	42.5%	39.8%	100.0%	0.0%	2.000
Single Cutter	46.6%	49.9%	100.0%	0.0%	1.000
Single Welder	99.7%	5.2%	100.0%	100.0%	1.000
V-Notch Machine	91.3%	28.2%	100.0%	0.0%	1.000

Figure 3-29: Resource Utilization Rate Sample

A smooth workflow and harmonious cooperation between workstations are essential to high productivity. A workstation can become a bottleneck when the workload in that station is heavier than average. In this research, when the utilization rate of a workstation is higher than 90%, it is considered as a potential bottleneck. To determine if a workstation is a bottleneck, the following test will be conducted:

1) Run a simulation model that only targets one workstation to test the full capacity of that station. If it is close to the number of windows produced a day, then:

2) In the original model, put more resources in the bottleneck to check if the overall productivity increases significantly. If so, the workstation is considered a bottleneck in production.

3.7.5 Line balancing

In a balanced production line, the cycle time of all workstations should be close. In today's manufacturing sector, the unprecedented increase in requirements for product customization and personalization have increased the level of difficulty encountered when balancing production as product variances cause fluctuations in the cycle time of each station, which has in turn brought about difficulties in calculating line balancing through using lean manufacturing exclusively. In this research, validated simulation models will be used to assist in line balancing. Based on the validated original model and the bottleneck deduced previously, the goal is to reach evened utilization rates in each workstation by reallocating the number of resources in each workstation. More workers will be put into the workstations where the utilization rates are high. By doing so, not only will the utilization rate in the bottleneck be reduced, but lower utilization rates in workstations can be boosted.

In this research, the inputs and outputs of simulation analysis are given in Figure 3-30. As shown in Table 3-10, three types of analysis will be performed. In strategic change analysis, the inputs will be changed according to request, and resource utilization rate and overall productivity will be used as indicators to reflect efficiency. The utilization rate and productivity of each resource can also be used to identify bottlenecks in the production line. Line balancing analysis is achieved by changing resource layout and checking resource utilization rate.

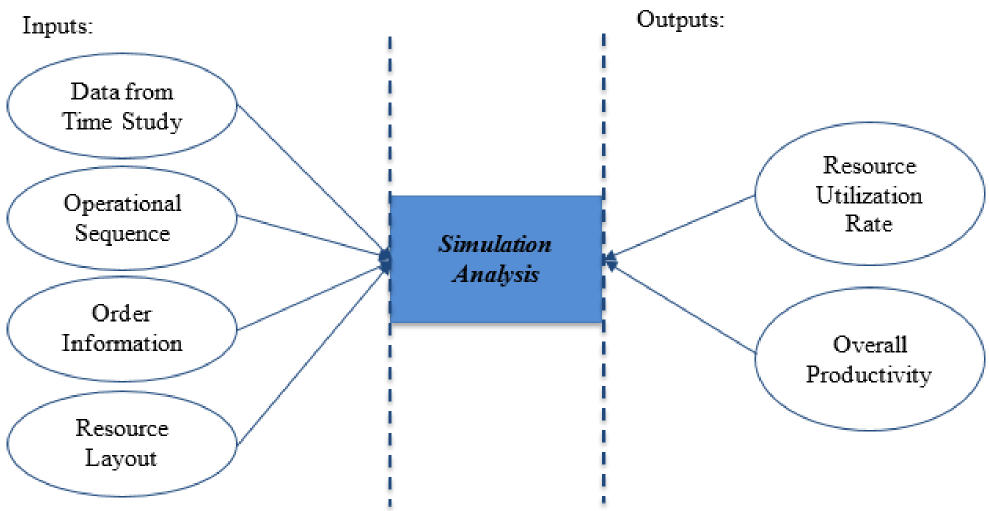


Figure 3-30: Inputs and Outputs of Simulation Analysis

Table 3-10: Variances and Indicators of Analysis

Analysis	***Variances***	***Indicators***
Strategic Change Analysis	As Required	Utilization Rate, Productivity
Bottleneck Identification	-	Utilization Rate, Productivity
Line Balancing	Resource Layout	Utilization Rate

3.8 Improvement Implementation

After the line manufacturing analysis, improvements will be categorized into don't do, gems, strategic, and quick hits. The improvements fall into gems and quick hits will be implemented directly as they don't require much effort in their application. Gems will be conducted before quick hits because the value returned is larger. For those improvements belonging to the strategic category, further analysis in simulation is required. If the simulation analysis shows a significant growth in overall productivity in a strategic change, it will also be put into practice.

Once the favorable changes in line manufacturing are implemented, simulation will be used again to identify bottlenecks in production. Based on the bottleneck identified, resource (workers and machines) reallocation will be performed in the simulation model to test out the best resource allocation for a balanced production line. A new resource layout will be implemented afterward.

3.9 Applicability of Methodology

This research presented a template to break down window manufacturing process, and the This research presented a template to break down windows manufacturing process, and the template can be applied to all window manufacturing companies. A template of conducting time study for window manufacturing is also provided in this research, and the template can be applied to similar manufacturing processes, such as door manufacturing process. The core of the presented methodology is to integrate lean and simulation analysis to identify waste, reduce waste, and statistically analyze the payback before actually implementing changes. The integrated method can be applied to any manufacturing flow.

Chapter 4 Implementation of Proposed Methodology

4.1 Apex line Introduction

The case study of this research was carried out at WD company. The case study concerned the most complicated and busy production line at WD, which is called the Apex line. In most cases, there were 200–300 windows produced on the Apex line per day. With mass customization and personalization, it was difficult to find the exact same window produced more than once on the same production day. The company found the current productivity lower than their expectation. Also, with so many variations in production, the company found it hard to balance the line given the cycle time of each order. The layout of the Apex line is shown in Figure 4-1. The raw materials were placed in the inbound area, and were then processed through different workstations. The finished windows were transferred to the outbound area waiting to be shipped.

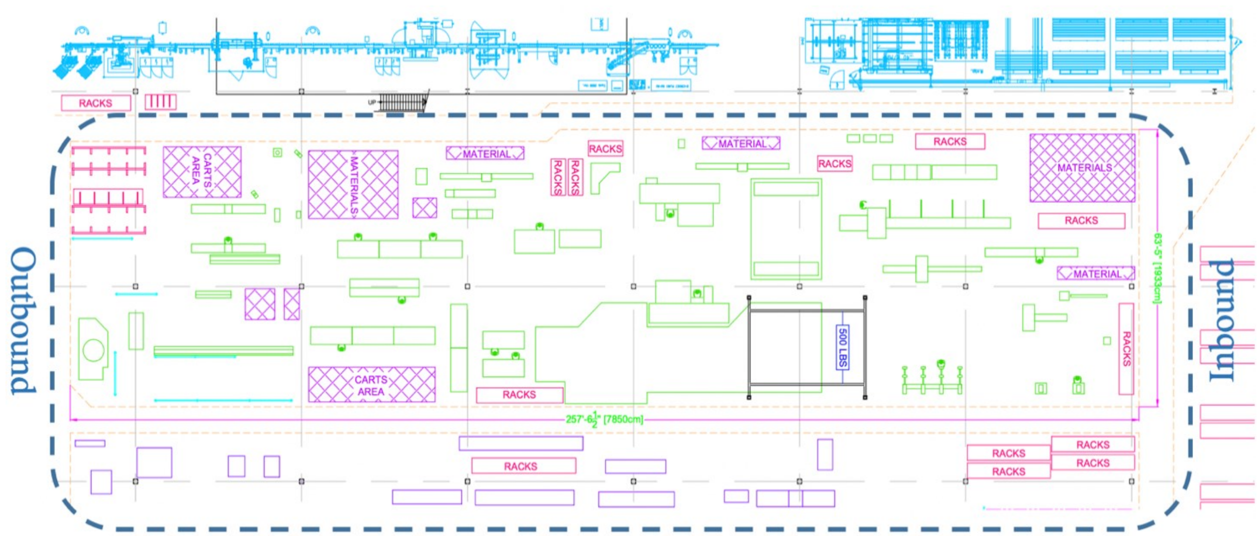


Figure 4-1: Apex Line Layout

4.2 Apex Line Current State Mapping

4.2.1 Apex line current resource layout

There were 10 workstations on the Apex line. The operation and resources for each station were recorded in Table 4-1 as the raw data for analysis.

Table 4-1: Apex Line Resource Layout

<table>
<tr><td rowspan="3">Frame Cutting Station</td><td>Operations</td><td>Cut and Route Frame Profiles</td></tr>
<tr><td>Number of Operators</td><td>A Shift - 1
B Shift - 1</td></tr>
<tr><td>Machines List</td><td>SD 800 saw *1</td></tr>
<tr><td rowspan="2">Mullion Prep and Frame Welding Station</td><td>Operations</td><td>Cut Mullions
V-notch
Install Reinforcing
Install Fixed Sash Clips
Router Lock on Mullion
Router Operator on Mullion
Weld Mullion to Frame on Single Head Welder
Weld Mullion to Frame on Double Head Welder
Weld Mullion to Mullion on Single Head Welder
Weld Frame</td></tr>
<tr><td>Number of Operators</td><td>A Shift - 6
B Shift - 6</td></tr>
</table>

	Number of Machines	Mullion Cutting Machine*1 V-notch Machine *1 Reinforcing Machine *1 Manual Router Machine *1 Manual Welding Machine *1 6 points Horizontal Welder *1
Frame Corner Clean Station	Operations	Auto Corner Clean Manual Corner Clean
	Number of Operators	A Shift - 1 B Shift - 2
	Number of Machines	Corner Clean Machine *1
Gasket/ Tape Installation Station	Operations	Install Gasket/Tape Paint Welding Joints
	Number of Operators	A Shift - 2 B Shift - 3
Frame Hardware Installation Station	Operations	Cut Fin Install Brickmould Install Frame Hardware Install Cladding Install Sash
	Number of Operators	A Shift - 4 B Shift - 4
Final Assembly Station	Operations	Install Jamb Extension Install Cardboard and Shipping Blocks Install Lumber
	Number of Operators	A Shift - 4 B Shift - 4
Glazing Station	Operations	Glaze Sealed Unit

		Install Screen
	Number of Operators	A Shift - 5 B Shift - 5
Glazing Stop Preparation Station	Operations	Cut Glazing Stop Punch Glazing Stop
	Number of Operators	A Shift - 2 B Shift - 1
Wrapping and Scan Station	Operations	Quality Check and Scan Wrapping
	Number of Operators	A Shift - 2 B Shift - 2
Cladding Preparation Station	Operations	Cut Cladding Punch Cladding
	Number of Operators	A Shift - 1 B Shift - 1

4.2.2 Apex line time study

According to the guidelines listed in section 3.4.1, the cycle time of all the operations on the line were collected and recorded. This included the value-added activities and the non-value-added activities. Multiple time data were collected for each operation, and the average of these time data was used as the operation duration. Value-added activities are tabulated Appendix A, and the non-value-added activities are given in Appendix B.

4.2.3 Apex line value stream mapping

Using the data collected, the current state map of the Apex line was drawn in Figure 4-2. There was inventory before cutting operations, but no inventory was found before other operations. The value stream map showed two kinds of important flows, the material flow and the information flow. In the operation and data box, the number of workers, uptime, and shift number were recorded. Note that the cycle time of operations was not given in this value stream mapping because due to mass customization, almost every single order was unique, and the cycle time of each window in each workstation varied a lot depending on the customized parameters. Taking the frame hardware installation as an example, a single 9100 series picture unit required no hardware, and the cycle time would be 0 seconds, but a 4000mm perimeter 9950 single awning unit with brickmould would take around 835 seconds. Considering the number of combinations of units, there was a relatively large variance in cycle times. Since there is wide range of cycle times for each operation, the cycle time was not included in the value stream mapping. The parts of the analysis that required quantitative analysis of cycle times, namely the line balancing and capacity check, would be performed using simulation models.

4.3 Apex Line Future State Mapping

After mapping the current value stream, a meeting with all the line supervisors, process analysts, the project manager, and team leaders was held to identify the existing issues on the Apex line. Multiple lean tools were used in identifying waste. After listing all the existing issues, the 5 Why technique was used to determine the root causes of the waste. Following the root cause analysis, corresponding solutions were presented for each existing issue. On a scale from 1 to 10, the effort required and benefit of solving each issue is also presented in the meeting. The results were tabulated into Table 4-2. There were 32 issues identified on the Apex line, and they were categorized into the four types depending on the effort required and the benefit, as described below. Figure 4-3 plotted the 32 issues in the value graph.

I. Quick Hits

The solutions that fall into this category could be summarized into 5 types: 1) There was no Kanban system on the line; therefore, the supply of materials was often delayed and workers had to travel all the way to inbound to pick up profiles. A Kanban system was needed to pull materials. 2) It was observed that some tools on the line were old and slow. An upgrade of the old tools was essential to high productivity. Also, a feedback system from the line should be developed to track the status of the tools. 3) Many issues on the line were caused by a lack of standard, or that an employee was not following the standard closely. To solve this problem, standard operating procedures (SOPs) needed to be developed, and also employee training was scheduled to ensure the implementation of SOPs. 4) There were issues related to the central planning system not being fully used. There was no cutting list for cladding and J-clips, which resulted in the late supply of components. Later, the cut list should be automatically generated by the central planning system every shift. 5) Besides the ageing of tools, the ageing of machines also raised concerns. A few machines on the line were operational the entire shift non-stop, which makes maintenance and regular cleaning imperative. In the solutions, a preventive maintenance (PM) schedule was created.

II. Gems

Two gem solutions were found on the line. Caused by a communication issue, the sash hardware supply was wrong from time to time, which is a problem that could be easily solved by improving coordination. For the glazing operations, if the sealed unit was placed on the cart in sequence, this simple step could reduce the potential of missing glass and time spent finding the correct glass.

III. Strategic

There were two major changes proposed that were classified as strategic. 1) The cutter needed to manually input the order information, while the machine actually had the ability to read saw files and cut accordingly. The company was planning to develop saw files that could eliminate manual input and increase productivity. At the time of the meeting, the saw capacity was 160 frames/shift. The company wanted to achieve 200 frames/shift once the saw files were developed. 2) The 6-points welder could only weld around 150 frames per shift, while 250 frames were required to be welded. It was observed that another 4-points welder for welding sash was not working at full capacity at the time of the meeting. A proposal was to separate single units out, which means it is possible to use sash welding and sash corn clean machines for single units to improve overall productivity. These two proposals required a great amount of effort and investment. Further analysis in simulation was needed to support decision making.

IV. Don't do

The solutions that required relatively more effort but had a small benefit in return were currently placed on hold.

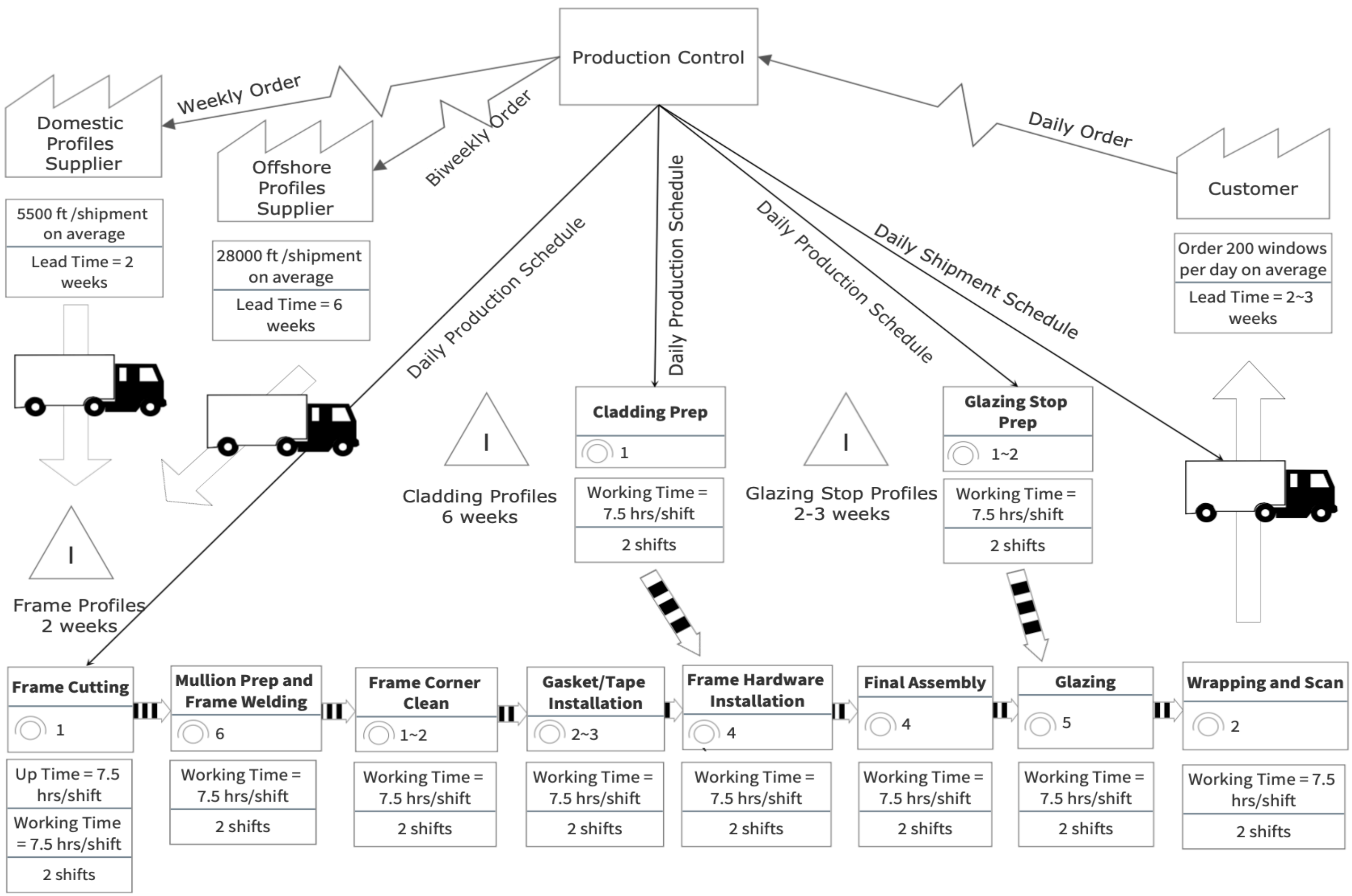


Figure 4-2: Apex Line Value Stream Mapping

Table 4-2: Issues and Solutions

Operations	***Issues***	***Root Causes***	***Solutions***	***Effort***	***Value***	***Strategic***	***GEMs***	***Quick Hits***	***Don't Do***
Cut and Router Frame Profiles	currently the operator enters router operator and lock location manually, it is time consuming and mistakes are common	the machine has the ability to cut automatically, yet there are no valid saw files	create saw files that carry the cutting information, eliminate the manual input	7	6	X			
Cut and Router Frame Profiles	9100C profiles are too far away in inbound area	no space for Renolit material, no Kanban system	create proper Kanban system (visual aids, tracking)	3	4			X	
Cut and Router Frame Profiles	saw capacity: current 160 frames/shift, need 200 frames/shift	due to volume saw capacity makes frame cutting a bottleneck in production	use saw files to eliminate manual input time, or add another SD-8000 saw, or add C shift operator to pre-cut frames	9	7	X			
V-Notch	the machine requires cleaning, too much PVC dust inside	no vacuum system, not connected	connect/fix vacuum system	3	3			X	

V-Notch	Dewalt handgun too old/slow, battery change too often	tools are too old and need replacement	improve battery and tool exchange program, improve feedback system from the line	4	3			X	
Cut Mullions	Renolit mullion materials are too far away	no space for Renolit material, no Kanban system	create proper Kanban system (visual aids, tracking).	3	4			X	
Cut Mullions	inbound material in front of mullion racks	no space for the material to be wrapped in the wrapping room ends up in the way of Apex line	create a home for to-be-wrapped profiles and wrapped profiles	3	4			X	
Weld Mullion to Frame on Single/Double Head Welder	an extra step, have to move clip before weld then screw down in correct position after weld	not training operator to put out of the way of welding, need a new standard for how to install	create SOPs for operator inserting clips at loose away from the welder fixture areas	2	3			X	
Weld Frame	6pt welder machine downtime	6pt welder runs nonstop 3 shifts, no time for preventive maintenance schedule, or no PM schedule set	create preventive maintenance schedule, improve machine utilization to create machine downtime	4	4			X	

Weld Frame	6pt welder cannot weld more than 150 frames, each shift requires 250 frames welded	6pt welder capacity	offload single unit load to 4pt welder	6	7	X			
Auto Corner Clean	pass through corner clean downtime	pass through corner clean runs nonstop 3 shifts, no time for preventive maintenance schedule, or no preventive maintenance schedule set	create preventive maintenance schedule, improve machine utilization to create machine downtime	4	4			X	
Auto Corner Clean	transport conveyor belts are damaged before and after passing through corner clean	belts are old and worn down and not replaced on time	replace belts on corner cleaner and 6pt and create a preventive maintenance schedule	5	4			X	
4-Point Welder Single F/S 9950	welder not being used 8hrs	no schedule for single units to run on the 4pt welder	scheduling to separate singles (9100C, 9950, 9100, 9100BM)	6	7	X			

Cut Cladding	20% of the cladding profiles are damaged in forklift handling and have to be manually sorted out	damage through transportation from inbound	work with inbound on transportation standards and operator training	2	4			X	
Install Gasket/Tape	too much CSA on 6 box	not following CSA standard	check CSA standards	1	2			X	
Install Cladding	9950 frame cladding cut the wrong size, paperwork is wrong sometimes	for special box insert cladding, cladding is different, but the cut list doesn't change. need a new cut list to account for different cladding	configure BOM for box insert cladding, check through cut lists, make sure box insert cladding is also being ordered on time	2	3			X	
Install Brickmould	all BM mixed up with different line, not organized	not organized in the prep area, need a cart in prep area for 9100 BM only, implement for other BM series	designated cart system for 9100BM	2	4			X	
Install Frame Hardware	not enough tools	need tool and battery replacement lifecycle, tools that are refurbished	improve battery and tool exchange program,	4	3			X	

		do not have the same lifespan as new tools	improve feedback system from the line						
Install Frame Hardware	waiting for material delivery from inbound	no Kanban ordering system, no automated system to pre-emptively stock the line with needed materials	make automatic part ordering system from hardware picklist	6	4				X
Install Sash	wrong hardware, wrong location	not effective enough coordination for changes to be communicated to the line updating saw files etc.	clear direction for the line with respect to hardware locations for any changes	4	6		X		
Install Sash	sash not center, 3 and 4 box combination size 2 to 3 mm off mullion position from top and bottom, results in the frame being rebuilt	saw file from SD-8000, cutting front and back of frame different lengths, compounded by V-notch, mullion arrowhead, 4 head F-M, and 6 points, need quality check at each step	operator training with clear SOPs to prevent tolerance stack up	2	4			X	

Install Jamb Extension	jamb not properly ripped	no feather board on the table saw, fences are low quality and damaged, the table saw is too short to handle long pieces of jamb extensions	table saws need new, better fences, feather boards and roller in front and behind the table saw to support long material	3	4			X	
Install Jamb Extension	PVC jamb corner too soft, screws overtightened	not proper tooling to prevent overtightening, use different design with thicker screw guides	redesigned jamb extensions with stronger and double walled screw guides	6	4				X
Install Brickmould	no drip lip cut list for 9100C	need drip lip cut list for 9100C	make drip lip cut list for 9100C	3	4			X	
Glaze Sealed Unit	missing glass for combination windows	no proper sequencing for glass	sequence production on glass line to optimize for production (start with high sequence # and end with low sequence # on the outside of a frame)	4	7		X		

Glaze Sealed Unit	in house searching for CIG glass taking a long time	need a home location for Plant 3 glass for APEX line on APEX line, need tracking system for shipments	location and a new layout to accommodate CIG glass	3	4			X	
Glaze Sealed Unit	backorder glass always comes out after 12:00 am	need backorders no later than 11:30 pm	run back orders earlier in production	3	4			X	
Glaze Sealed Unit	needs side cart for moving big glazed windows to the wrapping area	need a designated cart for APEX	get a designated cart from APEX	6	4				X
Glaze Sealed Unit	glass rack too hard to move	no PM schedule, greased, replaced wheels, frames etc.	maintenance PM schedule	4	4			X	
Wrapping	needs three guys to wrap large windows	need a holder to eliminate 2 operators to hold it, need to drop down clamp	attached clamp to window rack to hold large windows	3	4			X	

Quality Check and Scan	miss scanning window, mixed up label	operator training, look at labelling sequences differently for different series	training of operators	3	4			X	
Quality Check and Scan	need a better tracking system for completed windows. Don't need to mark down SU/window	eliminate manual entry of completed product, automated scan system to capture hour by hour production data	Syteline data displayed on floor	4	3			X	

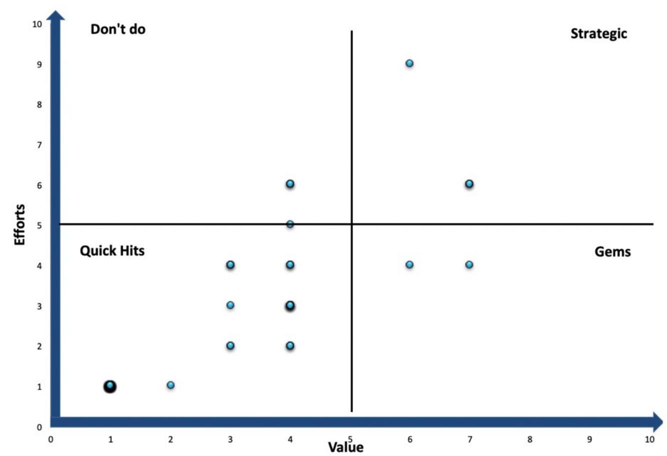


Figure 4-3: Apex Line Value Graph

4.4 Apex Line Simulation Analysis

4.4.1 Apex line simulation model development

According to the operational sequence listed in Figure 3-13, a simulation model was designed. The layout of the model is shown in Figure 4-4. The resources composite contained the type and number of all the resources on the line. The code in the element called “Add workers” shifted the number of workers in each station from shift A to shift B. The Apex Test Data was connected to a database of all the order information.

As mentioned before, due to the mass personalization and customization, it was hard to find two identical windows produced in the same shift. There were many variations in each operation, which brought fluctuation to the operation time. The attributes used in the simulation model to reflect the variations were as follows.

LS (3): Series 9100 represented 9100 series white windows, 9100C represented 9100 series coloured windows, and 9950 represented 9950 series

LS (4): Brickmould Option. “Re” represented renovation brickmould, “No” represented no brickmould

LS (5): Jamb Extension Type. This attribute could be “Drywall” or “PVC” or “DPVC” or “No”

LN (1): Number of Mullions

LN (2): Number of V-Notch on Mullion

LN (3): Number of M-F Welding Points on single head welder

LN (4): Number of M-F Welding Points on double head welder

LN (5)-Number of M-M Welding Points on single head welder

LN (6): Frame Welding Type: "6" represented using a 6-point frame welder and "4" represented using a 4-point frame welder

LN (7): Number of Picture Units

LN (8): Number of Fixed Units

LN (9): Number of Awning Units

LN (10): Number of Casement Units

LX (1): Height (mm)

LX (2): Touch up (1=YES, 0=NO)

LX (3): Perimeter (mm)

LX (4): Cut Fin (1=YES, 0=NO)

LX (5): Number of Site Glaze Sealed Unit

LX (6): Number of Regular Sealed Unit

LX (7): Screen (1=YES, 0=NO)

LX (8): Mullion Reinforcing ((1=YES, 0=NO)

LX (9): Number of Route Lock (Mullion Only)

LX (10): Number of Route Operator (Mullion Only)

LX (11): Width (mm)

Entities were generated in the "Generate Orders" element, and the attributes of each entity carried of the order information of each window. When an entity passed through an event, the coding inside the event element controlled the duration of each operation. This model used the value-added activities and non-value-added activities collected in Time Study. The detailed time data is given in Appendix A and Appendix B. At the end of the model, the units produced in each shift were tracked. The productivity of each shift and the entire day were calculated in the model and returned in the trace window as shown in Figure 4-4.

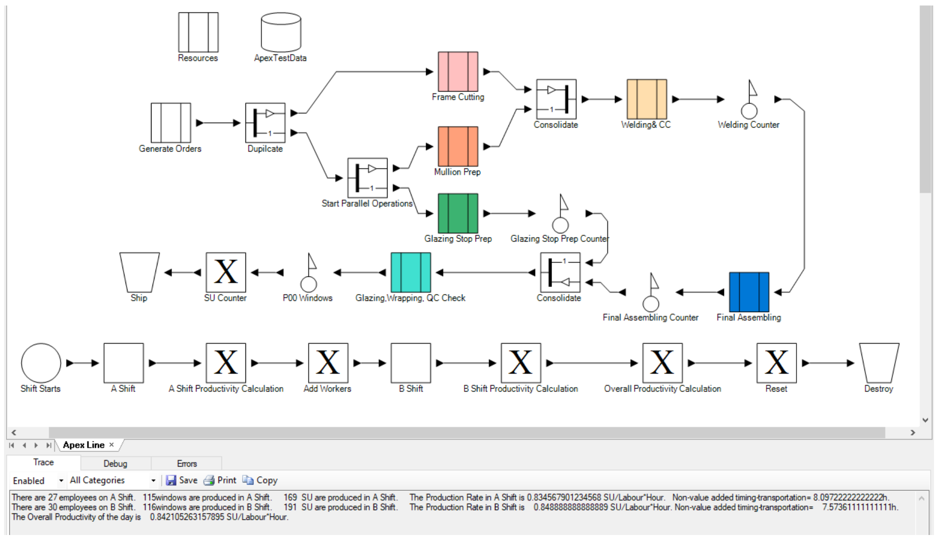


Figure 4-4: Apex Line Simulation Layout

4.4.2 Model validation and verification

After examining and fixing all the logical errors, syntax errors, data errors, experimental errors, bugs within the model, to validate the accuracy of the model, a comparison between actual productivity and simulated productivity was performed. This case study used the production on April 1st and April 2nd to conduct validation. The scanned finished order information was translated into attributes and was tabulated into a database as the input for model validation. The resources layout was set up based on the employee attendance record on the test days. The test results were given in Table 4-3

Table 4-3: Simulation Validation Test Results

Date	Shift	Employee Number	Units Produced		Productivity (sealed unit/labour hour)		Difference
			Actual	Simulated	Actual	Simulated	
April 1st	A Shift	26	165	169	0.85	0.87	2%
	B Shift	29	226	203	1.04	0.93	-10%
	Overall	55	391	372	0.95	0.90	-5%
April 2nd	A Shift	27	180	164	0.89	0.81	-9%
	B Shift	29	240	240	1.10	1.10	0%
	Overall	56	420	404	1.00	0.96	-4%

It was noted that the difference in each shift was less than 10%, and the difference between simulated overall productivity and actual productivity on both April 1st and April 2nd was less than 5%. The difference was minor. Figure 4-5 showed the number of windows produced on April 1st and April 2nd, 2019. The horizontal axis represented the production time in seconds and the vertical axis represented the number of windows produced. As shown in Figure 4-5, the production curves for both days fell close to straight lines which indicated the production flow were smooth throughout the day. The simulation model was considered as having passed validation.

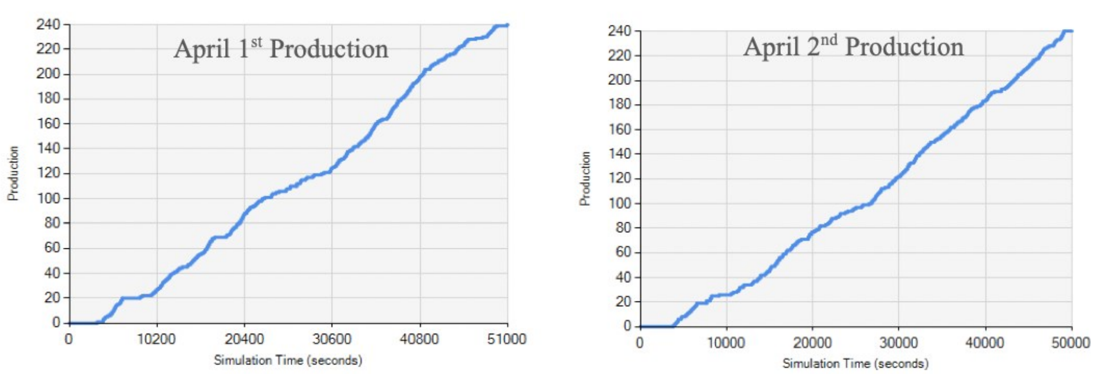


Figure 4-5: Simulation Production

4.4.3 Pre-analysis on strategic paybacks

I. Saw files

The frame cutting saw on the Apex line had the ability to read saw files and cut required lengths accordingly; however, WDWD was not using the saw files to cut, and instead, the worker responsible for cutting typed in the dimension of a frame manually. A strategic plan was to develop a program to generate saw files automatically to eliminate manual input. The company wanted to know the benefits of saw files before putting energy in to develop it. Also, the company wanted to increase the number of windows produced on the line: the goal for the cutting area was to increase productivity by 25%. The company was hoping that the saw files could help in reaching this goal.

To analyse the payback, firstly, the cutting operation was broken into sub-operations. Ten operation time of each sub-operation were collected as raw data, and the average was used as the operation duration. The operation information was given in Table 4-4. Note that once saw files were in use, the "Type Label Information" operation would no longer be needed.

Table 4-4: Apex Cutting Sub-operations

Operation Name	***Pick Materials***	***Load Materials***	***Type Label Information***	***Place Label***	***Rack Profiles***	***Machine Cutting***	***Router One Locker***	***Router One Operator***
Worker Needed?	Yes	Yes	Yes	Yes	Yes	No	No	No
Machine Needed?	No	Yes	No	No	No	Yes	Yes	Yes
Operation Duration	10.5	9.5	13.5	19.3	10.6	62.0	27.9	36.0

A simulation model was built based on the time data above. Figure 4-6 showed the design of the simulation model. The orders of April 1st and April 2nd, 2019 (405 orders in total) were used as input.

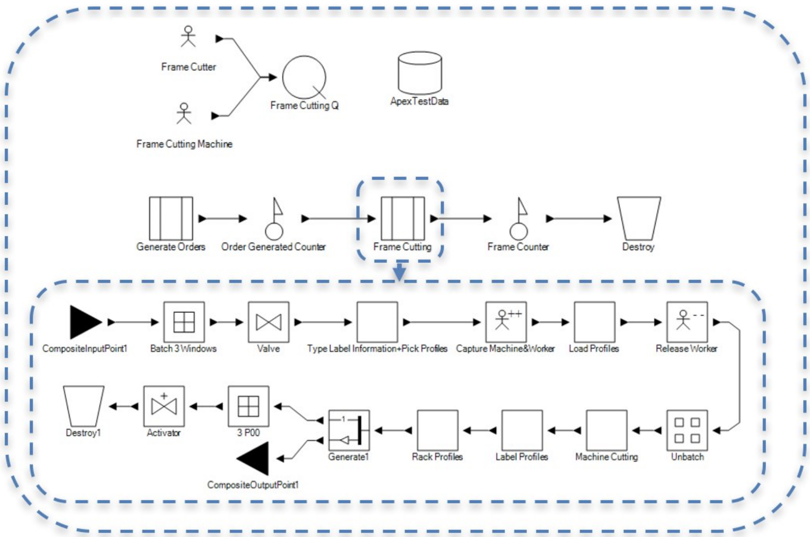


Figure 4-6: Apex Cutting Simulation

The statistical report in both scenarios, with and without using saw files, indicated that saw files could increase the machine utilization rate from 75.6% to 83.70%, while reducing the worker utilization rate from 45.4% to 39.6%, which means the machine can be better utilized while the workload on the worker can be reduced. The productivity of the cutting operation could be boosted from 25.82 frames/labour hour to 28.58 frames/ labour hour, which means the productivity of cutting can increase by 10.7%. However, to achieve the goal of a 25% increase in cutting operations, solely developing saw files was not enough. Other changes such as purchasing another saw, redesigning the operation process, or adding another shift were required.

II. Single unit separation

The cutting, welding, and corner clean machines on the Apex line were used throughout each entire shift, while there were extra cutting, welding and corner clean machines not fully utilized in the Apex line sash preparation area. Considering that the mixing of single units and combination units may contribute to the fluctuation in the cycle time of each operation, a strategic change proposed was to separate out the single units. All the orders would be divided into single unit orders and combination orders at the beginning of the line. The combination orders would still be manufactured on the existing Apex line, while the signal units would be cut, welded, and automatically corner cleaned in the Apex sash preparation line using the idle machines there. Four workers would be added to the separate single lines: 1 in the cutting area, 1 worker doing welding, corner clean and hardware installation, and 2 workers added in final assembly. Corresponding changes were made in the simulation model to test out the benefits of such changes. The test used the order information from April 1st and April 2nd, 2019. The design of simulating model mimics single units separation was shown in Figure 4-7.

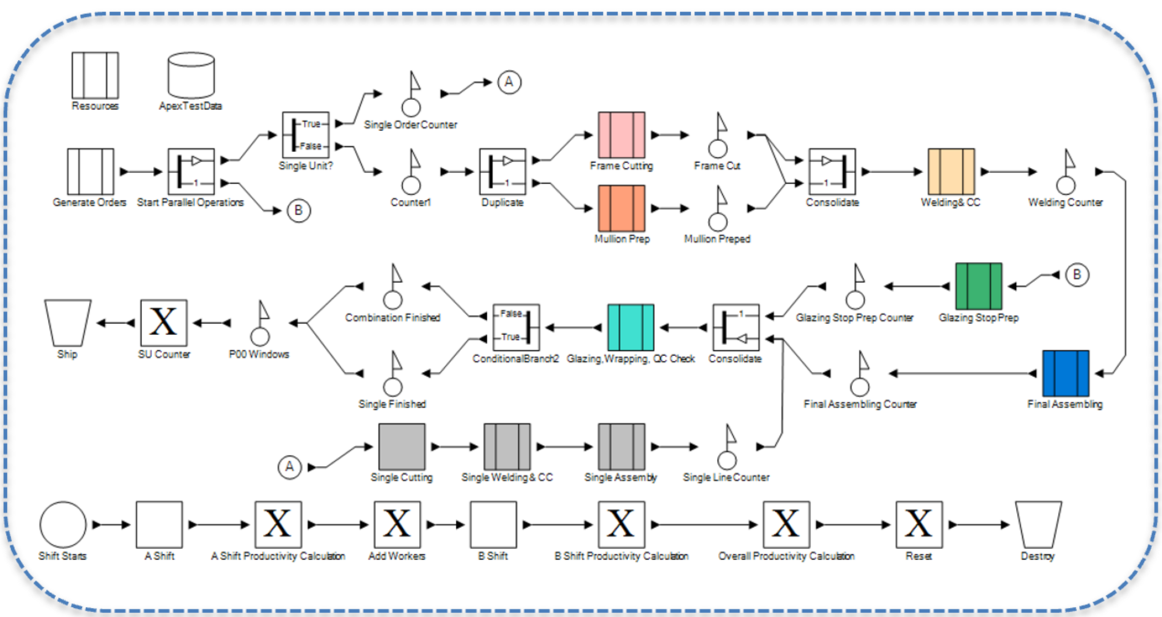


Figure 4-7: Single Units Separation Simulation

The test result was given in Table 4-5. As shown in the table, there was a decrease of around 20% in the productivity when single units were separated out from the main line. This result was unexpected. To figure out why separating single units would lead to a decrease in productivity, further analysis was performed. It was found that in the single unit part, the workload was distributed unevenly. There was only one worker doing all the welding, corner cleaning, and hardware installation. The heavy workload made that workstation a bottleneck in production, so the productivity in the single line didn't meet up the company's expectations. But this problem could be easily fixed by adding one more worker in that workstation. When looking into the resources utilization rate, it was found that the utilization rate of the mullion welding machine was over 90%, which indicated that the mullion welding machine was a potential bottleneck.

Table 4-5: Single Units Separation Test Results

Date	***Shift***	***Employee Number***		***Simulated Units Produced***		***Simulated Productivity (sealed unit/labour hour)***		***Change***
		Original	*Single Separated*	*Original*	*Single Separated*	*Original*	*Single Separated*	
April 1st	A	26	30	169	158	0.87	0.70	-20%
	B	29	33	203	179	0.93	0.72	-23%
	A+B	55	63	372	337	0.90	0.71	-21%
April 2nd	A	27	31	164	139	0.81	0.60	-26%
	B	29	33	240	239	1.10	0.97	-12%
	A+B	56	64	404	378	0.96	0.79	-18%

A simulation test was performed using the combined orders from April 1st and April 2nd, 2019 to test out the capacity of the mullion welding process. The design of simulation model testing the capacity of mullion welding was given in Figure 4-8. It was found that less than 140 windows could be welded in 2 shifts. As a result, although separating single units could free up some of the resources on the Apex combination line, because of the limitation of mullion welding capacity, the productivity didn't improve much in the combination line.

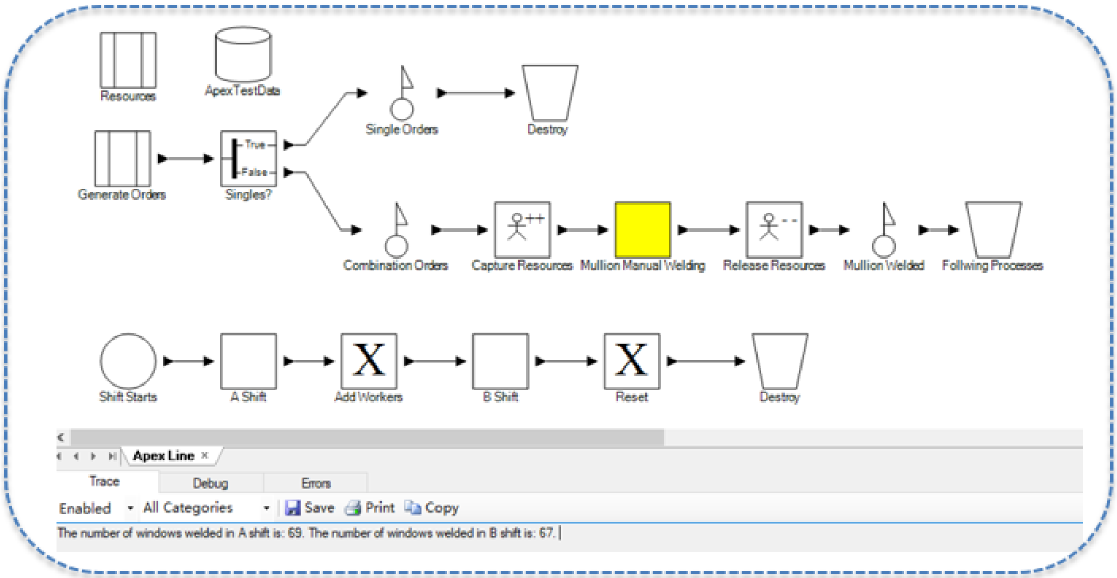


Figure 4-8: Apex Current Mullion Welding Capacity Test

The last test in the combination line was to test what would happen if the bottleneck mentioned above was eliminated, and whether single unit separation would improve productivity. Based on the separation simulation model, one worker was added in the single unit line, and one more mullion welding machine was added. The test result is shown in Table 4-6. The results showed that, when under a balanced flow, if single units were separated out, the Apex line was able to produce 15%-20% more units than before. However, since there were more resources put into the line, the change in productivity was minor. The analysis on single separation was given to the managers, and the board decided not to implement this strategic change because the company was trying to improve productivity while it was less concerned about the number of units produced per day.

Table 4-6: Test Results of Single Units Separation with More Resources

Date	***Shift***	***Employee Number***		***Simulated Units Produced***		***Simulated Productivity (sealed unit/labour hour)***		***Change***
		Original	*Separated*	*Original*	*Separated*	*Original*	*Separated*	
April 1st	A	26	31	169	197	0.87	0.85	-2%
	B	29	34	203	252	0.93	0.99	6%
	A+B	55	65	372	449	0.90	0.92	2%
April 2nd	A	27	32	164	214	0.81	0.89	10%
	B	29	34	240	248	1.10	0.97	-12%
	A+B	56	66	404	462	0.96	0.93	-3%

The simulation analysis on Apex line single separation exposed a major disadvantage of lean manufacturing which was that it is hard to express a dynamic workflow using lean analysis especially when the cycle time of each workstation fluctuates. This analysis also embodied the power of simulation analysis in supporting and improving lean analysis. By combining lean manufacturing and simulation analysis, not only could we identify waste, but we also found the solutions that could actually eliminate the waste and statistically analyse the gains before implementation. In addition to supporting lean, because simulation could capture the dynamic changes in cycle time it could also be used to identify bottlenecks and help to reach a smoother workflow by reallocating resources.

4.4.4 Apex line bottleneck identification

Based on the pre-analysis described in Section 4.4.3, saw files would be put in use while the idea of signal unit separation would not be implemented. A simulation model was developed based on future status after lean and simulation analysis. The order information of April 1st and April 2nd, 2019 was used as the test data. The simulation time was one shift (7.5 hours). This part of the analysis was using simulation to mimic the dynamic flow on the line and identify any existing bottlenecks in the production flow. The utilization rates of all resources on the line are shown below in Figure 4-9. The productivity of the shift was 0.87 sealed units/labour hour.

Counters

Element Name	Final Count	Production Rate	Average Interarrival	First Arrival	Last Arrival
Final Assembling Counter	131.000	0.005	182.255	3,133.050	26,826.160
Glazing Stop Prep Counter	305.000	0.011	88.391	110.000	26,980.970
Mullions Cut	284.000	0.011	95.338	1.000	26,981.600
P00 Windows	122.000	0.005	192.843	3,612.920	26,946.950
Welding Counter	137.000	0.005	178.423	2,699.200	26,964.760

Resources

Element Name	Average Utilization	Standard Deviation	Maximum Utilization	Current Utilization	Current Capacity
Final Assembler	45.5%	35.5%	100.0%	40.0%	5.000
Flow Person	NaN	NaN	NaN	NaN	1.000
Frame Cutter	39.6%	48.9%	100.0%	100.0%	1.000
Frame Cutting Machine	83.7%	36.9%	100.0%	100.0%	1.000
Frame Welding Machine	64.8%	47.8%	100.0%	100.0%	1.000
Frame&Mullion Welder	63.9%	20.7%	100.0%	83.3%	6.000
Gasket Installer	30.2%	32.0%	100.0%	50.0%	2.000
Glazer	39.3%	33.6%	100.0%	25.0%	4.000
Glazing Stop Cutting Machine	99.7%	4.0%	100.0%	100.0%	2.000
Glazing Stop Preparer	100.0%	0.6%	100.0%	100.0%	2.000
Hardware Assembler	63.6%	38.8%	100.0%	100.0%	3.000
Manual Corner Cleaner	50.0%	50.0%	100.0%	100.0%	1.000
Mullion Cutting Machine	100.0%	2.0%	100.0%	100.0%	1.000
Mullion Welding Machine	76.8%	42.2%	100.0%	100.0%	1.000
QC Checker	63.0%	42.9%	100.0%	100.0%	2.000
V-Notch Machine	83.8%	36.9%	100.0%	100.0%	1.000

Figure 4-9: Apex Production Information

From the chart, it was found that the workstations with higher utilization rates were the glazing stop preparation station, mullion preparation, and frame welding station. However, the number of glazing stops finished in one shift was much larger when compared to the number of windows produced, hence the glazing stop preparation area was not a bottleneck. The number of windows finished in the welding station was close to the total number of windows finished, and the resource utilization rates in the welding station were high. The utilization rate of resources through the shift in the welding were given in Figure 4-10. As a result, mullion preparation and frame welding station were identified as the bottlenecks in production. More specifically, the bottleneck operations were mullion welding and frame welding, as the utilization rate of resources involved in these operations were high, and the numbers of windows finished after these operations were much lower in comparison to the preceding operations, also the numbers of windows finished in these operations were close the number of windows finished on the line.

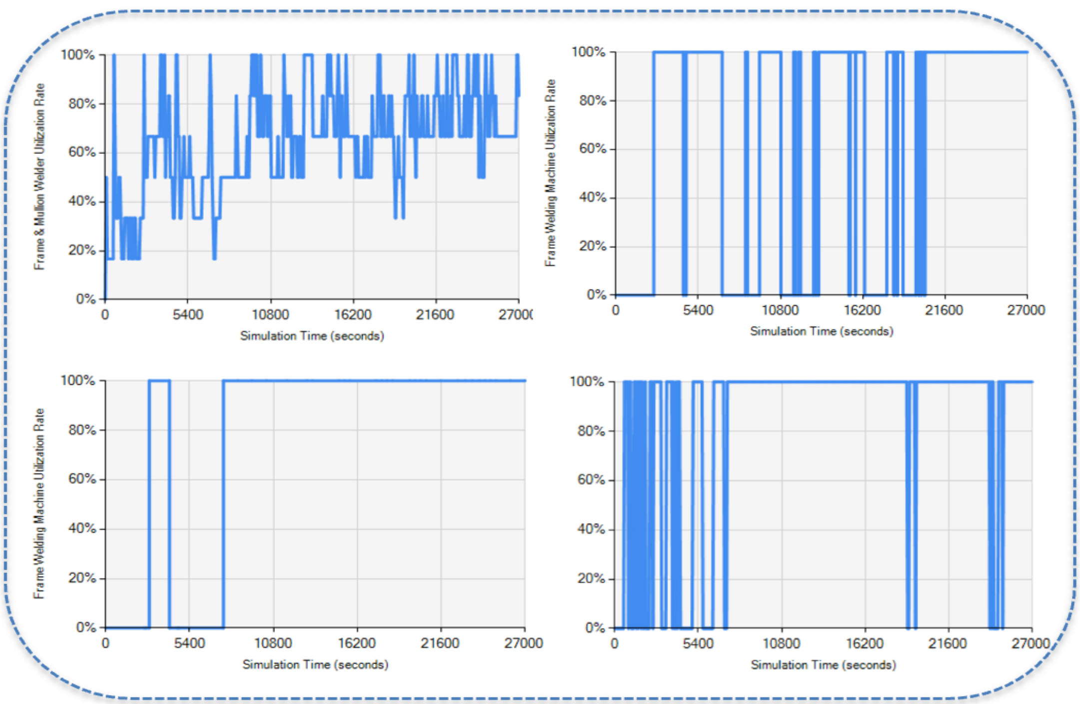


Figure 4-10: Resource Utilization Rates in Welding Station

4.4.5 Apex line balancing

Mullion welding and frame welding were identified as the bottlenecks, and there was only one mullion welding machine and one frame welding machine on the line. It is costly to purchase a new machine and there was no space on the line for new machines. Since the company was more focused on improving productivity and was less concerned about the number of units produced per day, the best strategy to balance the line was to remove workers from the workstations where the worker utilization rates were low. An algorithm was designed to drop one worker from the workstation where the worker utilization rate was the lowest, after which, the new productivity was compared to the last scenario. If the productivity increases, the utilization rates of all resources are calculated again, and another worker would be dropped in the workstation with the lowest utilization rate. The loop repeated until dropping a worker didn't benefit productivity.

The productivities under different worker allocation scenarios are tabulated in Table 4-7. In the table, the abbreviations listed represented the workstations as follows:

WS1: Frame Cutting Station

WS2: Mullion Prep and Frame Welding

WS3: Frame Corner Clean Station

WS4: Gasket/ Tape Installation Station

WS5: Frame Hardware Installation Station

WS6: Final Assembly Station

WS7: Glazing Station

WS8: Glazing Stop Preparation Station

WS9: Wrapping and Scan Station

WS10: Cladding Preparation Station

As shown in the table, to even out the cycle times of different workstations, the best resources allocation design was Scenario No.5 in which compared to the original plan, one worker was dropped in the Gasket/Tape Installation Station, one worker was reduced in the Final Assembly Station, two workers were reduced in the Glazing Station, and there was one less employee in the Wrapping and Scan Station. Compared to the current resources allocation, the proposed worker allocation could increase productivity from 0.87 sealed units/labour hour to 0.98 sealed units/labour hour, which is an increase of 12.6%.

Table 4-7: Productivities under Different Scenarios

Scenarios	***Number of Workers***										***Productivity (SU/hour)***
	WS 1	***WS 2***	***WS 3***	***WS 4***	***WS 5***	***WS 6***	***WS 7***	***WS 8***	***WS 9***	***WS 10***	
Original	1	6	1	2	4	4	4	2	2	1	0.87
No.1	1	6	1	1	4	4	4	2	2	1	0.90
No.2	1	6	1	1	4	4	3	2	2	1	0.92
No.3	1	6	1	1	4	3	3	2	2	1	0.93
No.4	1	6	1	1	4	3	2	2	2	1	0.94
No.5	1	6	1	1	4	3	2	1	2	1	0.98
No.6	1	6	1	1	4	2	2	1	2	1	0.95

4.5 Case Study Conclusions

In order to examine and verify the proposed methodology, a case study was conducted in a window and door manufacturing company. The case study focused on the most complicated production line in the company called Apex line. The case study started with studying the process, resources, and operation time of the manufacturing process. The data collected in the study were used as raw data to feed the value stream mapping and simulation analysis.

First, the current value stream of the production line was mapped. Through value stream mapping, and by using lean manufacturing tools, the case study identified the wastes on the line and proposed corresponding solutions. The solutions were categorized into four types based on the benefits and efforts required. In total, 32 improvements were suggested on the line. The changes suggested in gem improvements, for instance, improving the communication in sash hardware supply and placing sealed units in sequences, were implemented first as they required low effort but are associated with a great number of benefits in return. Quick hits improvements included developing a Kanban system, upgrading the ageing tools, developing Standard Operating Procedures (SOPs), making better use of planning systems, and scheduling machine preventive maintenance (PM). Two strategic improvements were proposed, one was developing saw files to eliminate manual inputs, and the other one was separating single units from current production flow. Simulation analysis was performed on the strategic proposals to statistically analyse the payback of changes before actual implementation.

A simulation model of the Apex line was developed using the data and information collected in the time study and process study. The simulation was verified and validated using the actual production information. The simulated productivity was compared to actual productivity. The difference was minor; therefore, the model was considered as having passed verification and validation. Simulation was used to mimic having saw files in the production, and it showed that saw files could increase the saw capacity by 10.7%. The simulation analysis also showed the single unit separation was not able to increase overall productivity. With single units separated, the number of windows produced in a shift can increase, but the productivity stayed relatively the same. Finally, the simulation was used to identify the bottlenecks in production and perform line balancing. Mullion preparation and frame welding station were identified as the bottlenecks in production. Using an algorithm, the productivity under different worker allocation scenarios was calculated in the simulation model. A best resource allocation scenario was found, which was able to increase the overall productivity by 12.6%.

Chapter 5 Conclusions and Recommendations for Future Research

5.1 Research Summary

This research presented a framework to combine lean manufacturing and simulation analysis in productivity improvement for window manufactures. Multiple lean manufacturing tools are used to identify the existing waste on the production lines, determine the root causes of the waste, and present solutions to eliminate the identified waste. Traditionally, most companies have been reluctant to implement the strategic changes proposed through lean analysis as those changes require a great amount of effort, and lean analysis cannot calculate the payback. To solve this problem, this research categorized the changes into four types using a concept called value graph. For the changes requiring a great amount of effort but which also have potentially great benefit returns, simulation models were developed to mimic the changes, and statistically analyse the payback of the changes. With the combination of lean manufacturing and simulation, not only could we identify the waste and find ways to eliminate the waste, but we could also statistically forecast the resulting benefits before actual implementation of the suggested changes.

A trend in the manufacturing industry is mass customization, which results in large fluctuations in the cycle times of each manufacturing process. This makes line balancing and resource allocation using traditional techniques almost impossible as the cycle times are no longer constant. This research used simulation models to mimic the dynamic changes in cycle times and tested out the overall productivity under various resource allocation scenarios. The algorithm in the simulation model was able to find the best resource allocation scenario under which the production line was more balanced, and the productivity was higher.

5.2 Research Contributions

This research presented a method to combine lean manufacturing tools and simulation analysis to identify waste, eliminate waste, statistically analyse the payback of changes before implementation, and find the best resource allocation scenario. The method presented can be applied to any production line(s). The specific contributions of this research are as follows:

- This research provided a template to break down the window manufacturing process, collect operation time, and determine the resource layout. The template can be used in similar industries.
- This research presented a method to use multiple lean manufacturing tools to identify the wastes on the value stream, find root causes and solutions, and categorize the solutions.
- This research developed simulation models that can mimic the dynamic manufacturing processes. The model was built, verified, and validated using actual production data.

- This research used simulation models to statistically analyze the influence of changes on productivity before actual implementation.
- This research presented an algorithm to find the best resource allocation scenario using simulation models. In the best resource allocation scenario, the production line is more balanced and the overall productivity is improved.

5.3 Limitations

This research is subject to several limitations, as follows:

- The simulation model in this research was validated using the test data for two production days. If the test was conducted based on a larger amount of data, the result may be more compelling.
- The operation time were fixed numbers in this research, which reflected an assumption that all workers can work at the same pace all the time. Different workers might work at different paces.

5.4 Recommendations for Future Study

This research demonstrated a method to improve the productivity of windows manufacturing process by combining lean manufacturing and simulation analysis. Several recommendations are made for future study:

- This research presented a linear line balancing method which changing the number of worker in each workstation one at a time. Future study can develop an algorithm to perform line balancing using simulation model by changing worker number in multiple work stations at the same time

- In the area of simulation verification and validation, even though there are already a few existing validation methods presented, there is no clear boundary at which a model would be considered as either passing or failing the validation. Developing a guideline on how to judge the accuracy of a simulation model can standardize the simulation verification and validation process.
- The sequencing of orders can be another variable influencing the productivity of production lines, and it is also an input in the simulation model. Developing an algorithm to find the best order sequence and using simulation models to validate the result can also be a direction for future study.

References

Abdullah, F., & Rajgopal, J. (2003). Lean manufacturing in the process industry. *IIE Annual Conference Proceedings*, 1-6.

Abdulmalek, F. A., & Rajgopal, J. (2007). Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study. *International Journal of production economics, 107*(1), 223-236.

AbouRizk, S. M., Hague, S. A., & Ekyalimpa, R. (2016). *Construction simulation an introduction using simphony.* Edmonton: Hole School of Construction Engineering Department of Civil and Environmental Engineering University of Alberta.

All Weather Windows. (2017). *Window catalogue.* Retrieved June 8, 2019, from All Weather Windows: https://www.allweatherwindows.com/catalogues/window-catalogue/

Bako, B., & Božek, P. (2016). Trends in simulation and planning of manufacturing companies. *Procedia Engineering, 149*, 571-575.

Bayview Windows. (2017). *Anatomy of a window - exterior view*. Retrieved March 25, 2019, from Bayview Windows: https://www.bayviewwindows.ca/blog/anatomy-of-a-window-exterior/vinyl_windows

Bhamu, J., & Sangwan, K. S. (2014). Lean manufacturing: literature review and research issues. *International Journal of Operations & Production Management, 34*(7), 876-940.

Chan, C. O., & Tay, H. L. (2018). Combining lean tools application in kaizen: a field study on the printing industry. *International Journal of Productivity and Performance Management, 67*(1), 45-65.

Chryssolouris, G. (2013). *Manufacturing systems: theory and practice.* Cambridge: Springer Science & Business Media.

Chung, C. A. (2014). *Simulation modeling handbook: a practical approach.* Boca Raton: CRC press.

Detty, R. B., & Yingling, J. C. (2000). Quantifying benefits of conversion to lean manufacturing with discrete event simulation: a case study. *International Journal of Production Research, 38*(2), 429-445.

Elbert, M. (2013). *Lean production for the small company.* Boca Raton, FL, USA: Taylor & Francis Group.

Encyclopedia Britannica. (2017). *Computer simulation*. Retrieved April 3, 2019, from Encyclopedia Britannica: https://www.britannica.com/technology/computer-simulation

Gahagan, S. M. (2007). Adding value To value stream mapping: a simulation model template For VSM. *M. IIE Annual Conference. Proceedings*, 712-717.

Government of Canada. (2019). *Canadian manufacturing sector gateway*. Retrieved March 15, 2019, from Canada.ca: https://www.ic.gc.ca/eic/site/mfg-fab.nsf/eng/home

Huber, V. L., & Brown, K. A. (1991). Human resource issues in cellular manufacturing: A sociotechnical analysis. *Journal of Operations Management, 10*(1), 138-159.

Hyer, N., & Wemmerlov, U. (2001). *Reorganizing the factory: Competing through cellular manufacturing.* Portland: CRC Press.

Jones, D. T., & Womack, J. P. (2002). *Seeing the whole: mapping the extended value stream.* Brookline, MA: The Lean Enterprise Institute.

Kämpf, M., & Köchel, P. (2006). Simulation-based sequencing and lot size optimisation for a production-and-inventory system with multiple items. *International Journal of Production Economics, 104*(1), 191-200.

Kanawaty, G. (1992). *Introduction to work study.* Geneva: International Labour Office.

Kapp, R., Löffler, B., Wiendahl, H. P., & Westkämper, E. (2005). The logistics bench: Scalable logistics simulation from the supply chain to the production process. *CIRP Journal of Manufacturing Systems, 34*(1), 45-54.

Kühn, W. (2006). Digital factory - simulation enhancing the product and production engineering process. *Proceeding of the 20016 winter simulation conference*, 1899-1906.

Kumar, D., Singh, S. K., & Sharma, K. (2014). Implementation of lean in continuous industry: a case study (steel industry). *Jornal of Engineering Research and Application, 4*(4), 05-12.

Lean Enterprise Institue, Inc. (2016). *The five steps of lean implementation*. Retrieved May 6, 2019, from Lean Enterprise Institute: https://www.lean.org/WhoWeAre/LEINewsStory.cfm?NewsArticleId=17

Lee, J. Y., Kang, H. S., Kim, G. Y., & Do Noh, S. (2012). Concurrent material flow analysis by P3R-driven modeling and simulation in PLM. *Computers in Industry, 63*(5), 513-527.

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

Liker, J. K. (2004). *Becoming lean: inside stories of U.S. manufacturers.* New York: Productivity Press.

Losonci, D., Demeter, K., & Jenei, I. (2011). Factors influencing employee perceptions in lean transformations. *International Journal of Production Economics, 131*(1), 30-43.

Marvel, J. H., & Standridge, C. R. (2009). Simulation-enhanced lean design process. *Journal of Industrial Engineering and Management, 2*(1), 90-113.

Masood, S. (2006). Line balancing and simulation of an automated production transfer line. *Assembly Automation, 26*(1), 69-74.

McLaughlin, P., & Durazo-Cardenas, I. (2013). Cellular manufacturing applications in MRO operations. *Procedia CIRP, 11*, 254-259.

Mehta, R. K., Mehta, D., & Mehta, N. (2012). An exploratory study on employee's perception towards lean manufacturing systems. *Management & Marketing, X*(1), 98-104.

Melouk, S. H., Freeman, N. K., Miller, D., & Dunning, M. (2013). Simulation optimization-based decision support tool for steel manufacturing. International Journal of Production Economics. *International Journal of Production Economics, 141*(1), 269-276.

Melton, P. M. (2004). To lean or not to lean? that is a question. *The Chemical Engineer*, 34-37.

Melton, T. (2005). The benefits of lean manufacturing: what lean thinking has to offer the process industries. *Chemical engineering research and design, 83*(6), 662-673.

Mendes, A. R., Ramos, A. L., Simaria, A. S., & Vilarinho, P. M. (2005). Combining heuristic procedures and simulation models for balancing a PC camera assembly line. *Computers & Industrial Engineering, 49*(3), 413-431.

Misiurek, B. (2015). *Standardized work with TWI eliminating human errors in production and service processes.* New York: Productivity Press.

Mourtzis, D., Doukas, M., & Bernidaki, D. (2014). Simulation in manufacturing: Review and challenges. *Procedia CIRP, 25*, 213-229.

Neirotti, P. (2018). Work intensification and employee involvement in lean production: new light on a classic dilemma. *The International Journal of Human Resource Management*, 1-26.

Ohno, T. (1988). *Toyota production system: beyond large-scale production.* Portland: Productivity Press.

Omogbai, O., & Salonitis, K. (2016). Manufacturing system lean improvement design using discrete event simulation. *Procedia CIRP, 57*, 195-200.

Patel, N., Chauhan, N., & Trivedi, P. (2014). Benefits of value stream mapping as a lean tool implementation manufacturing industries : a review. *International Journal for Innovative Research in Science & Technology, 1*(8), 53-57.

Pavnaskar, S. J., Gershenson, J. K., & Jambekar, A. B. (2003). Classification scheme for lean manufacturing tools. *International Journal of Production Research, 41*(13), 3075-3090.

Pegden, C. D., Shannon, R. E., & Sadowski, R. P. (1995). Introduction to simulation using SIMAN. *Introduction to simulation using SIMAN.*

Prashar, A. (2014). Adoption of Six Sigma DMAIC to reduce cost of poor quality. *International Journal of Productivity and Performance Management,, 63*(1), 103-126.

Rohani, J. M., & Zahraee, S. M. (2015). Production line analysis via value stream mapping: a lean manufacturing process of color industry. *Procedia Manufacturing, 2*, 6-10.

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

Russell, R. S., & Taylor, B. W. (2011). *Operations Mmanagement.* Hoboken: John Wiley and Sons,Inc.

Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., & Harnisch, M. (2015). Industry 4.0: The future of productivity and growth in manufacturing industries. *Boston Consulting Group, 9*(1), 54-89.

Sargent, R. G. (2010). Verification and validation of simulation models. *Proceedings of the 2010 winter simulation conference*, 166-183.

Seth, D., & Gupta, V. (2005). Application of value stream mapping for lean operations and cycle time reduction: an Indian case study. *Production Planning & Control, 16*(1), 44-59.

Spear, S. J. (2004). Learning to lead at Toyota. *Harvard Business Review*, 1-10.

Sundar, R., Balaji, A. N., & Kumar, R. S. (2014). A review on lean manufacturing implementation techniques. *Procedia Engineering, 97*, 1875-1885.

Yu, H. (2010). An integrated approach toward lean for production homebuilders.

Zahraee, S. M., Hashemi, A., Abdi, A. A., Shahpanah, A., & Rohani, J. M. (2014). Lean manufacturing implementation trrough value stream mapping: A case study. *Jurnal Teknologi, 68*(3), 119-124.

Appendix A – Apex Value-added Activities

Series	***Workstation***	***Operation***	***Size Range***	***Time Calculation Unit***	***Rules***	***Operation Description***	***Observed Time 1***	***Observed Time 2***	***Observed Time 3***	***Avg. Time***
9950	Cladding Preparation	Cut Cladding	Any	each frame	Frame cladding only	Get frame cladding profile, cut profile in saw, attach label and place on conveyor, cart or table	308.5	316.2	264.5	296.4
9950	Cladding Preparation	Cut Cladding	Any	each mullion	Mullion cladding only	Get mullion cladding profile, cut profile in saw, attach label and place on conveyor, cart or table	68.2	75.2	65.3	69.6
9950	Cladding Preparation	Punch Cladding	Any	each frame	Frame cladding only	Get frame cladding profiles, punch 4 pieces and place on conveyor, cart or table	210.9	213.2	220.5	214.9
9100, 9950	Final Assembly	Install Cardboard and	Any	each window	Frame has jamb extension but no BM	Install cardboard on only the front side of the window and shipping blocks	154.6	173.4	149.0	159.0

		Shipping Blocks								
9100, 9950	Final Assembly	Install Cardboard and Shipping Blocks	Any	each window	Frame has both jamb extension and BM	Install cardboard on both the front and back sides of the window and shipping blocks, plus door sweeps on the bottom.	367.6	366.7	367.2	367.2
9100, 9950	Final Assembly	Install Cardboard and Shipping Blocks	Any	each window	No jamb extension (or have drywall jamb extension)	Install cardboard on both the front and back sides of the window and shipping blocks.	270.8	290.5	330.1	297.1
9100, 9950	Final Assembly	Install Jamb Extension	Any	per mm	Double PVC jamb extension	Install jamb extension and accessories	0.1676	0.1282	0.0984	0.1314
9100, 9950	Final Assembly	Install Jamb Extension	Any	per mm	Drywall jamb extension	Install jamb extension and accessories	0.0367	0.0555	0.0445	0.0456

9100, 9950	Final Assembly	Install Jamb Extension	Any	per mm	PVC jamb extension	Install jamb extension and accessories	0.0513	0.0641	0.0519	0.0558
9100, 9950	Final Assembly	Install Lumber	Perimeter ≥ 7600 mm	each window	-	Install 2x4 Lumber, only on the bottom of the frame.	86.3	80.9	93.2	86.8
9100, 9950	Final Assembly	Install Lumber	5400 ≤ Perimeter < 7600 mm	each window	-	Install 2x4 lumber, on four sides of the frame plus an extra lumber strip on the bottom	204.5	224.4	215.3	214.7
9100, 9950	Frame Corner Clean	Auto Corner Clean	<1500 mm*600mm	each frame	Auto-corner clean for 4 points	Automatically clean 4 corners of a single frame	67.6	59.6	67.3	64.8
9100,	Frame Corner Clean	Auto Corner Clean	<1500 mm*600mm	each frame	Auto-corner clean for 6 points	Automatically clean 6 corners of a single frame	105.3	113.9	106.5	108.6

9950										
9100, 9950	Frame Corner Clean	Auto Corner Clean	>1500 *600 mm	each frame	Single Units. Size>1500*600mm, Auto-corner clean for 4 points	Automatically clean 4 corners of a single frame	134.0	140.3	131.5	135.3
9100, 9950	Frame Corner Clean	Manual Corner Clean	Any	each frame	-	Manual corner clean single frame	104.6	90.9	97.9	97.8
9100, 9950	Frame Cutting	Cut Frame Profiles	Any	each frame	-	Cut PVC profiles in a saw, unload and place stickers	73.3	74.4	78.3	75.3
9100, 9950	Frame Cutting	Router Lock on Frame	Any	each lock	Each casement unit has one lock, each awning unit has two locks	Router for one lock inside the cutting machine	31.5	30.2	34.0	31.9
9100,	Frame Cutting	Router Operator on Lock	Any	each operator	Each casement/awning unit has one operator	Router for one operator inside the cutting machine	39.0	36.0	35.0	36.7

9950										
9100, 9950	Frame Hardware Installation	Cut Fin	Any	per mm	-	Cut four sides of the frame fin off	0.0355	0.0432	0.0368	0.0385
9950	Frame Hardware Installation	Install Cladding	Any	per mm	-	Install cladding and screw corners	0.0476	0.0385	0.0455	0.0439
9100, 9950	Frame Hardware Installation	Install Frame Hardware	Any	each Awning	-	Install track, ramp, operator, snubber, lock handle	294.6	306.8	256.9	286.1
9100, 9950	Frame Hardware Installation	Install Frame Hardware	Any	each casement	-	Install track, ramp, operator, snubber, lock handle	267.5	298.9	257.5	274.6
9100,	Frame Hardware	Install Frame Hardware	Any	mm	One side for a casement, two sides for an awning.	Install tie bar for casement and awning units	0.0587	0.0523	0.0556	0.0555

9950	Installation				Time= tie bar amount*height*unit time					
9100, 9950	Frame Hardware Installation	Install Sash	Any	each sash	Fixed Sash	Install one fixed sash on a frame, punch, screw in nails	153.5	158.3	150.5	154.1
9100, 9950	Frame Hardware Installation	Install Sash	Any	each sash	Casement and awning sash	Install one casement/awning sash on frame	81.8	76.5	84.4	80.9
9100, 9950	Frame Hardware Installation	Install Brickmould	Any	per mm	No Brickmould, 9100 white frames, on the bottom only	Install J-clip and accessories on the bottom of the frame	0.0194	0.0162	0.0145	0.0167
9100, 9950	Frame Hardware Installation	Install Brickmould	Any	per mm	No Brickmould, 9100 coloured or 9950, on the bottom only	Install metal J-clip and accessories on the bottom of the frame	0.0981	0.0846	0.1370	0.1066

9100, 9950	Frame Hardware Installation	Install Brickmould	Any	per mm	Renovation Brickmould	Install brickmould and accessories	0.0440	0.0755	0.0765	0.0653
9100, 9950	Gasket/ Tape Installation	Install Gasket/Tape	Any	each picture	-	Apply tape and stickers	78.4	72.0	69.6	73.3
9100, 9950	Gasket/ Tape Installation	Install Gasket/Tape	Any	each casement /awning/fixed	-	Apply gasket and stickers	118.5	114.2	118.9	117.2
9100	Gasket/ Tape Installation	Paint Welding Joints	Any	each	4 frame joints	Paint welding joints	40.1	43.3	40.0	41.1
9100	Gasket/ Tape Installation	Paint Welding Joints	Any	each	1 mullion to frame joint	Paint welding joints	11.1	11.3	10.2	10.8

9100	Gasket/ Tape Installation	Paint Welding Joints	Any	each	1 mullion to mullion joint	Paint welding joints	35.2	33.2	30.6	33.0
9100, 9950	Glazing	Glaze Sealed Unit	Any	each SU	Site Glaze (Wrap glazing stops on the frame for site glaze)	Glaze unit (wrap glazing stops on the frame for site glaze)	16.8	19.6	15.9	17.4
9100, 9950	Glazing	Glaze Sealed Unit	Any	each SU	Regular Sealed Units	Glaze unit (glaze regular sealed unit)	207.0	210.7	195.7	204.5
9100, 9950	Glazing	Install Screen	Any	each screen	Screen (Included)	Install screen	49.5	51.3	47.8	49.5
9100, 9950	Glazing Stop Prep	Cut Glazing Stop	Any	each SU	-	Get glazing stop profile, cut profile in a chop saw, Install glazing gasket and place in cart	113.5	118.2	95.4	109.0

9100, 9950	Glazing Stop Prep	Punch Glazing Stop	Any	each SU	9950 picture unit only	Drill holes on glazing stop, place in cart	56.7	65.1	49.1	57.0
9100, 9950	Mullion Prep and Frame Welding	Cut Mullions	Any	each mullion	-	Pick mullion PVC Profile and load to mullion saw, cut PVC mullion profile in mullion chop saw, router, unload and place stickers, arrowhead mullion, place on the table	172.5	180.3	159.3	170.7
9100, 9950	Mullion Prep and Frame Welding	Install Fixed Sash Clips	Any	each unit	9100C & 9950 (Fixed)	Install fixed sash clips on mullion	16.2	15.8	13.8	15.3
9100, 9950	Mullion Prep and Frame Welding	Install Reinforcing	Any	each frame	Configuration: Picture/Fixed	Install reinforcing on the bottom of the frame	48.7	53.3	61.8	54.6

9100, 9950	Mullion Prep and Frame Welding	Install Reinforcing	Any	each mullion	multiply time by # of reinforcing pieces	Install mullion reinforcing	68.4	65.5	102.4	78.8
9100, 9950	Mullion Prep and Frame Welding	Router Lock on Mullion	Any	each lock	Each casement unit has one lock, each awning unit has two locks	Router lock manually	22.9	21.5	19.5	21.3
9100, 9950	Mullion Prep and Frame Welding	Router Operator on Mullion	Any	each operator	Each casement/awning unit has one operator	Router operator manually	32.3	30.6	31.9	31.6
9100, 9950	Mullion Prep and Frame Welding	V-Notch	Any	each V-notch	Multiply time by the number of V notch locations	V Notch mullion or frame	38.7	39.9	40.1	39.6
9100, 9950	Mullion Prep and Frame Welding	Weld Frame	>1500*600 mm	each frame	Single Frame, Size>1500*600mm	Weld frame on horizontal 4 points single frame welder	136.0	138.3	141.1	138.5

9100, 9950	Mullion Prep and Frame Welding	Weld Frame	Any	each frame	2 Unit Combination	Weld frame on horizontal 6 points single frame welder	198.7	168.3	159.6	175.5
9100, 9950	Mullion Prep and Frame Welding	Weld Frame	<1500 *600 mm	each frame	Single Unit. Size<1500mm*600 mm	Weld frame on vertical 4 points single frame welder	101.2	108.3	103.8	104.4
9100, 9950	Mullion Prep and Frame Welding	Weld Mullion to Frame on Double Head Welder	Any	Each double M-F weld points	3+ Units - Mullion to Frame	Perform mullion to frame welding operation on double head welder	442.7	479.6	465.3	462.5
9100, 9950	Mullion Prep and Frame Welding	Weld Mullion to Frame on Single Head Welder	Any	Each single M-F weld point	3+ Units - Mullion to Frame	Perform mullion to frame welding operation on single head welder	350.9	363.8	350.5	355.1

9100, 9950	Mullion Prep and Frame Welding	Weld Mullion to Mullion on Single Head Welder	Any	Each single M-M weld point	3 boxes or more combination unit- Mullion to mullion Weld	Assembly V-notched mullion and cross pieces and perform mullion to mullion welding operation on the single head welder and Manual Corner Clean and Move to M-F Welder	192.3	196.9	186.7	192.0
9100, 9950	Wrapping and Scan	QC/Scan	Any	each window	-	Quality check and scan unit, apply stickers and a new label.	133.7	123.7	119.0	125.5
9100, 9950	Wrapping and Scan	Wrapping	Any	each window	-	Pick, wrap, put the wrapped window on the cart	144.2	150.3	155.2	149.9

Appendix B – Apex Non-value-added Activities

Waste Category	*Operation Name*	*Series*	*Description*	*Observed Time 1*	*Observed Time 2*	*Observed Time 3*	*Average Time*	*Frequency /Possibility*
transportation	Cutting-welding	Apex	In the cutting area, when a cart is full, the frame welder will bring the cart to welding area and return an empty cart.	58s	55s	67s	60s	Every cart (20 windows)
transportation	Cut mullion-route	Apex	After a mullion is cut, a work will bring it to the route area.	4.3s	3.9s	6.1s	5s	Each mullion
transportation	Install Hardware	Apex	In Apex A shift, there is one worker whose job is to find the right components for others, bring the empty cart to prep area and bring back new carts of components.	27000s	27000s	27000s	27000s	Each A shift