Windows Hardware Installation Production Line Improvement

by

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ABSTRACT

Window manufacturing process involves a series of operations including cutting profiles, welding profiles, corner cleaning, installation of hardware and assembling the other components that complete a functional window (such as jam extension, brickmould). The main bottleneck of the manufacturing process is the hardware installation process, since it involves a large variety and number of the hardware, takes a lot of shop floor space, and promotes interaction between workers constantly. As a result, errors could be made on the hardware installation operations, and most importantly delay of the production line and inconsistency in operation cycle time could occur, which results in difficulties in production levelling. Therefore, this research focuses primarily on the improvement of the hardware installation process, in order to smooth the production process and increase the overall production capacity and efficiency.

The issue related to the hardware installation process has been investigated using the lean concept. The option for changing the hardware installation operation sequence has been proposed. And the proposed changes were verified based on the lean concept and simulation results. The simulation method was used for both current practice and future state to verify the effect of the proposed changes on production time and resource utilization rate. This proposed concept is tested and investigated with a cooperating company, one of the largest window manufacturers in Western Canada with headquarters in Edmonton.

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LIST OF ABBREVIATIONS

A/C	Awning/Casement
CAD	Computer-aided Design
DES	Discrete Event Simulation
GDP	Gross Domestic Product
JIT	Just-in-time
LM	Lean Manufacturing
P/F	Picture/Fixed
SALM	Simulation-aided Lean Manufacturing
SOP	Standard Operation Procedure
TPS	Toyota Production System
VSM	Value Stream Mapping

1 INTRODUCTION

1.1 Research background and motivation

According to the Government of Canada (2020), the manufacturing industry ranks as one of the backbones of the Canadian economy, creating nearly 1.7 million jobs across the country and accounting for around $199.2 billion of Canada's gross domestic product (GDP). As it faces the growing challenges of international competition and the demand for highly customized products, manufacturers have needed to become leaner and improve their production systems to stay competitive and profitable.

Having originated at Toyota car manufacturing plants in Japan after the second world war, lean manufacturing (LM) is an approach aimed at eliminating waste or non-value added activities within the production systems in order to be highly responsive to customers' demands and to produce high-quality products with shorter lead times (Rose et al., 2009). The lean approach has the reputation of being beneficial for organizations who seek to gain a competitive edge against companies not using the lean concept, and to reduce operational costs and increase profits (Abdulmalek & Rajgopal, 2007). Numerous methods and tools have been developed throughout the years, such as Kanban, Kaizen, and value stream mapping (VSM), which all assist in implementing the LM concept (Belekoukias et al., 2014). By using a set of symbol representations, VSM is recognized as one of the most effective tools able to expose the non-value added activities under the current operational conditions, providing managers with clear insights into the improvement opportunities (Jasti & Sharma, 2015).

Traditional systems issues, such as component interaction, time dependencies, and uncertainties, are often neglected in the lean analysis, which is a significant drawback in the implementation of lean concepts (Marvel & Standridge, 2009). On the other hand, with the ability to imitate dynamic and complex processes, simulation is considered an ideal complement together with lean tools to overcome the lean assessment limitations (Goienetxea Uriarte et al., 2020). A simulation analysis can not only realistically mimic the current production process and expose issues on the production line, but facilitates the evaluation of non-existing processes before implementation. For many manufacturers, one of the factors that prohibit the adoption of LM concept is the high costs and the risks associated with each change. However, with the statistical data from simulation runs, decision-makers have clear insights regarding the extent of the lean approach's performance and therefore gain more confidence in actual LM practices. Hence, the integration of LM and simulation analysis is a more powerful tool than the LM approach alone, which leads to the fundamental idea behind this research.

ABC Ltd, a pseudonym used to protect the privacy of the industry partner, is a window and door manufacturing company with over ten well-designed production lines on which the company produces a wide range of different types of windows and doors, such as awning, casement, hung, and slider windows, entry doors, folding, garden, and patio doors. Facing growing competition within the industry and higher demand and expectations from customers, ABC Ltd is constantly searching for innovations to maintain and gain a larger market share as well as provide high-quality service and products to its customers. Holding the same goal for innovation and improving the manufacturing process, this research employs LM concepts to identify improvement opportunities on the production line for one of the most popular window series. The impacts of improvements will be determined by the results of the production simulation, providing evidence to decision-makers to facilitate a smoother adoption of changes.

1.2 Research objectives

This research aims to propose a framework for window manufacturing productivity improvement with the integration of simulation modelling to assist manufacturers with validating the impact of the production line design.

This research is based on the following hypothesis:

"Segregating the hardware installation process from its current practice, being after welding and corner cleaning (on a square welded window), to a linear production (1-D), being installed some of the hardware before welding (on a linear window profile), has the potential of increasing productivity and reduce required the factory space."

To achieve this goal, the specific research objectives are carried out as follows:

- to understand the current operations and study on the window assembly rule and operation durations;
- identify the main wastes and bottlenecks in the current production process;
- to apply root cause analysis to reduce the waste and propose improvements;
- to propose a leaner redesigned manufacturing operation sequence;
- to develop a simulation model to analyze the impact of proposed process changes;
- to assess the simulation results and make recommendations on the production line change.

1.3 Thesis organization

This thesis consists of five chapters. Chapter 2 (Literature Review) covers production process simulation and the evolution, tools, and methods of LM. Chapter 3 (Methodology) outlines the proposed framework, dividing it into five sections of detailed production process introduction, data collection, wastes identification, solution proposal, and production process simulation. Chapter 4 (Implementation and Case Study) describes the development of process improvement scenarios and the analysis of each scenario's simulation results on the impact of overall productivity based on the input of actual production data. Chapter 5 (Conclusion) summarizes the case study results and contributions of this research, as well as limitations on the current work and recommendations for future research.

2 LITERATURE REVIEW

2.1 Production process simulation

2.1.1 Simulation introduction

Simulation modelling has been recognized as one of the most useful paradigms for analyzing complex systems and aiding in decision-making across industries. Simulation is an approximate imitation of the system and its dynamic processes abstracted into a model that is able to simulate the experiments and obtain valuable information (Wanitwattanakosol & Sopadang, 2012). As the object of simulation, according to Encyclopedia Britannica (2014), the system can be defined as *"a portion of the universe that has been chosen for studying the changes that take place within it in response to varying conditions."* There are two methods of simulation: physical simulation, which employs actual human and material resources and takes place in an actual real-life environment; and computer-aided simulation, which is established in a computer program using mathematical descriptions and models to mimic the functional relationships within the real system (Abourizk et al., 2016; Lian & Van Landeghem, 2007). In this research, a computer-sided simulation will be used to build simulation models and provide insight on the production process redesign/improvement.

A model can exist in the form of a conceptual and/or programmed computerized model: The conceptual model helps to reveal the scope and objectives of the targeted issue, and the computerized model is the detailed description of the conceptual model and the system using mathematical equations and codes in a computer software environment (Abourizk et al., 2016; Sargent, 2013). The relationship between the models and the real world can be summarized as shown in Figure 1. During the simulation modelling process, verification and validation, which will be discussed in a later section, can guarantee the accuracy and reliability of the model (Bako & Božek, 2016). The objective of a simulation can fall into one or more of the following four categories (Chung, 2004):

- gaining insight into a complex system operation, especial for manufacturing process bottleneck detection;
- developing operation or resource policies to improve system performance, such as deciding on changes in job scheduling method, or staffing arrangement;
- testing new concepts and/or systems before implementation; and
- gathering information without disturbing the actual system.

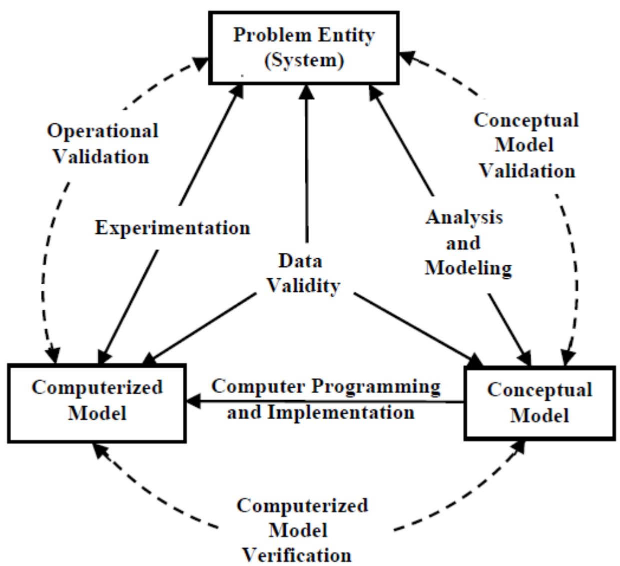


Figure 2-1. Relationship of simulation and real world problem (Sargent, 2013)

2.1.2 Simulation model classification and software

As shown in Figure 2-2, the simulation model can be classified as belonging to one of two major branches: probability/randomness dimension class, and time dimension class. The class of probability/randomness dimension consists of deterministic and stochastic/Monte Carlo simulation models (Abourizk et al., 2016). In contrast to the stochastic/Monte Carlo simulation models, deterministic simulation models will always produce the same results no matter how many runs have been executed (Mourtzis et al., 2014). Influenced by the time factor, dynamic simulation models and static simulation models can be found under the category of the time dimension. Static simulation models do not change with respect to time incrementation, whereas the dynamic simulation models evolve over time, and can be further categorized into discrete and continuous simulation models (Abourizk et al., 2016; Mourtzis et al., 2014). The variable of time in continuous simulation models is continuous and increased by an equal amount, while in discrete simulation, it will change at discrete points. Furthermore, the discrete simulation models are divided based on the types of discrete points: time-stepped or event-driven (Mourtzis et al., 2014). In the time-stepped simulation, the time interval is fixed, and in an event-driven simulation, the time interval is irregular and only based on the occurrence of the scheduled events. Discrete event simulation (DES) is considered one of the most widely used simulation techniques in manufacturing system design and operation (Xia & Sun, 2013). In a streamlined manufacturing process, the materials flow from one workstation to the next upon the completion of tasks, meaning the tasks can be considered as the events in the simulation model. Thus, DES creates dynamic visualization of lead time and resource utilization, which enables the evaluation of operation and system designs using quantified results before the actual implementation of the plan. In recent years, DES has even been viewed as a lean method for manufacturing system improvement and redesign (Jarkko et al., 2013).

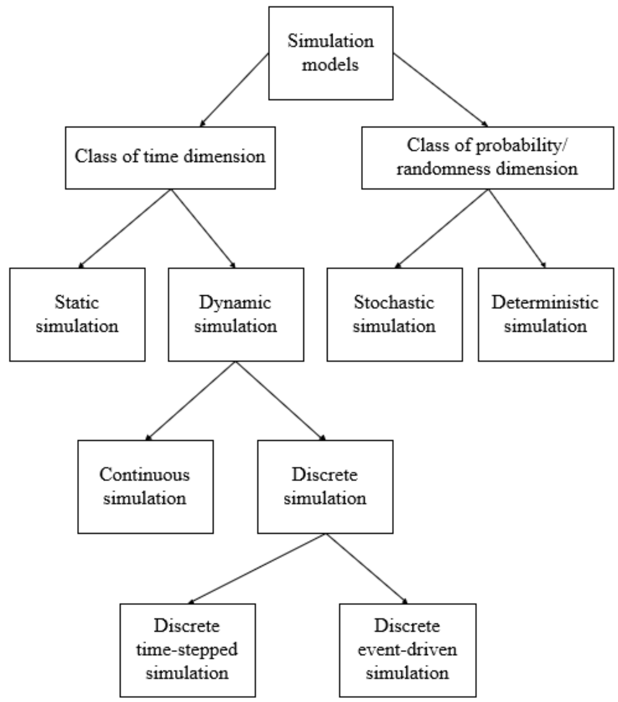


Figure 2-2. Family of simulation models

Simulation software has been developed for decades since the first introduction of the Micro CYCLONE system (Halpin, 1973). Several well-established commercial and academic simulation software have since been developed; for instance, ARENA, AnyLogic, and SIMSCRIPT are popular commercial computer software programs, and STROBOSCOPE, Simphony.NET, and SLAM are examples of academic simulation software (Abourizk et al., 2016). Simphony.NET is a comprehensive and complete simulation tool providing a hierarchical, modular and integrated modelling interface and allows for quick, flexible analysis of various types of projects (AbouRizk & Mohamed, 2000). In this research, the production process modelling will be carried out using the DES technique and Simphony.NET, as DES can best represent the manufacturing process and is easy to model in the environment of Simphony.NET using a library of general-purpose tools and CYCLONE templates.

2.1.3 Simulation model verification and validation

To take full advantage of simulation, it is critical to verify and validate the simulation model, ensuring the simulation model operates as intended and its results are credible. As was shown in Figure 2-1, verification and validation are required throughout the whole cycle of the simulation modelling process, from the analysis and modelling phase to the experimentation phase. In this section, the definitions and the techniques of verification and validation are discussed in detail.

i. Verification

Verification is often recognized as assuring the model is built and implemented correctly (Sargent, 2013). The verification process ensures all the components of the real system are included and the program can run without any error (Chung, 2004). Thus, specification and implementation verification need to be done to complete the verification process. Specification verification is primarily undertaken in the conceptual modelling stage to ensure that the software design and specification of the designated computer system is suitable for programming and implementing the desired conceptual model (Sargent, 2013). During the model construction process, implementation verification is undertaken to discover and avoid errors, such as logical errors, data errors, and bugs within the simulation environment (Abourizk et al., 2016). Several techniques can be used to accomplish the verification process: animation of the simulation, utilizing trace log and entity counters, and performing a walkthrough of the model structure (Abourizk et al., 2016; Sargent, 2013). As a built-in feature of some simulation environments, animation is the most effective way to reveal logical errors by visualizing the activities as the program proceeds (Abourizk et al., 2016). Animation can be realized in different ways, for example, by using different entity annotations for different types of entities, or by graphically displaying details of a simulation model (such as global variables or entity attributes and values, and system statistics) (Chung, 2004). By tracking the order and timestamp of the traced events and the flow of entities, trace log and entity counters can also assist in detecting logical errors (Abourizk et al., 2016). The model can also be verified based on the feedback of peer review through the structured walkthrough and built-in integrity check of robust simulation environments before the execution of the simulation model (Abourizk et al., 2016; Sargent, 2013).

ii. Validation

Validation is the process of guaranteeing the computerized model reflects the actual system in its intended application at a satisfactory range of accuracy (Sargent, 2013), which means it is impossible to have a 100% match between reality and the simulation model. This may be due to assumptions made during the modelling process, inaccuracies, over-simplification, human error, and simulation software and data limitations (Chung, 2004). As presented in Figure 2-1, there are two required validation processes: conceptual model validation and operational validation. The theories and assumptions employed during the conceptual modelling stage and the structure and logic of the model need to be tested and validated as they need to be correctly and reasonably implemented (Sargent, 2013). The operational validation takes place during the experimentation phase to determine the accuracy of the model's output against the desired confidence level (Sargent, 2013). A variety of validation techniques and approaches are discussed by Abourizk et al. (2016), Chung (2004), Sargent (2013), and Sabaghi et al. (2015), and include face validity, comparison to other models, historical data validation, and degenerate tests. Face validity is to acquire comments from knowledgeable individuals about the structure and the behaviour of the model. The comparison to other models is a technique that compares the output of the model with that of an already validated model (Abourizk et al., 2016). The historical data validation approach is also using a comparison technique, in which a part of the data collected is used to set up the model and the rest of the data collected is used to test the behaviour of the model (Sargent, 2013). With carefully selected input values and parameters, the model's behaviour is tested by asking whether the behaviour is as expected or not.

2.2 Lean manufacturing

2.2.1 Lean manufacturing introduction

Lean manufacturing (or lean production) is now a widely discussed and reviewed methodology in a variety of industries around the world. The concept of lean production was first introduced by Eiji Toyoda and Taiichi Ohno at the Toyota Motor Company in Japan after the second world war (Womack, 1991). At the time, mass production was the predominant system employed in manufacturing industries. However, severe financial difficulties and labour shortages, caused by the disruption of war, resulted in the failure of mass production system implementation in Japan and facilitated the birth of lean production, also known as the Toyota Production System (TPS) (Holweg, 2007). Aimed at addressing the defects of the mass production system, which include large inventory and less product diversity, the TPS redesigned and improved the production lines to produce the product just in time for their customer with minimum costs (Holweg, 2007). Despite the success of the TPS in Japan, the concept of LM was still unfamiliar to the Western manufacturing community until the early 1990s with the publication of the book *The Machine that Changed the World*, highlighting the performance gaps between TPS and the other systems (Hines et al., 2004; Womack, 1991).

Over the last decades, the LM concept was broadened and evolved through numerous studies and applications from the original just-in-time (JIT) and Kanban concepts in the TPS (Bhamu &

Sangwan, 2014; Moyano-Fuentes & Sacristán-Díaz, 2012). LM can be generally categorized two ways: 1) lean is a philosophy, focusing on defining the guiding principles and goals; and 2) lean is a set of practical tools or methods that can be directly implemented to reduce wastes (Pettersen, 2009). It was recognized by Bhasin and Burcher (2006) that in order for an organization to reap the full benefits of LM the key factor is the combination of adopting LM philosophy as the basis of management principles and a corporate culture that includes the utilization of lean tools on the production line. As the target of LM, waste is defined as any unnecessary expense or effort that does not add value to the product, and the waste can exist in the production process design, company policy, and manufacturing operations. The following waste types are suggested and agreed upon by most researchers: overproduction, waiting, transportation, inappropriate processing, excessive inventory, unnecessary motions, and defects (Bhasin & Burcher, 2006). By removing the wastes out of the system, organizations could experience the benefits of reduced lead time and inventory levels, less rework, and financial saving in costs (Melton, 2005). The most significant benefit is the overall strengthening of the system, ensuring sustainable development for the company. With a well-established LM system and effective execution, any flaws that appear in the system will be quickly detected and eliminated (Bhasin & Burcher, 2006).

2.2.2 Lean manufacturing implementation tools and methods

The implementation of LM follows five steps. The first step is to identify the wastes within the system by specifying the product value and mapping the value stream (Gupta & Jain, 2013; Moyano-Fuentes & Sacristán-Díaz, 2012). Second, the types of waste and their root causes need to be recognized in order to find the solution and effective tools to eliminate them (Gupta & Jain, 2013). The next step is required to identify the impacts of the solution on the entire system without interrupting the value flow (Gupta & Jain, 2013; Moyano-Fuentes & Sacristán-Díaz, 2012). The fourth step is to establish the pull system, maintaining the balance between production and demand, which is the key factor to ensure no value is created ahead of time (Moyano-Fuentes & Sacristán-Díaz, 2012). Last, the solutions and improvements need to be tested and then implemented, along with the continuous effort to keep improving by following up on the work in the previous four steps (Gupta & Jain, 2013; Moyano-Fuentes & Sacristán-Díaz, 2012). In LM, various tools and methods are developed to help with waste elimination, such Kanban, Kaizen, and value stream mapping (VSM), etc. (Pettersen, 2009). The four LM tools and methods used in this research are reviewed and listed below.

i. Value stream mapping

Value stream mapping is one of the most important LM tools to improve the process and pinpoint the wastes by recording both material flows and information flows (Braglia et al., 2006). By utilizing a set of symbols, metrics, and arrows, a value stream map provides a visual representation of the production process from raw materials to the end product delivery (Venkataraman et al., 2014). VSM includes three major activities: value-added, non-value-added, and waste. According to Tyagi et al. (2015), the value-added activities are categorized as the ones that create value or increase the benefit of the product from the perspective of the customer. On the other hand, the non-value-added activities can be defined as those that do not increase the value of the product to the customers, but are still necessary under the current conditions. Based on work by Rohani and Zahraee (2015) and Braglia et al. (2006), a three-step procedure for performing VSM analysis is introduced. The first step is to select the target product or product family and construct a current state map, which reflects the current production process based on the data collected from the shop floor. The next step is to pinpoint the wastes and analyze the root cause of the waste along the value stream. Finally, a future state map is drafted to illustrate an improved production process after removing the wastes. The implementation of the future state map is also included in this step. Then, a continuous production flow should be established, which is defined as producing one unit at a time and immediately moving it to the next working station (Guner Goren, 2017). Continuous flow is considered one of the most efficient ways to reduce wastes in production.

ii. Kanban

Kanban is a visual signal system for controlling inventory levels and material movement between workstations on a production line, and is based on cards with inventory numbers that are attached to a part (Gupta & Jain, 2013). The Kanban system ensures the practice of just-in-time production. The materials should only be delivered to the production line when the workstations require them, leaving no valuable space on the production floor for storage (Gupta & Jain, 2013). The combination of utilizing VSM and Kanban system could bring significant benefit to manufacturers, resulting in better product flow and inventory levelling. The Kanban system performs as a pull system, while most production lines employ the push system (Gupta & Jain, 2013). The push system requires the manufacturers to forecast the customers' demand and produce the goods ahead of time, which could result in huge problems, such as cumulative inventory stock at the facilities (Melton, 2005). During the demand uncertainty period, the Kanban system can support mixed model production and provide optimal inventory level control to offer less lead time and better resource utilization rates (Sundar et al., 2014).

iii. Cellular manufacturing

The concept of cellular manufacturing is achieved by closely grouping workstations producing similar products so that the operations can be carried out with similar material and human resources and machines close by (Abdulmalek & Rajgopal, 2007). VSM can also be used as the reference for this process, ensuring the continuous flow of the process and providing guidance in planning resources and workstation locations (Sundar et al., 2014). By doing so, significant improvements in productivity, lead time, material movement, space utilization, and cycle times are reported by manufacturers (McLaughlin & Durazo-Cardenas, 2013). To reap the full benefits of cellular manufacturing, it is essential to design an effective social system (focus on the aspect of the employee, such as employee interactions, training, and reward programs) combined with the technical system (e.g., group arrangement, production process design) (McLaughlin & Durazo-Cardenas, 2013). Sundar et al. (2014) suggest the performance of cellular manufacturing relies on the implementation of U-line manufacturing system, line balancing, and flow manufacturing.

iv. Kaizen/Continuous improvement

Kaizen is a Japanese term meaning continuous improvement, and promotes corporate cultural change as a management element (Sundar et al., 2014). Aimed at developing the zero waste manufacturing process, Kaizen tools could be adopted to determine the root cause of defects and apply the feasible solution to the defects with the assistance of collected data (Gupta & Jain, 2013). The benefits of implementing Kaizen have been widely recognized and have garnered a growing amount of attention from companies, particularly in the context of idle time, waiting time, and inventory cost reduction as well as working process and product quality improvement, which provide companies with a competitive edge in the market (Chan & Tay, 2018; Sundar et al., 2014). Many influencing factors contribute to the success of Kaizen; for example, employee perception, adaptation, and engagement. Kaizen events provide an open channel for employees to engage in the company's development (Chan & Tay, 2018). Within these Kaizen events, there are three types of organizational capabilities acting as stepping stones in the implementation of Kaizen. The first type is to establish the employee encouragement and recognition system, which promotes workers' self-awareness on continuous learning and work efficiency improvement. The second one is a mechanism to ensure an open channel for cross-functional communication within the system. The last type is the policy system to safeguard the execution of proper working standards (Chan & Tay, 2018).

2.2.3 Simulation-aided lean manufacturing application

In today's manufacturing sector, manufacturers have recognized the LM approach as one of the optimal solutions in terms of satisfying the growing demand for broadening the variety of products and enabling more customization options. However, due to the risk and cost involved in reconfiguring the production plant, some traditional organizations are still biased towards the full implementation of LM techniques (Atieh et al., 2016). In this case, a simulation-aided lean manufacturing (SALM) approach can be employed to predict the performance of the planned changes and compare different solutions to discover the most suitable strategy for each company prior to fully committing to spending the time and investing resources on the production changes. Marvel and Standridge (2009) propose a five-stage simulation-enhanced lean manufacturing implementation approach, as shown in Figure 2-3.

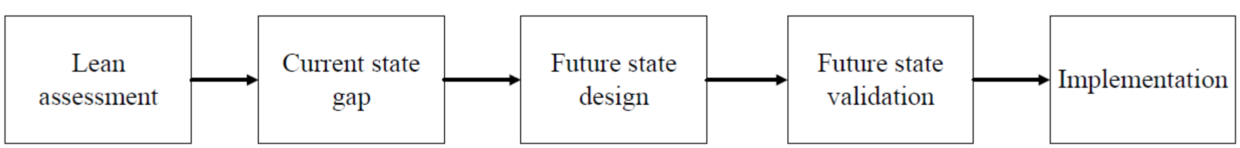


Figure 2-3. Simulation-enhanced lean manufacturing implementation approach (Marvel & Standridge, 2009)

Typically, lean tools, such as VSM, are utilized in stages one to three. And the future state validation can be achieved by DES, which provides confidence in the effectiveness of the proposed changes (Marvel & Standridge, 2009; Omogbai & Salonitis, 2016). The whole process starts with developing a current state map based on the collected data of material and information flow on the current production line. Meanwhile, a current state simulation model can be built, displaying both the value stream and the operations of machine and labour (Diaz-Elsayed et al., 2013). Then by applying lean tools and specifying the desired system performance, the current state gap and the design of the future state can be identified. Finally, various stepwise improvements determined from the last stage can be translated into simulation models and its results can be used to support the decision-making on the final implementation.

Various case studies have been conducted based on this SALM scheme. Esfandyari et al. (2011) applied the scheme specifically using VSM as the lean tool to improve the production lead time for a metal-based fabrication shop. By employing VSM, issues, such as highly inconsistent operation cycle times for stations and uncertain production lead times, are detected. Proposed solutions are simulated in the simulation model, giving an optimal result of 47% production lead time reduction and unplanned released orders reduction. In Detty and Yingling's work (2000), an electronic product assembly process was analyzed and improved using a simulation model and multiple lean tools. The benefits of implementing the SALM approach can be found in several areas: reduction in the requirements for floor space, transportation, inventory, and other resources; reduction in variability in supplier demand; and enhanced production system in model changeover time, lean time, and system flow time. Atieh et al. (2016) adopted VSM and DES to examine the possibility of relieving the system and resulting in better lead time and increasing throughput for a glass fabrication company. The utilization of both tools exposes the hidden bottlenecks, also produces recommendations that could reduce manufacturing lead time by 6% and increase the system performance by 32% after solving primary bottlenecks. An LM and simulation-integrated scheme was employed to improve the productivity of a window manufacturing company (Wang, 2019). Validated by simulation results, the best resource allocation plan can be discovered and ultimately the productivity is increased with a more balanced production line.

3 METHODOLOGY

3.1 Overview

3.1.1 Window types

This research was conducted on one of the most popular window series production line, named the 2100 line, at a window and door manufacturing company. Four types of window units are included and produced on the 2100 line, as shown in Figure 3-1. An awning window refers to the horizontally hung window which can swing outward upon opening; a casement window is defined as the window swing outward and hinged on the side. Both fixed and picture windows are not operational, while the PVC frame profile of the fixed window is thicker than that of the picture window. Each type of window unit is referred to as a box. By producing individual boxes and later joining boxes together, the 2100 series provides the customer with a large amount of freedom to customize the product, and the window design configuration can be considered as a matrix containing up to 12 boxes for one product.

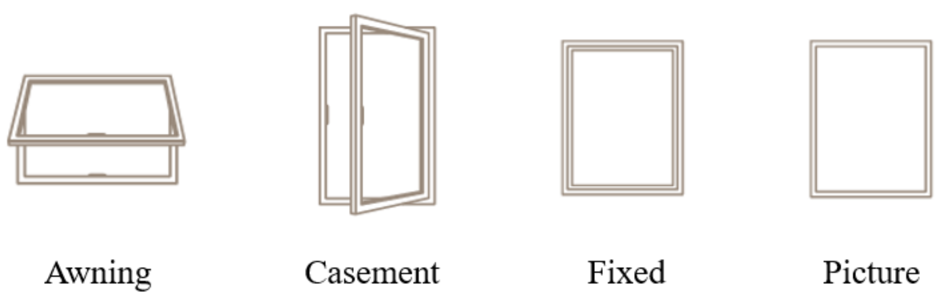


Figure 3-1. Window types for 2100 series

3.1.2 Window production line workstations and operations

The 2100 line consists of two separate sub-production lines: the awning/casement (A/C) line, and the picture/fixed (P/F) line. The layout of the sub-production lines and included workstations are as shown in Figure 3-2. There are a total of six workstations on the A/C line and four workstations on the P/F line, and an additional two workstations for final product assembly and glazing. A total of thirty-five operation steps are required to produce a window and the steps are classified according to the line and workstation at which the step is performed, as shown in Table 3-1, Table 3-2 and Table 3-3. Due to the different window designs, the awning and casement windows require more operations than the picture and fixed windows. Table 3-3 shows the required operations after all the individual boxes have been produced according to order and ultimately finish the entire window product. Moreover, the labour and machine resources within each workstation are recorded in Table 3-4.

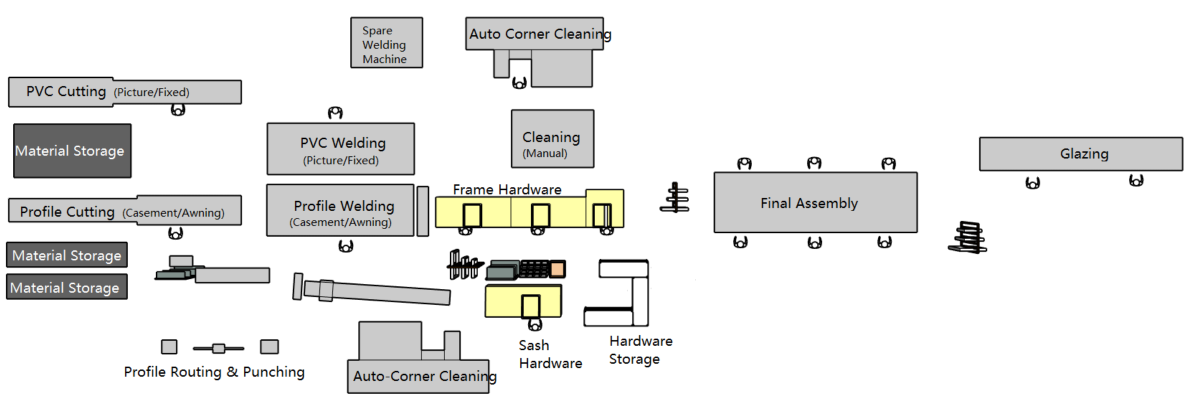


Figure 3-2. Current production line workstation layout

Table 3-1. Summary of window manufacturing operations for awning and casement window

No.	Operations	Workstation
1	Cut sash and frame profiles	Profile cutting station
2	Router multi-lock handle cutout on frame profile	Profile routing and punching station
3	Router operator cutout on frame profile	
4	Punch weep hole on sash profile	
5	Insert weather stripping on sash profile:	
6	Frame and sash profiles welding	Profile welding station
7	Auto corner cleaning	Auto-corner cleaning station
8	Cut nail-fin off frame profile	Frame hardware installation station
9	Manual corner cleaning on frame	
10	Hinge track installation on frame	
11	Casement ramp installation on frame	
12	Snubber installation on frame	
13	Multi-lock handle and tie bar connector installation on frame	
14	Tie bar and Tie bar guide installation on frame	
15	Operator installation on frame	
16	Limit device bracket on frame	
17	Manual corner cleaning on sash	Sash hardware installation station
18	Tie bar keeper installation on sash	
19	Hinge arm installation on sash	
20	Operator bracket installation on sash	
21	Operator track installation on sash	
22	Limit device track on sash	
23	Frame-sash assembly	Frame hardware installation station

Table 3-2. Summary of window manufacturing operations for picture and fixed window

<table>
<tr><th>No.</th><th>Operations</th><th>Workstation</th></tr>
<tr><td>1</td><td>Cut PVC profiles</td><td rowspan="2">PVC cutting station</td></tr>
<tr><td>2</td><td>PVC profiles punching</td></tr>
<tr><td>3</td><td>Profile welding</td><td>PVC welding station</td></tr>
<tr><td>4</td><td>Auto corner cleaning</td><td>Auto corner cleaning</td></tr>
<tr><td>5</td><td>Cut nail-fin</td><td rowspan="2">Cleaning station</td></tr>
<tr><td>6</td><td>Manual corner cleaning</td></tr>
</table>

Table 3-3. Summary of window manufacturing operations for completing final products

<table>
<tr><th>No.</th><th>Operations</th><th>Workstation</th></tr>
<tr><td>1</td><td>Box to box join</td><td rowspan="5">Final production assembly station</td></tr>
<tr><td>2</td><td>Mullion cover installation</td></tr>
<tr><td>3</td><td>Brickmould installation</td></tr>
<tr><td>4</td><td>Jamb extension installation</td></tr>
<tr><td>5</td><td>Cardboard and shipping block installation</td></tr>
<tr><td>6</td><td>Glazing unit assembly</td><td rowspan="4">Glazing station</td></tr>
<tr><td>7</td><td>Screen installation</td></tr>
<tr><td>8</td><td>Quality check:</td></tr>
<tr><td>9</td><td>Wrapping</td></tr>
</table>

Table 3-4. Machine and labour resources account in each workstation

Line name	Workstation name	Machine number	Labour number	Description
A/C line	Profile cutting station	1 cutting machine	1	-
	Profile routing and punching station	2 punching machine and 1 router	-	The labour from profile cutting and welding stations will share this task upon availability.
	Profile welding station	1 welding machine	1	-
	Auto-corner cleaning station	1 profile corner cleaning machine	-	The labour from profile welding and sash hardware installation stations will share this task upon availability.
	Frame hardware installation station	-	3	-
	Sash hardware installation station	-	1	-
P/F line	PVC cutting station	1 cutting machine and 1 punching machine	1	-
	PVC welding station	1 welding machine	1	-
	Auto corner cleaning station	1 profile corner cleaning machine	1	-
	Cleaning station	-	-	The labour from auto corner cleaning station is also responsible for this station.
Joint line of A/C line and P/F line	Final production assembly station	-	6	-
	Glazing station	-	3	-

i. Workstations on the A/C line

1. **Profile cutting station** (shown in Figure 3-3): A worker feeds the raw material for sash or frame profile into the cutting machine. The machine automatically cuts the profile with 45-degree angle corners into designated lengths guided by the instruction from the control panel computer. Then, the worker unloads the profiles, places an information sticker, and passes it down to the next station. The awning and casement window share the same profile design, thus, no need for window type distinction here.

Figure 3-3. Profile cutting station

2. **Profile routing and punching station** (shown in Figure 3-4): Before welding, the worker finishes the details on both sash and frame profiles, including routing the multi-lock handle cutout and operator cutout on the frame profile, punching weep hole, and inserting weather stripping on the sash profile for insulation purpose.

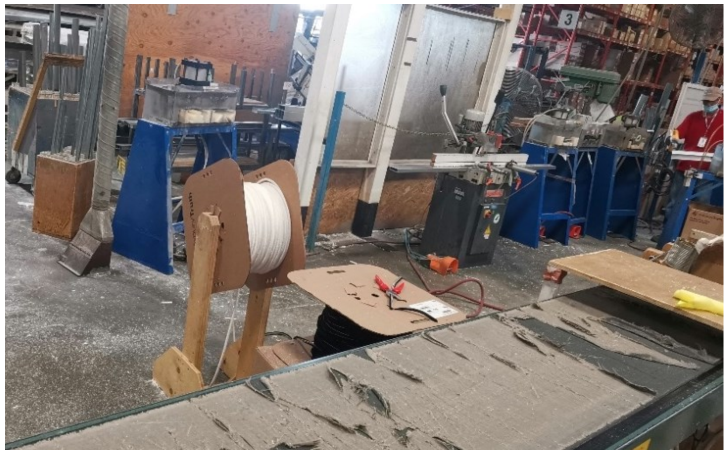


Figure 3-4. Profile routing and punching station

3. **Profile welding station** (shown in Figure 3-5): A worker loads both the sash and frame profiles onto the welding machine and selects the corresponding operation instruction on the control panel. Then the welding machine automatically clamps down the profile into the correct position and releases the heat plates on four 45-degree corners, melting the material from both sides, and finally applying high pressure to force the melted material contacted and welded together. After finishing welding, the worker unloads the ejected sash and frame onto the next station.

Figure 3-5. Profile welding station

4. **Auto-corner cleaning station** (shown in Figure 3-6): A worker is required to push the welded sash or frame into the cleaning position, after which the corner cleaning machine automatically cleans two corners of sash or frame. Then the worker rotates the ejected sash or frame 180 degrees and pushes it back into the corner cleaning machine to clean the remaining two corners. During the welding process, the corner PVC material is melted, which results in material residue on the four corners. Unfortunately, sometimes the cleaned surface still needs to be cleaned by hand.

Figure 3-6. Auto-corner cleaning station

5. **Frame hardware installation station** (shown in Figure 3-7): Three workers are responsible for competing for the operations of cutting nail-fin, manual corner cleaning, hinge tack installation, casement ramp installation, snubber installation, multi-lock handle and tie bar connector installation, tie bar and tie bar guide installation, and operator installation, as well as frame and sash assembly.

Figure 3-7. Frame hardware installation station

6. **Sash hardware installation station** (shown in Figure 3-8): A worker finishes the tasks of manual corner cleaning, tie bar keeper installation, hinge arm installation, operator bracket installation, and operator track installation.

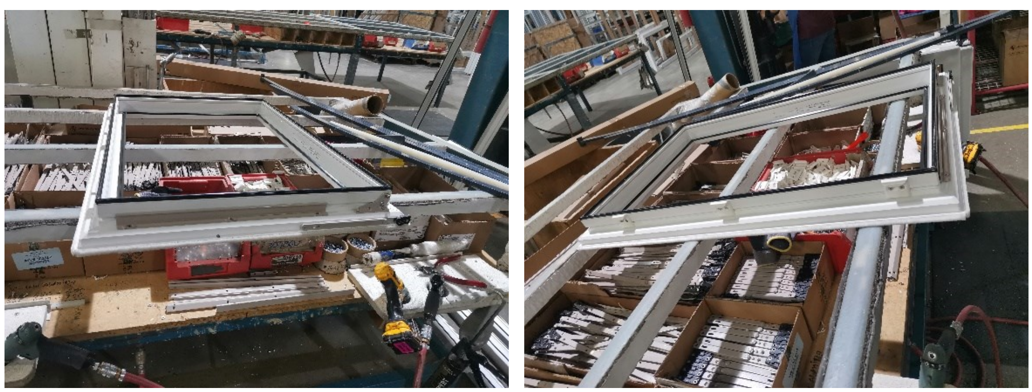


Figure 3-8. Sash hardware installation station

ii. Workstations on the P/F line

1. **PVC cutting station** (shown in Figure 3-9): The actions performed in this station are similar to that of the profile cutting station on the A/C line, with an additional task for PVC profile punching. However, the profile design for the picture window is different

than the fixed window, thus before loading the raw material, the type of profile material needs to be checked according to the order.

Figure 3-9. PVC cutting station (Paniquar De Souto, 2020)

2. **PVC welding station** (shown in Figure 3-10): A worker loads the profiles of one box (either picture window or fixed window) onto the welding machine and selects the corresponding operation instruction on the control panel. Then the welding machine will automatically weld the four PVC pieces together. After finishing welding, the machine ejects the welded profile. The worker then unloads the box frame onto the next station.

Figure 3-10. PVC welding station

3. **Auto corner cleaning** (shown in Figure 3-11): The actions performed in this station are the same as those performed at the auto-corner cleaning station on the A/C line.

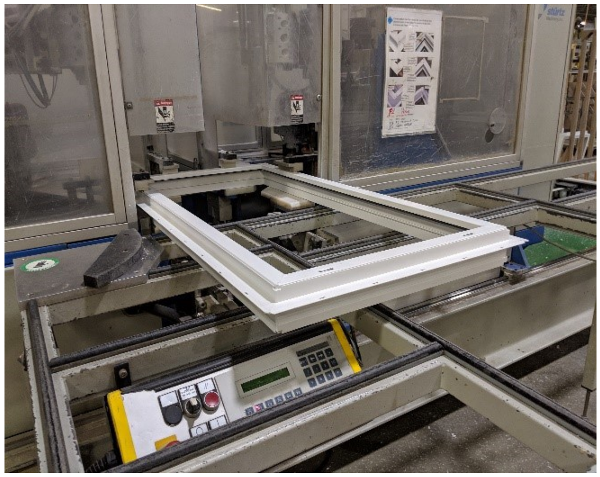


Figure 3-11. Auto corner cleaning (Paniquar De Souto, 2020)

4. **Cleaning station** (shown in Figure 3-12): Manual corner cleaning and cutting nail fin will be performed at this station. Then, the worker will move the picture or fixed window box onto the waiting area for further operations.

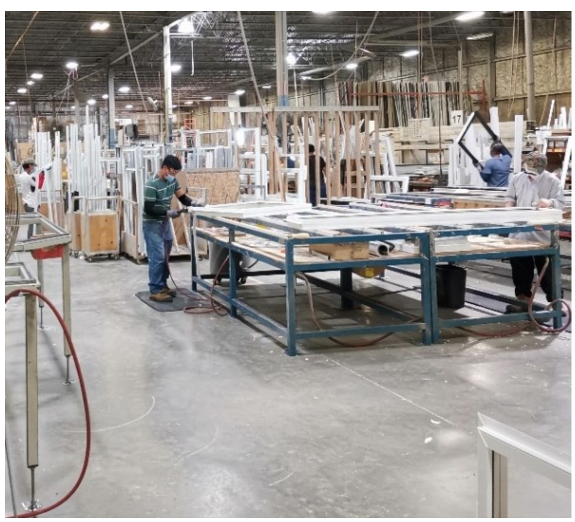


Figure 3-12. Cleaning station

iii. Workstations after the joining of A/C line and P/F line

1. **Final production assembly station** (shown in Figure 3-13): A pair of workers are assigned to this station to first join the boxes together with glue, cut the mullion cover into the desired length, then hammer the mullion cover in place. Next, depending on the order requirements, another pair of workers are responsible for installing the brickmould and preparing the product for jab extension installation. Finally, another two workers will screw the jab extension as required and install the cardboard and shipping block for product protection.

Figure 3-13. Final production assembly station (Paniquar De Souto, 2020)

2. **Glazing station** (shown in Figure 3-14): The glazing unit and screen installation, quality check, as well as wrapping tasks will be completed at this station by two workers.

Figure 3-14. Glazing station

By summarizing Tables 3-1, 3-2 and 3-3, Figures 3-15 and 3-16 are constructed to illustrate the flow and operation sequence of the 2100 line. Based on the operation study, it is determined that the limit device, consisting of limit device bracket and track, is only used for special orders and is not frequently required in production. Therefore, the operations associated with the limit device will be excluded from the present study.

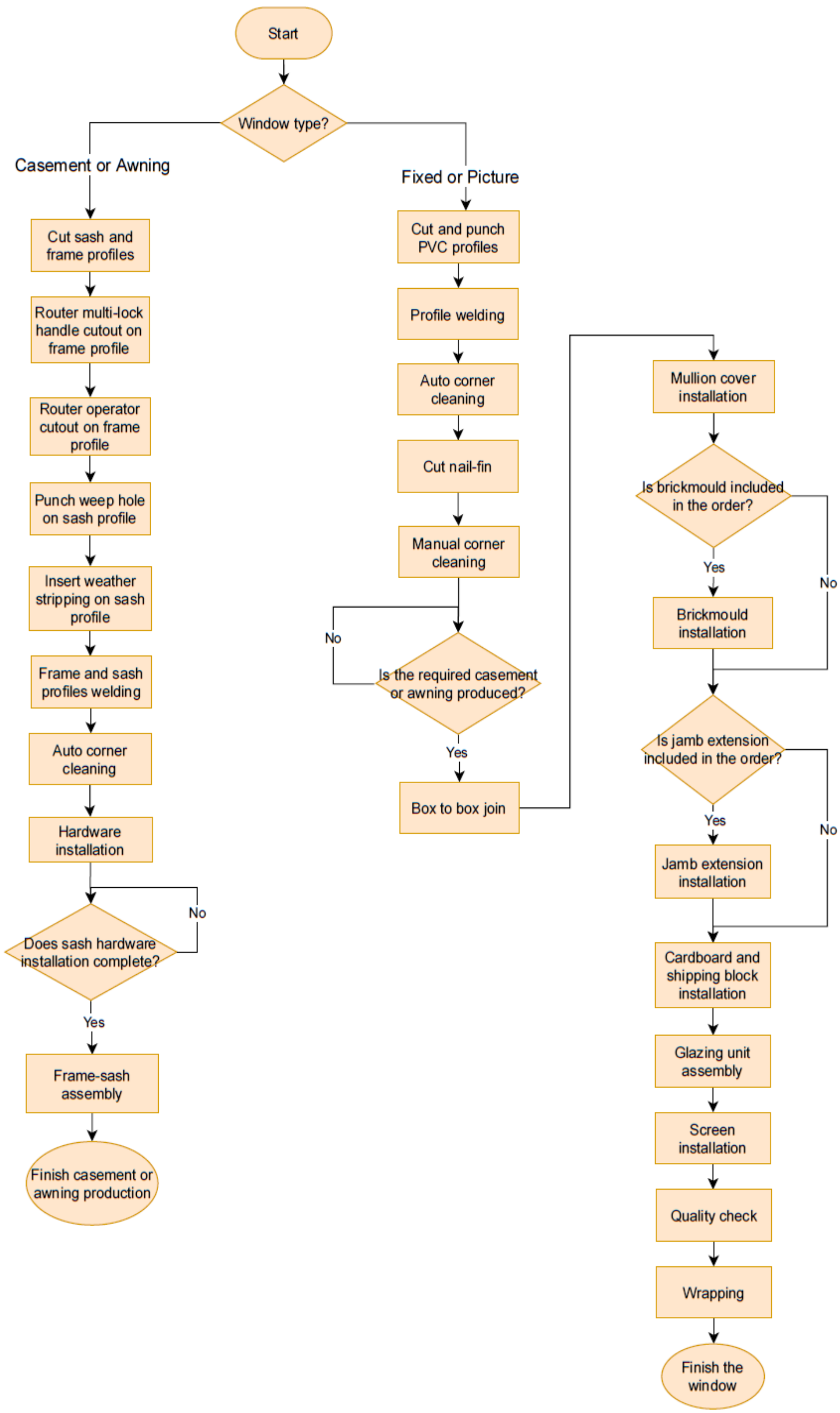


Figure 3-15. 2100 line production sequence flow chart

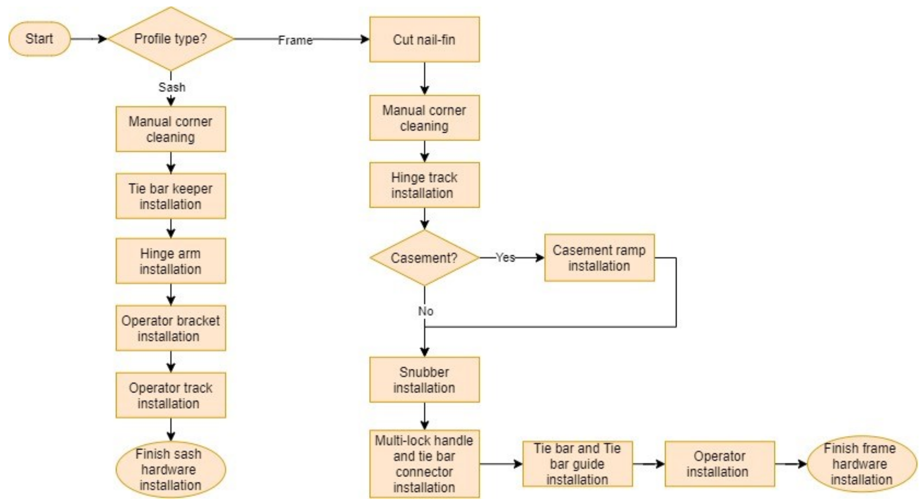


Figure 3-16. Frame and sash hardware installation flow chart

3.1.3 Methodology overview

This section introduces the methodology implemented in this research. An overview of the framework for window production line improvement is demonstrated in Figure 3-17. The framework includes inputs, criteria, main process, and outputs.

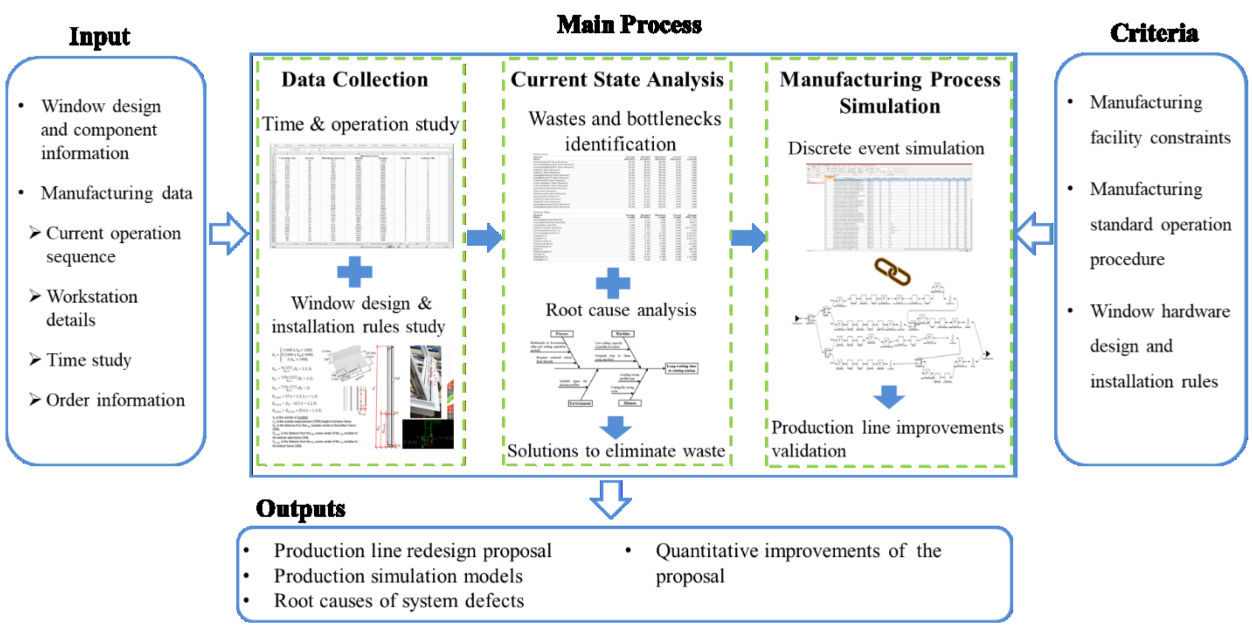


Figure 3-17. Methodology overview

There are three main phases undertaken in the presented research: data collection, current state analysis, and manufacturing process simulation. Multiple time data will be collected for every individual operation on the 2100 line by conducting a time study, which will be described in the following section. The operational sequence and actions will also be recorded and studied, as well as the resource (equipment and labour) layout. Moreover, information pertaining to window design and installation rules are gathered and investigated to understand the constraints of window assembly process design. VSM and current state simulation model will be utilized as the main tools to identify wastes and bottlenecks. After determining the targeted issues, a root cause analysis can be performed to find the root cause of the issue and inform the potential solutions. As discussed previously, computer simulation can be utilized to detect bottlenecks in current practice and analyze the impact of proposed solutions. The simulation model for both the current production process and the redesigned production process will be constructed based on the data collection in the first phase. The models will be verified and validated by comparing the simulated production rate to the historical data, in which the production rate is defined as the number of produced sealed units (or completed orders) per man-hour. Then, by analyzing and comparing the simulation statistical results, the most applicable production line design with highest production rate improvement and lowest required changes can be selected.

The inputs include window design and component information, current operation sequence, workstation details (job duties and resources detail), time study data, and window order information. The criteria that need to be considered during the execution of the main process can be categorized as manufacturing facility constraints, manufacturing standard operation procedures (SOP), window hardware design rules, and installation rules. The redesign of the production line needs to follow the manufacturer's SOP and will not exceed the facility constraints, such as floorspace capacity, resource capacity. The strict following of the window hardware design and installation rules is key to ensure product integrity and functionality. The expected outputs of this research include production simulation models, the root causes system defects, a proposal of the redesigned production process, and finally the statistical results of the potential process changes.

3.2 Data collection

3.2.1 Time study

Time study is a work measurement technique that records the actual time for completing a specific task or operation by skilled workers, which can inform a bottleneck analysis and productivity improvement study (Chandra, 2007; Kulkarni et al., 2014). In this research, a time study will be conducted for all the operations mentioned in Tables 3-1, 3-2 and 3-3. Since numerous factors, such as window size, types of each box, types of required components (e.g., require brickmould, jamb extension or not), can play a huge role in the variation in the time data, the additional information shown in Table 3-5 must also be recorded.

Table 3-5. Time study information category for each observation

Category	Description
Workstation	The name of the workstation at which the operation happens
Operation	The name of the operation
Time when operation starts	The start time of the operation
Time when operation finishes	The end time of the operation
Window size	Window height and width
Types of each box	The types of each window unit and the operation style
Types of required components	Order specification indicating whether any of the following components are required: mullion cover, jamb extension, brickmould, screen

The duration of the operation can be calculated by subtracting the start time from the finish time, and the order specification can be recorded from the job order information sheet; an example of which is shown in Figure 3-18.

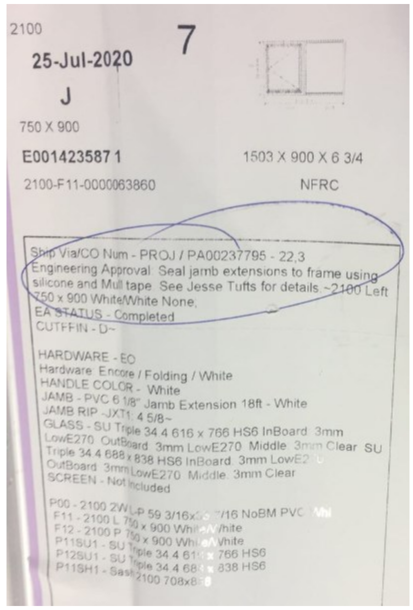


Figure 3-18. Sample of job order information sheet /sticker

3.2.2 Window hardware assembly rule

Based on the manufacturing operation study, the hardware installation process on the A/C line is recognized as the most complicated and technical of the operations. Thus, to fundamentally improve the production line, the engineering design of the window hardware and its installation logic should be investigated. In this research, by carefully studying a collection of CAD and PDF files, all the design logic is interpreted into mathematical models, which facilitates the process of checking the relative location of the hardware on the host profile (either frame or sash). It provides the theoretical foundation for redesigning the hardware installation sequence within the overall operation sequence, assuring no fatal design flaw occurs that may result in production line failure. As shown in Tables 3-6 and 3-7, the types of hardware are categorized by the host type (either frame or sash). Awning and casement windows share the same set of hardware, except the casement ramp and the operator bracket are installed only on the casement frame and sash, respectively.

Table 3-6. Summary of hardware on the 2100 series awning window

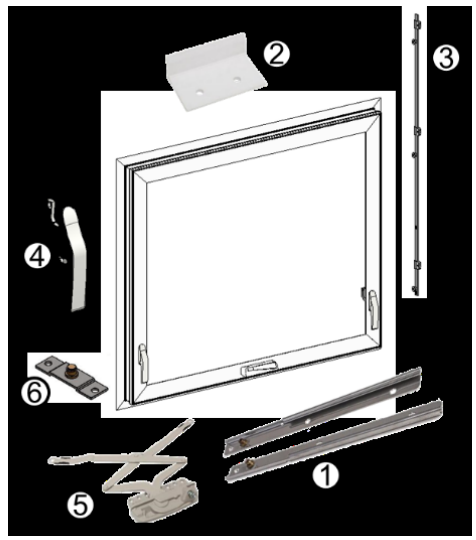
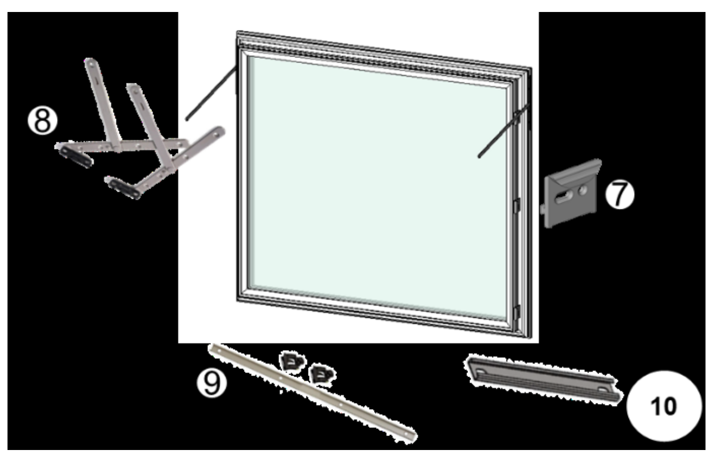
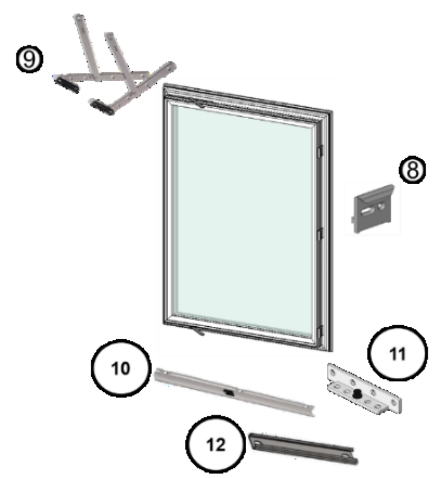
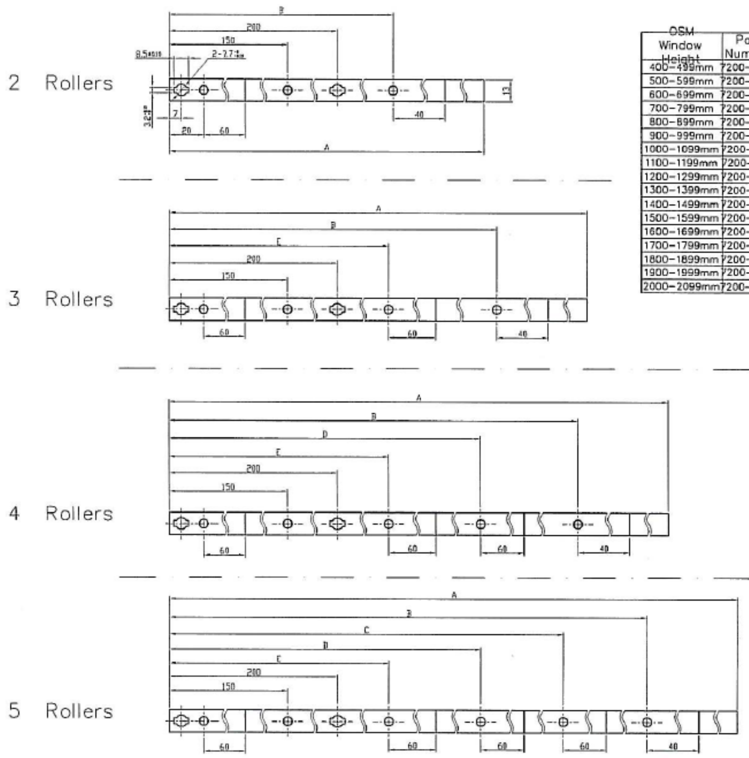
No.	Location	Hardware name	Picture
1	Frame	Hinge track	
2		Snubber	
3		Tie bar & tie bar guide	
4		Multi-lock handle	
5		Operator	
6		Limit device bracket	
7	Sash	Tie bar keeper	
8		Hinge arm	
9		Operator track	
10		Limit device track	

Table 3-7. Summary of hardware on the 2100 series casement window

No.	Location	Hardware name	Picture
1	Frame	Hinge track	
2		Snubber	
3		Casement ramp	
4		Tie bar & tie bar guide	
5		Multi-lock handle	
6		Operator	
7		Limit device bracket	
8	Sash	Tie bar keeper	
9		Hinge arm	
10		Operator track	
11		Operator bracket	
12		Limit device track	

A sample of the mathematical model translation process can be found in the following discussion, demonstrating the calculation for tie bar selection, tie bar, and tie bar guide installation on frame profile and tie bar keeper installation on sash profile. Equation 3-1 illustrates the tie bar selection rule for the various window sizes as per the original document shown in Figure 3-19, where h_w is the outside measurement (OSM) height of the window frame and l_{tb} is the length of the tie bar.

$$l_{tb} = \begin{cases} 230 & \text{for } 350 \le h_w < 500 \\ \lfloor h_w - 400 \rfloor + 230 & \text{for } h_w \ge 500 \end{cases} \tag{3-1}$$



OSM Window Height	Part Number	Rollers	"A"	"B"	"C"	"D"	"E"
400–499mm	7200–0400	2	230mm	N/A	N/A	N/A	N/A
500–599mm	7200–0500	2	330mm	250mm	N/A	N/A	N/A
600–699mm	7200–0600	2	430mm	350mm	N/A	N/A	N/A
700–799mm	7200–0700	2	530mm	450mm	N/A	N/A	N/A
800–899mm	7200–0800	2	630mm	550mm	N/A	N/A	N/A
900–999mm	7200–0900	3	730mm	650mm	N/A	N/A	365mm
1000–1099mm	7200–1000	3	830mm	750mm	N/A	N/A	415mm
1100–1199mm	7200–1100	3	930mm	850mm	N/A	N/A	465mm
1200–1299mm	7200–1200	4	1030mm	950mm	N/A	686.7mm	343.3mm
1300–1399mm	7200–1300	4	1130mm	1050mm	N/A	753.3mm	376.7mm
1400–1499mm	7200–1400	4	1230mm	1150mm	N/A	820mm	410mm
1500–1599mm	7200–1500	4	1330mm	1250mm	N/A	886.7mm	443.3mm
1600–1699mm	7200–1600	4	1430mm	1350mm	N/A	953.3mm	476.7mm
1700–1799mm	7200–1700	5	1530mm	1450mm	1092.5mm	735mm	377.5mm
1800–1899mm	7200–1800	5	1630mm	1550mm	1167.5mm	785mm	402.5mm
1900–1999mm	7200–1900	5	1730mm	1650mm	1242.5mm	835mm	427.5mm
2000–2099mm	7200–2000	5	1830mm	1750mm	1317.5mm	885mm	452.5mm

Figure 3-19. Tie bar selection rule.

As for the tie bar and tie bar installation criteria, Figure 3-20 shows a sample CAD design of the two rollers tie bar installation on different sizes of window, corresponding to Equations 3-2, 3-3 and 3-4. The variables involved in the calculation are h_w, N_{tbg} (number of tie bar guide), N_r (number of rollers of a tie bar), D_{tbg_si} (distance from tie bar guide screw location to frame bottom), D_{tb_li} (distance from i_{th} guider installation line to tie bar bottom), and D_{tb_ri} (distance from i_{th} tie bar roller center to tie bar bottom). Equation 3-2 summarizes the information in Figure 3-19, and serves as the operating condition for Equation 3-4. Equation 3-3 is used to calculate the distance from tie bar guide screw location to frame bottom, in which D_{tb_li} can be determined by Equation

3-4. Based on the engineering design, the longest tie bar contains five tie bar rollers, which splits the D_{tb_ri} calculation into five conditional equations, shown as Equations 3-5, 3-6, 3-7, 3-8, 3-9.

$$N_{tbg} = N_r = \begin{cases} 1 & \text{for } h_w < 500 \\ 2 & \text{for } 500 \le h_w < 900 \\ 3 & \text{for } 900 \le h_w < 1200 \\ 4 & \text{for } 1200 \le h_w < 1700 \\ 5 & \text{for } 1700 \le h_w < 2100 \end{cases} \tag{3-2}$$

$$D_{tbg\_si} = D_{tb\_li} + 76.3 \tag{3-3}$$

$$D_{tb\_li} = \begin{cases} D_{tb\_ri} + 60 & (i < N_{tbg}, or\ N_{tbg} = 1) \\ D_{tb\_ri} + 40 & (i = N_{tbg}, N_{tbg} > 1) \end{cases} \tag{3-4}$$

$$D_{tb\_r1} = 20 \tag{3-5}$$

$$D_{tb\_r2} = \begin{cases} l_{tb} - 80 & (N_r = 2) \\ \frac{l_{tb}}{N_r - 1} & (N_r = 3,4) \\ \frac{l_{tb} - 100}{N_r - 1} + D_{tbr\_1} & (N_r = 5) \end{cases} \tag{3-6}$$

$$D_{tb\_r3} = \begin{cases} l_{tb} - 80 & (N_r = 3) \\ \frac{l_{tb}}{N_r - 1} \times 2 & (N_r = 4) \\ \frac{l_{tb} - 100}{N_r - 1} \times 2 + D_{tbr\_1} & (N_r = 5) \end{cases} \tag{3-7}$$

$$D_{tb\_r4} = \begin{cases} l_{tb} - 80 & (N_r = 4) \\ \frac{l_{tb} - 100}{N_r - 1} \times 3 + D_{tbr\_1} & (N_r = 5) \end{cases} \tag{3-8}$$

$$D_{tb\_r5} = l_{tb} - 80\ (N_r = 5) \tag{3-9}$$

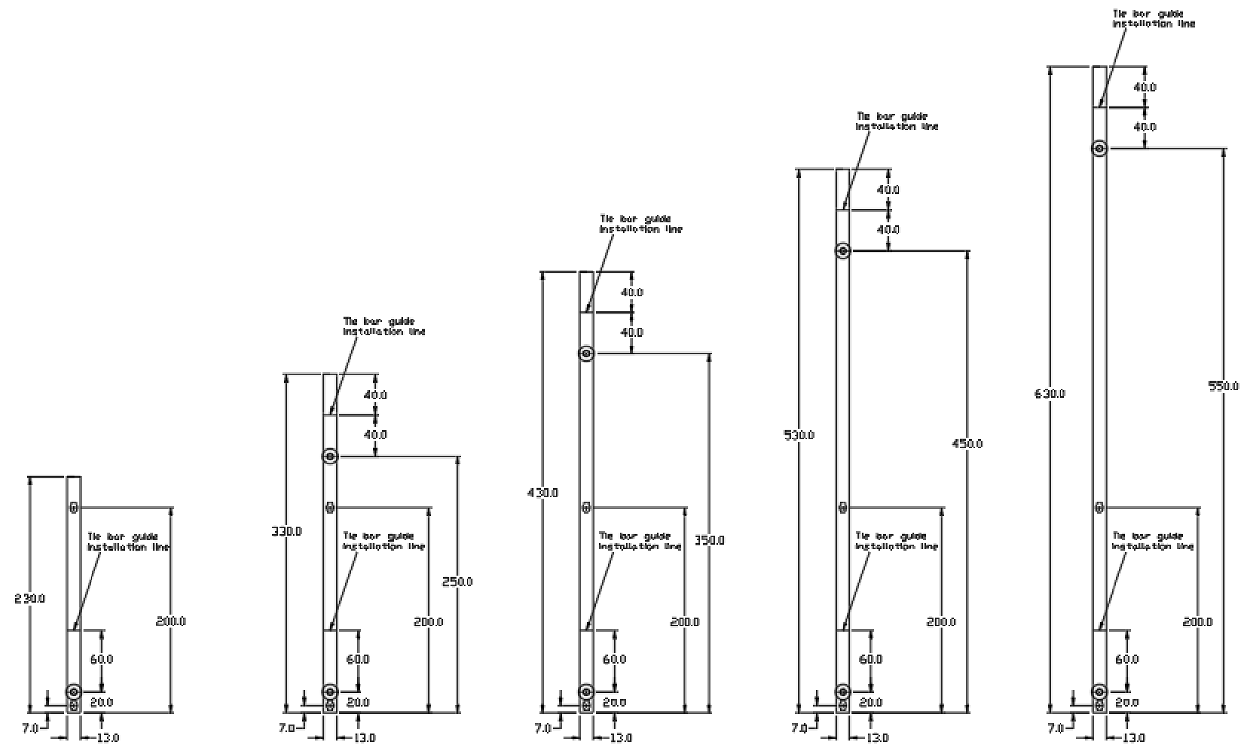


Figure 3-20. Schematic of tie bar and tie bar installation location.

Tie bar keeper is installed on the sash profile, which is a critical component for the multi-point lock system, stabilizing the tie bar in place. The number of tie bar keeper (N_{tbk}) equals to the number of tie bar roller (N_r), which the relationship is summarized in Equation 3-10. Based on the calculation for D_{tb_li}, the distance from the i_{th} tie bar keeper bottom to sash bottom (D_{tbk_i}) can be calculated by Equations 3-11, 3-12, 3-13, 3-14, 3-15.

$$N_{tbk} = N_r = \begin{cases} 1 & \text{for } h_w < 500 \\ 2 & \text{for } 500 \le h_w < 900 \\ 3 & \text{for } 900 \le h_w < 1200 \\ 4 & \text{for } 1200 \le h_w < 1700 \\ 5 & \text{for } 1700 \le h_w < 2100 \end{cases} \tag{3-10}$$

$$D_{tbk\_1} = 45.8 \tag{3-11}$$

$$D_{tbk\_2} = \begin{cases} l_{tb} - 54.2 & (N_r = 2) \\ \frac{l_{tb}}{N_r - 1} + 25.8 & (N_r = 3,4) \\ \frac{l_{tb} - 100}{N_r - 1} + D_{tbr\_1} + 25.8 & (N_r = 5) \end{cases} \tag{3-12}$$

$$D_{tbk\_3} = \begin{cases} l_{tb} - 54.2 & (N_r = 3) \\ \frac{l_{tb}}{N_r - 1} \times 2 + 25.8 & (N_r = 4) \\ \frac{l_{tb} - 100}{N_r - 1} \times 2 + D_{tbr\_1} + 25.8 & (N_r = 5) \end{cases} \tag{3-13}$$

$$D_{tbk\_4} = \begin{cases} l_{tb} - 54.2 & (N_r = 4) \\ \frac{l_{tb} - 100}{N_r - 1} \times 3 + D_{tbr\_1} + 25.8 & (N_r = 5) \end{cases} \tag{3-14}$$

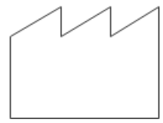
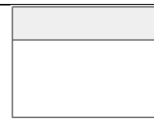
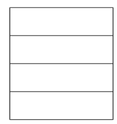
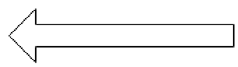
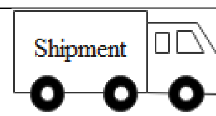
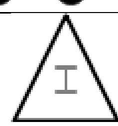
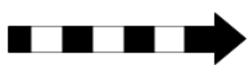
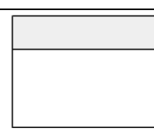
$$D_{tbk\_5} = l_{tb} - 54.2 \quad (N_r = 5) \tag{3-15}$$

3.3 Current state analysis

3.3.1 Current state value stream mapping

VSM is a visualization tool, utilizing a set of icons to construct flow charts of the material and information flow of the entire manufacturing process, assisting in discovering wastes within the system. As discussed in Chapter 2, the first step of VSM is to conduct the current state value stream map to gain insight into the present situation. Nash and Poling (2008) and Rother and Shook (2003) summarized a set of standard VSM icons into three categories, process, material, and information icons, as listed in Table 3-8, which will be employed in this research.

Table 3-8. VSM icons (Nash & Poling, 2008; Rother & Shook, 2003)

Category	Icon name	Symbol	Description
Process	Supplier/customer		Identify the supplier, placing it on the far left side of the paper; identify the customer, placing it on the right-hand side of the paper
	Process box		Show where flow starts and stops within the process.
	Data box		Located directly underneath the process box, and contains any information that is important to the process.
	Shipment arrow		Show materials coming from suppliers or finished goods going from factory to customers.
	External shipment		Represent external shipment to customers or from suppliers.
Material	Inventory		Show the inventory between two processes or stored inventory.
	Operator		Show the number of workers that are needed in a particular station.
	Push arrow		Show material being pushed downstream from one process to the next.
Information	Manual information flow		Represent information flow from memos, reports, or conversation.
	Electronical information flow		Represent digital information flow, such as the electronic data interchange, intranets
	Production control		A centralized production scheduling or control department is represented by this symbol.

3.3.2 Root cause analysis

After the establishment of the current state value stream map, wastes and bottlenecks in the value stream can be now detected. The next steps will include identifying the root cause of all the targeted issues and proposing and selecting the best solutions to reduce or remove them. The 5 Whys and fishbone diagram methods are commonly used among business professionals to solve complex problems, and will also be used in this research. The 5 Whys method is a process that involves repeatedly asking "Why?" when a problem and its causes are identified until the true root causes are determined (Chen et al., 2010). The 5 Whys method typically includes the first step of determining the starting point of the analysis (either a problem or an identified cause); second, brainstorming the causes and writing them down below the starting point; then, continuing to ask the question of "Why is this a cause of the original problem?" for each identified cause until no more answers can be found; finally, displaying the causes in a chain sequence (Andersen & Fagerhaug, 2006). The fishbone diagram, also known as the cause and effect diagram, can systematically analyze the relationships between the problem and its causes by grouping the causes into different categories and determining the most likely root causes. The analysis usually explores the contribution from three basic types of causes: physical causes, human causes, and organizational causes. Figure 3-21 shows a typical structure of the fishbone diagram, with the identified problem on the right-hand side and main categories of causes branching out from the problem body. By exploring multiple causes within each category, the fishbone diagram provides a comprehensive collection of causes from all areas and a clear visualization of the relationship between the problem and the causes. Once the root causes are determined, the solutions that can best address the problem need to be discussed and selected. Some of the more effective solutions will be changes to improve the working process, and the effects of the changes can be visualized and validated by simulation models.

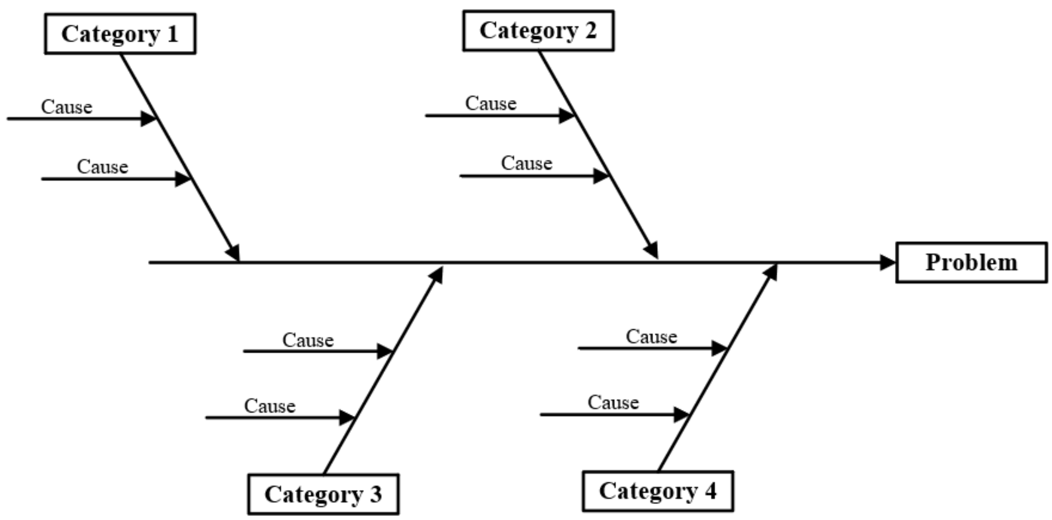


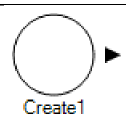
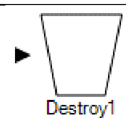
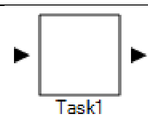
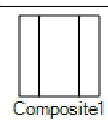
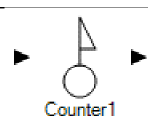
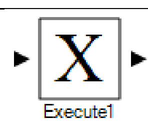
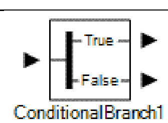
Figure 3-21. Typical fishbone diagram structure

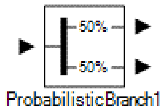
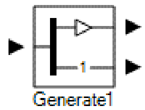
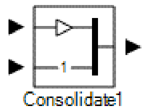
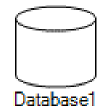
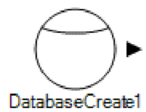
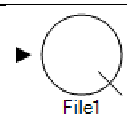
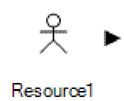
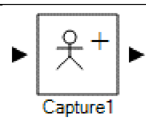
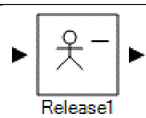
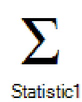
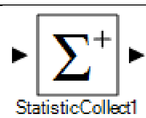
3.4 Simulation analysis

3.4.1 Building the simulation model

As mentioned in Section 2.1.2, DES and Simphony.NET are chosen as the simulation type and software program employed in this research. Since the window assembly process can be considered as an approximately streamlined manufacturing process, with the start of a task depending on the completion of the previous task; thus, DES is the best candidate to model the manufacturing process in the present study. A database of collected window order information was created using Microsoft Access and later connected with the simulation model as the inputs. Illustrated by Figure 2-1, building the simulation model starts with conceptual modelling for the problem and system as identified by lean analysis. The simulation assumptions, requirements, and specifications are also determined at this stage. Then, the conceptual model needs to be translated into a draft computerized model with the inputs of production sequence and workstation details and the data collected from time study. The draft model can be only applied to investigate the impact of the redesigned production process after being verified and validated. The verification and validation processes will be discussed in the following section. Modelling in Simphony.NET consists of connecting modelling elements with directional arrows indicating the flow of entities. Entities, in this case window orders, flow through and between the modelling elements, and the modelling elements are the representation of manufacturing operations. Table 3-9 includes the modelling elements that are used in this research.

Table 3-9. Modelling elements (Abourizk et al., 2016)

Element	Symbol	Description
Create		Create entities and introduce them into the model.
Destroy		Remove entities from the model.
Task		Model an activity by holding the entity for a period of time, as specified in its duration property.
Composite		A container for sub models.
Counter		Record the number of entities passing through and the simulation time at which they are observed.
Execute		Run a snippet of user written code (i.e., a formula) whenever an entity arrives at its input point.
Conditional Branch		Route an arriving entity out of one of two branches depending on a specified condition.

Probabilistic Branch		Model uncertainty associated with events in systems being modelled.
Generate		Create one or more clones of a passing entity.
Consolidate		Block an entity arriving via the upper branch until one or more entities arrive via the lower branch.
Database		Link to a specified database.
Database Create		Extract attributes from the database and introduce entities into the model.
File		A queue in which entities wait for a shared resource.
Resource		A shared resource.
Capture		Grant the exclusive use of one or more servers of a resource to an entity.
Release		Allow an entity to return servers it has previously captured to the pool of available servers.
Statistic		Define a custom statistic.
Statistic Collect		Add an observation to a statistic when entities passing through.

3.4.2 Simulation model verification and validation

The simulation model is typically employed to support the decision-making process, which often involves decisions corresponding to significant cost and investment. Therefore, the credibility of the simulation model must be assured and secured through verification and validation processes to ensure that the simulation model is developed correctly and imitates the real system behaviour as close as possible. Verification is to confirm the model follows and properly implements the specifications of the conceptual modelling stage. The four types of verification techniques, described in Section 2.1.3, are used to accomplish the goal of verification. Then, the draft model is validated by the historical data validation method to ensure the accuracy on the level of realistic representation of the simulation model. The order information from the Microsoft Access database will be the input of the model with a setup production time. After getting the simulation result, the simulated production rate (completed orders per man-hour) will be compared to the actual production rate from the company's production management system. This system constantly controls the flow and storage of information, such as the window order details, production jobs, personnel, equipment maintenance schedules, and delivery information.

3.4.3 Bottleneck detection

After running the current state model, the resource utilization rate and waiting time can be obtained from the statistics report generated by the simulation software, as shown in Figure 3-22. A bottleneck can be caused by many reasons, for instance, unbalanced distribution of operation duties and workload among workstations, insufficient operation sequence design, and poor production floor design. In this research, a bottleneck is considered to occur in two circumstances: 1) when both the waiting time and the resources utilization rate are very high, which means the resource is overloaded with tasks; 2) when the waiting time is high, but the utilization rate is considerably low, or vice versa, which means the resource is performing tasks inefficiently.

Resources

Element Name	Average Utilization	Standard Deviation	Maximum Utilization	Current Utilization	Current Capacity
CornerCleanerP/F (Inner Resource)	82.5%	38.0%	100.0%	0.0%	1.000
CornerCleanMachineA/C (Inner Resource)	42.2%	49.4%	100.0%	0.0%	1.000
CornerCleanMachineP/F (Inner Resource)	82.5%	38.0%	100.0%	0.0%	1.000
CutterA/C (Inner Resource)	37.8%	48.5%	100.0%	0.0%	1.000
CutterP/F (Inner Resource)	58.4%	49.3%	100.0%	0.0%	1.000
CuttingMachineA/C (Inner Resource)	36.6%	48.2%	100.0%	0.0%	1.000
CuttingMachineP/F (Inner Resource)	58.4%	49.3%	100.0%	0.0%	1.000
FinalAssembler (Inner Resource)	53.5%	33.1%	100.0%	0.0%	6.000
Frame Hardware 2 (Inner Resource)	16.5%	37.1%	100.0%	0.0%	1.000
Frame Hardware 3 (Inner Resource)	18.9%	39.1%	100.0%	0.0%	1.000
FrameAssembler (Inner Resource)	70.1%	45.8%	100.0%	0.0%	1.000
Glazer (Inner Resource)	75.1%	41.8%	100.0%	0.0%	2.000
SashAssembler (Inner Resource)	58.6%	49.3%	100.0%	0.0%	1.000
Screener (Inner Resource)	39.8%	49.0%	100.0%	0.0%	1.000
WelderA/C (Inner Resource)	70.7%	45.5%	100.0%	0.0%	1.000
WelderP/F (Inner Resource)	26.0%	43.8%	100.0%	0.0%	1.000
WeldingMachineA/C (Inner Resource)	58.7%	49.2%	100.0%	0.0%	1.000
WeldingMachineP/F (Inner Resource)	26.0%	43.8%	100.0%	0.0%	1.000

Waiting Files

Element Name	Average Length	Standard Deviation	Maximum Length	Current Length	Average Wait Time
ConsolidateAwning (InnerFile)	0.013	0.111	1.000	0.000	21.710
ConsolidateCasement (InnerFile)	0.117	0.329	2.000	0.000	60.811
Consolidate1 (InnerFile)	0.000	0.000	1.000	0.000	0.000
HaltRun Controller (InnerFile)	1.000	0.000	1.000	0.000	22,435.357
CornerCleanMachineA/C Q	0.014	0.119	1.000	0.000	2.869
CornerCleanMachineP/F Q	5.452	4.509	14.000	0.000	2,184.054
CuttingA/C Q	8.939	15.159	52.000	0.000	3,457.931
CuttingP/F Q	8.803	11.754	37.000	0.000	3,526.911
FinalAssembler Q	0.323	0.983	4.000	0.000	17.425
FrameAssembler Q	1.982	3.152	11.000	0.000	463.094
FrameHardware Q	0.020	0.143	2.000	0.000	4.064
Glazer Q	0.837	1.183	5.000	0.000	208.739
SashAssembler Q	0.231	0.426	2.000	0.000	72.039
Screener Q	0.005	0.073	1.000	0.000	2.000
WeldingA/C Q	11.409	10.726	31.000	0.000	1,153.009
WeldingP/F Q	0.000	0.000	1.000	0.000	0.000

Figure 3-22. Sample of simulation statistics report on resources utilization rate and waiting time

3.5 Future state and improvements implementation

Once the simulation model is verified and validated, the proposed changes on the production line can be modelled and simulated to realize the potential impacts on the overall productivity. Thus, a production trial on the redesigned production process with minimal investment is recommended. Depending on the level of commitment from the organization, the duration of the trial can range from one week to several weeks. Meanwhile, the time study will be reconducted and its data will be refed into the future state model to increase the accuracy of the simulation model, which can be used for continuous improvement. Due to the impact of the COVID-19 pandemic, the recommendation of the production trial is discussed in the following section. But the trial has not been conducted and the results are not available at this point.

4 IMPLEMENTATION AND CASE STUDY

In this section, a case study is conducted to demonstrate the proposed methodology. By utilizing LM tools and simulation models, wastes and bottlenecks are pinpointed on the current 2100 series production line at the ABC Ltd. production facility. Based on the outcome of the root cause analysis, redesigning the production operation sequence is considered as the optimal solution to address bottlenecks at multiple workstations without creating a new bottleneck. Supported by the window hardware assembly rule study, a new operation sequence and production layout are proposed.

A simulation model of current production is developed and validated with the data from the completed time study and operation observation, and the current state simulation model is set as the baseline for results comparison of different scenarios. Three scenarios of proposed changes are presented and examined along with the results in this section, with changing labour and material resources in different cases. The most important intention underlying these changes is avoiding a large capital investment and production interruption. Via results comparison, the best-case scenario and the implementation process are recommended at the end of this chapter. It should also be noted that a further feasibility and cost-benefit analysis is required for the proposed redesigned production operation sequence and implementation process.

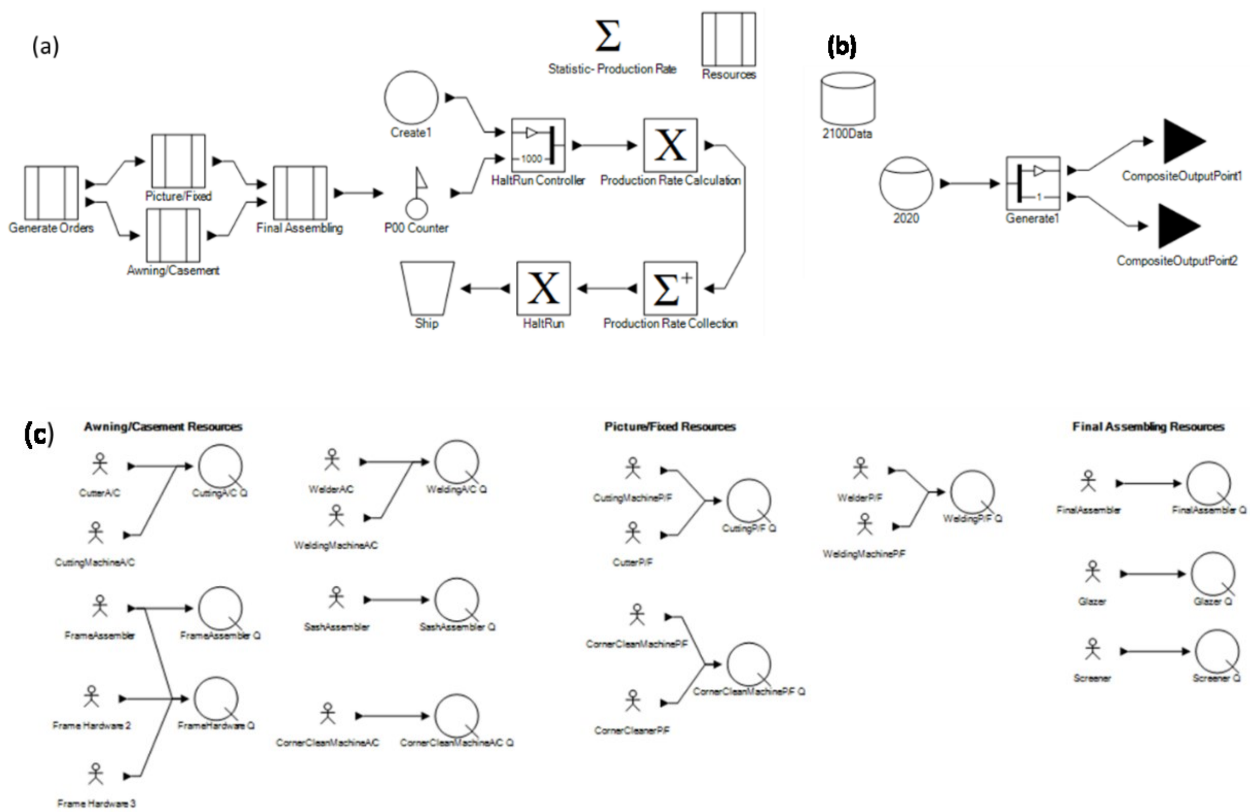
4.1 2100 line simulation analysis

4.1.1 Time study

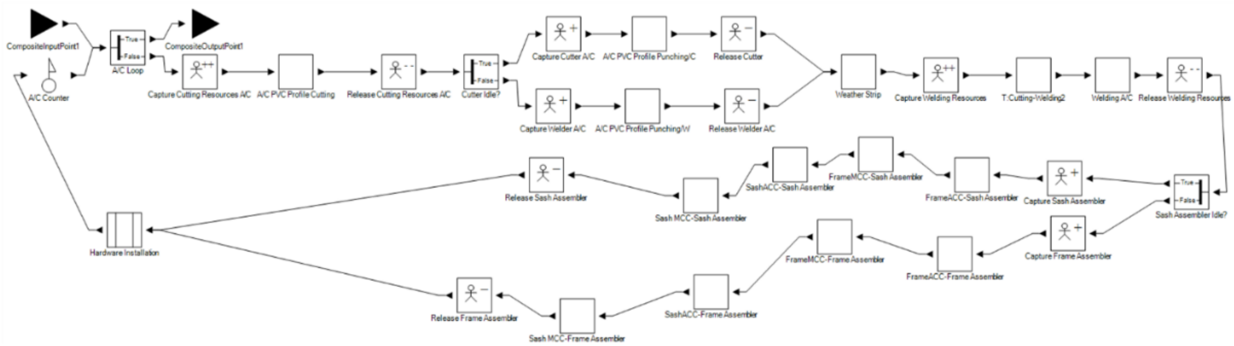
Based on the criteria set in Section 3.2.1, the working time for each operation on the 2100 line was recorded via a timer, starting with the worker picking up the material and ending with the material exiting the machine or the workstation. Multiple time data were collected for each operation and organized into Microsoft Excel datasheets, which will be fed into the simulation model to find the best-fitted distribution for the task duration. While recording the time data, the order information was also collected as required in Table 3-5, and was then summarized into a Microsoft Access database and connected with the simulation model as inputs. A sample of the time data and the order information database can be found in Appendices A and B, respectively.

4.1.2 Simulation model development

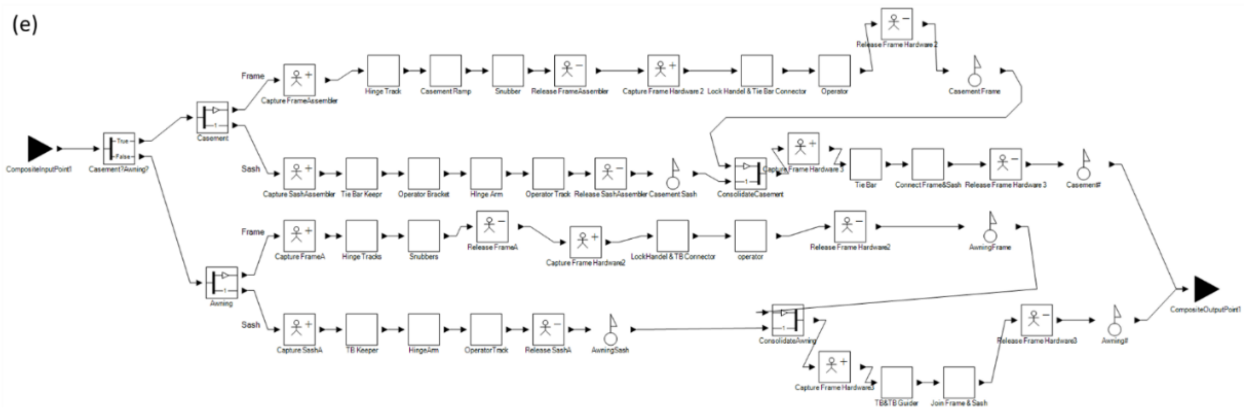
A current state manufacturing process simulation model is developed to mimic the production flow shown in Figures 3-15 and 3-16. The model consists of seven major layers: 1. 2100 line production, 2. generate orders, 3. resources, 4. awning/casement line, 5. hardware installation, 6. picture/fixed line, 7. final assembly, as shown in Figure 4-1 (a), (b), (c), (d), (e), (f) and (g), respectively.



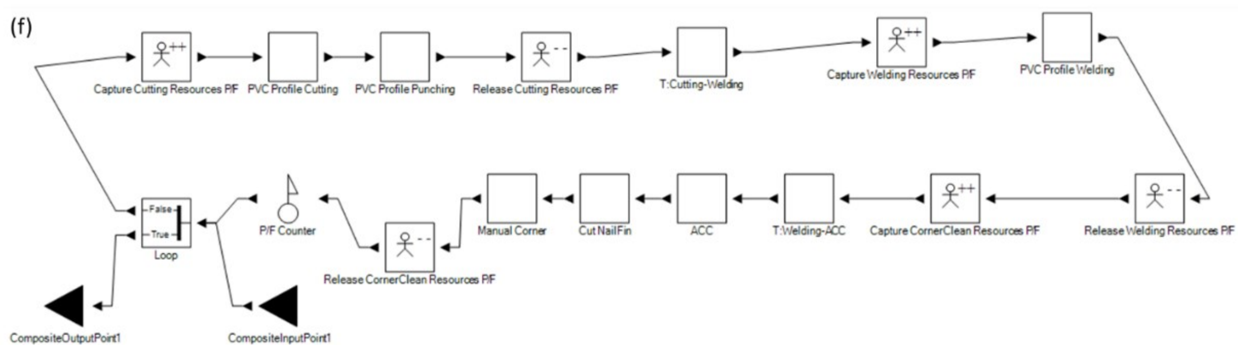
(d)



(e)



(f)


Capture Cutting Resources P/F
PVC Profile Cutting
PVC Profile Punching
Release Cutting Resources P/F
T:Cutting-Welding
Capture Welding Resources P/F
PVC Profile Welding
Release Welding Resources P/F
Capture CornerClean Resources P/F
T:Welding-ACC
ACC
Cut NailFin
Manual Corner
Release CornerClean Resources P/F
P/F Counter
False
True
Loop
CompositeOutputPoint1
CompositeInputPoint1

(g)

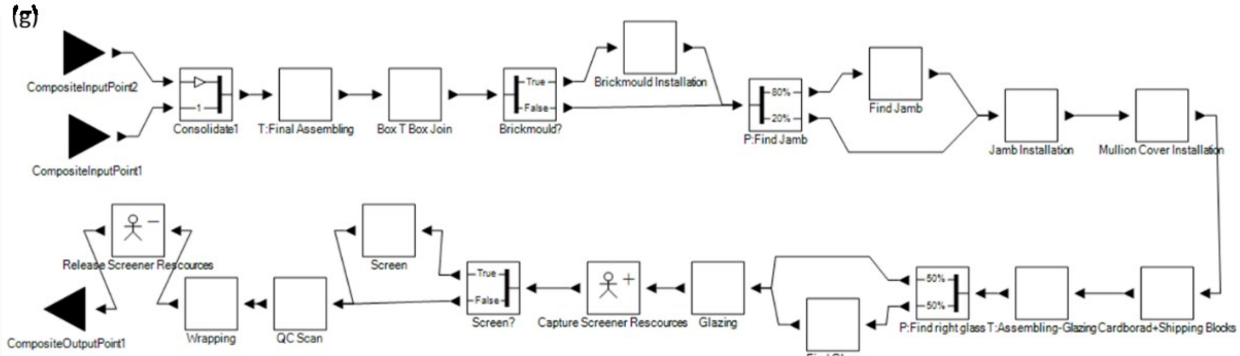

CompositeInputPoint2
CompositeInputPoint1
Consolidate1
T:Final Assembling
Box T Box Join
True
False
Brickmould?
Brickmould Installation
80%
20%
P:Find Jamb
Find Jamb
Jamb Installation
Mullion Cover Installation
Cardborad+Shipping Blocks
T:Assembling-Glazing
50%
50%
P:Find right glass
Find Glass
Glazing
Capture Screener Rescources
True
False
Screen?
Screen
QC Scan
Wrapping
Release Screener Rescources
CompositeOutputPoint1

Figure 4-1. Current state simulation model structure. (a) Overall 2100 production line; (b) Order generation from database; (c) Resources layout; (d) A/C line production process; (e) Hardware installation process on the A/C line; (f) P/F line production process; (g) Final assembly production process

Figure 4-1 (a) shows the overall 2100 series production line, splitting the production floor based on the window type and assembling the final product based on the order information generated by the scheduling department. As shown in Figure 4-1 (b), the production model is linked with a Microsoft Access database, 2100 Data, which creates the entities for the simulation model by reading the database tables. The attributes of each entity represent the information for each order and are defined as different parameters in the simulation model as listed in Table 4-1. The labour and machine resources on the current production line are shown in Figure 4-1 (c). The sequence of the tasks that occur in Figure 4-1 (d), (e), (f), and (g) is based on the real-world production process as illustrated by Figures 3-15 and 3-16. Based on the time study data, the duration of each task is fitted with distributions by Simphony or determined by the written code. When an entity passes through a task, the coding inside the element will be executed and control the duration. At the end of Figure 4-1 (a), the production rate can also be calculated by statistics elements and written code, which requires the use of the global attributes of the simulation model listed in Table 4-2.

Table 4-1. Entities' local attributes

Local attribute	Description
LX(1)	Height (mm)
LX(2)	Perimeter (mm)
LX(3)	Number of SU (sealing unit)
LX(4)	Is Jamb extension required in the order? (1=YES,0=NO)
LX(5)	Is Brickmould required in the order? (1=YES,0=NO)
LX(6)	Is Screen required in the order? (1=YES,0=NO)
LX(7)	Is Mullion cover required in the order? (1=YES,0=NO)
LN(1)	Number of Fixed windows
LN(2)	Number of Picture windows
LN(3)	Number of Casement windows
LN(4)	Number of Awning windows
LS(1)	Window type

Table 4-2. Simulation model global attributes

Global attribute	Description
GX(1)	Overall production time (simulation time)
GX(2)	Number of produced orders
GX(3)	Number of labours involved in the production
GX(4)	Calculation of production rate

4.1.3 Simulation model verification and validation

Simulation model verification is first conducted to eliminate all errors and bugs within the model to ensure the model runs and represents the real world correctly. At the early stage of model development, comments from experienced colleagues within the research group and the company are gathered and assist in ensuring the accuracy of the model structure and the behaviour of the model. The model is also validated by comparing the actual production data with the simulated results, which can be found in Table 4-3. The actual productivity rates are calculated based on six days of recorded finished product numbers, the shift schedule (16 hours/day), and the number of workers per shift. The simulation model was set up to produce the same number of orders as the historical data to obtain the simulated production time and production rate. The simulated production time is very close to the actual shift hours, with an absolute difference in the range of 3% to 7%. The production rate difference between simulated and the actual shows a similar result as the difference in production times, and is considered acceptable. Thus, the simulation model is reliable and accurate in imitating the actual production line, and can be used in further analysis.

Table 4-3. Simulation validation test results

Run No.	Number of workers	Number of orders completed	Production rate (orders completed / man-hour)		Production time (hours)		Difference in production rate	Difference in productio n time
			Actual	Simulation	Actual	Simulation		
1	18	168	0.583	0.563	16	16.58	-3.43%	3.62%
2	18	169	0.587	0.556	16	16.89	-5.28%	5.56%
3	18	170	0.590	0.56	16	16.86	-5.08%	5.38%
4	18	171	0.594	0.553	16	17.18	-6.90%	7.38%
5	18	166	0.576	0.576	16	16.00	0.00%	0.00%
6	18	160	0.556	0.574	16	15.48	3.24%	-3.25%

4.2 2100 line current state analysis

4.2.1 Value stream mapping

According to the operation study, the current state value stream map of the 2100 line is as shown in Figure 4-2. There is inventory before the profile and PVC cutting station and the hardware installation station, which are restocked on a weekly and daily basis. The daily production information flows from the production control and scheduling department. The current state number of workers and work schedule are also stated in the process and data box in the VSM, and are summarized in Table 3-4. However, due to the high degree of flexibility in window customization and the broad range of sizes available for the 2100 series, the cycle time of each window at each workstation differs from the other sizes. Thus, the cycle time of operations was not given in this figure. For instance, at the hardware installation station, the cycle time could range from 1,792 seconds for a 500 mm × 400 mm casement window to 3,356 seconds for an 800 mm × 1200 mm casement window. The cycle time at the final assembly station depends to a significant degree on the order information, such as the number of boxes in combination for one window (single unit or multiple units), and the requirements for jamb extension, brickmould, and mullion cover. For a single unit window order, the box may pass directly to the glazing station, which means the cycle time at the final assembly station is 0 seconds. Therefore, the task of calculating cycle time was completed later by the simulation model with embedded written code to distinguish each order information accordingly.

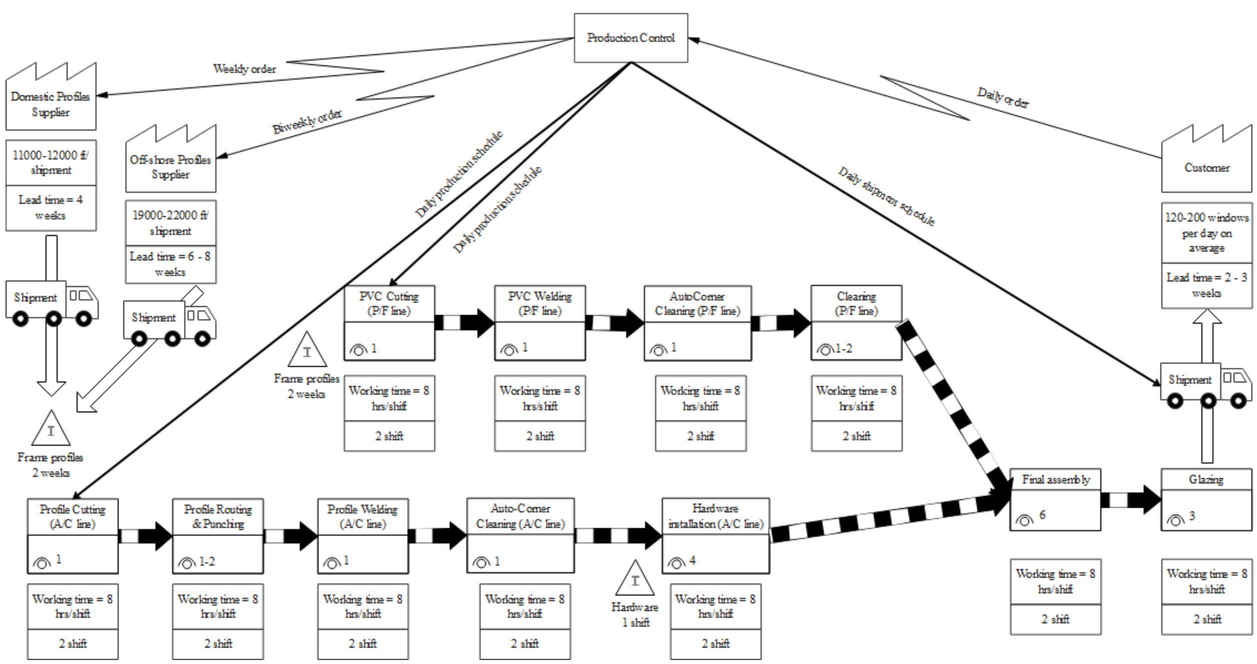


Figure 4-2. 2100 line current state value stream map

4.2.2 Bottleneck detection and wastes identification

After mapping the current state value stream, value-added activities are determined to be the only actions needed to complete the operations described in the section 3.1.2. Thus, the rest of the activities are considered as wastes/non-value added activities and listed in Table 4-4, which falls under the categories of waiting, transportation, inappropriate processing, unnecessary motions, and defects. By performing root cause analysis, the root cause of each waste is also summarized in Table 4-4. As shown in Figure 4-3, the statistics report, which includes average resource (labour and machine) utilization rates and waiting times for the resources, is available within Simphony. Based on the simulation model validation result, the simulation model produces almost identical results to actual production at the level of 166 orders produced per day. Thus, this production number is used to produce the production information report (Figure 4-3). By cross-comparing the utilization rate and the waiting time, it was found that the bottlenecks on the 2100 line are primarily located on the A/C line, specifically at the cutting station, welding station, and hardware installation station. This is also consistent with the manufacturing operation observation and the number of wastes identified at these workstations. A root cause analysis is conducted on each workstation problem. The fish diagrams are shown in Figure 4-4. The problem that occurs at the cutting station is that the utilization rate of both labour and machine is relatively low (about 45%), but the waiting time is quite significant. This may be caused by operational errors (resulting in rework), the low working capacity of the machine (which only holds two profiles at a time), or the labour requirement to restock and reload the materials from the pile onto the machine. However, the main cause observed from the manufacturing operation study is the operation on-hold due to the bottleneck downstream and the limited space on the conveyor belt to place the cut profiles. Most often the cutting operation needs to stop due to the long queue at the welding and auto-corner cleaning station. Thus, the bottleneck at the cutting station cannot be addressed until the bottleneck at other stations is resolved. At the welding station, it was found that both the utilization rate and the waiting time is very high; moreover, the operation time for welding is longer than the other tasks, which results in a long waiting queue and affects the cutting operation as well. It was noticed that the duration of the operations prior to the welding station are very short compared to the welding operation time, which creates a blockage in the production flow, meaning the materials flow into the station faster than it flows out. Thus, actions are required to slow down the material inflow, since the outflow path is impossible to change due to the fixed machine operating time, which initiates the idea of changing the working sequence around the welding station. As for the hardware assembly station, the utilization rate among the four workers is extremely unbalanced and the waiting time for frame-sash assembly cannot be ignored in comparison to the overall hardware installation time. This bottleneck can be predicted due to the uneven operation numbers between sash and frame, with ten operations required on frame and only six operations required on sash. Also, the frame hardware installation operations are more complicated and time-consuming than those required for sash hardware, which further worsens the bottleneck. The proposal to redesign the hardware installation sequence is considered as the best solution to resolve the bottleneck at both the welding and the hardware installation stations, and will be discussed in the next section.

Table 4-4. Issues and solutions

Workstation	Waste	Root cause	Solution
Cutting station	Profile waiting for punching and routing	Production bottleneck downstream, since the workers from both cutting and welding station share the tasks at the punching and routing station. The waiting ends only when workers are free from other stations.	Assigned a fixed worker at this station or solving the bottlenecks downstream to free the worker quickly.
	Profile rework due to wrong raw material or cutting for the wrong size	The machine requires manual input from workers, which increases the chance for errors	Create saw files to enable machine automation to eliminate manual input.
	Searching for raw materials	The restocking of inventories is inconsistent.	Create proper Kanban system and clear information flow system
Welding station	Profile waiting for welding	Uneven operation sequence design, with few short-duration tasks before welding and long duration tasks after welding.	Redesign operation sequence
	Unnecessary motions, such as repositioning profiles on the machine	No clear indication/drawing of profile orientation and position on the machine.	Use CAD software to automatically generate shop drawings of each window with a high level of details
Auto corner cleaning station	Profile waiting for auto corner cleaning	Production bottleneck downstream, since the workers from hardware installation station share the operations at this station. The waiting ends only when workers are free from other stations.	Redesign operation sequence or assign a fixed worker at this station

Hardware installation station	Profile waiting for hardware installation	Uneven operation sequence design. The hardware installation operations take a longer time compared to the tasks upstream.	Redesign operation sequence
	Rework due to inappropriate processing, e.g. installing wrong type of hardware	No clear instruction or drawing for each type and size of window on the production line. The operations are highly dependent on workers' experience.	Creating assembly drawings with the assistance of developed hardware assembly rule equations
	Unnecessary motions, such as travelling to different areas to pick up hardware	Lack of inventory tracking and Kanban system. The hardware inventory on the production line should be updated based on daily production information.	Create a proper Kanban system (tracking, visual aids)
Final assembly station	Profile waiting for final assembly	The operations at this workstation are very complex and time-consuming.	Redesign the SOPs at this workstation

Resources

Element Name	Average Utilization	Standard Deviation	Maximum Utilization	Current Utilization	Current Capacity
CornerCleanerP/F (Inner Resource)	99.4%	7.9%	100.0%	100.0%	1.000
CornerCleanMachineA/C (Inner Resource)	52.7%	49.9%	100.0%	100.0%	1.000
CornerCleanMachineP/F (Inner Resource)	99.4%	7.9%	100.0%	100.0%	1.000
CutterA/C (Inner Resource)	46.1%	49.8%	100.0%	0.0%	1.000
CutterP/F (Inner Resource)	71.7%	45.0%	100.0%	100.0%	1.000
CuttingMachineA/C (Inner Resource)	45.4%	49.8%	100.0%	0.0%	1.000
CuttingMachineP/F (Inner Resource)	71.7%	45.0%	100.0%	100.0%	1.000
FinalAssembler (Inner Resource)	56.9%	28.7%	100.0%	33.3%	6.000
Frame Hardware 2 (Inner Resource)	18.0%	38.4%	100.0%	0.0%	1.000
Frame Hardware 3 (Inner Resource)	21.0%	40.7%	100.0%	100.0%	1.000
FrameAssembler (Inner Resource)	84.6%	36.1%	100.0%	100.0%	1.000
Glazer (Inner Resource)	77.4%	39.9%	100.0%	100.0%	2.000
SashAssembler (Inner Resource)	74.2%	43.8%	100.0%	100.0%	1.000
Screener (Inner Resource)	41.4%	49.3%	100.0%	0.0%	1.000
WelderA/C (Inner Resource)	89.5%	30.7%	100.0%	0.0%	1.000
WelderP/F (Inner Resource)	31.8%	46.6%	100.0%	0.0%	1.000
WeldingMachineA/C (Inner Resource)	73.9%	43.9%	100.0%	0.0%	1.000
WeldingMachineP/F (Inner Resource)	31.8%	46.6%	100.0%	0.0%	1.000

Waiting Files

Element Name	Average Length	Standard Deviation	Maximum Length	Current Length	Average Wait Time
ConsolidateAwning (InnerFile)	0.034	0.186	2.000	0.000	94.387
ConsolidateCasement (InnerFile)	0.181	0.394	2.000	0.000	74.804
Consolidate1 (InnerFile)	0.000	0.000	1.000	0.000	0.000
HaltRun Controller (InnerFile)	1.000	0.000	1.000	0.000	57,903.776
CornerCleanMachineA/C Q	0.029	0.168	1.000	0.000	4.641
CornerCleanMachineP/F Q	20.944	11.930	43.000	2.000	6,919.634
CuttingA/C Q	38.189	54.046	173.000	0.000	11,952.821
CuttingP/F Q	39.436	43.283	129.000	0.000	12,828.601
FinalAssembler Q	0.572	2.578	16.000	0.000	28.401
FrameAssembler Q	6.506	10.581	35.000	20.000	1,066.192
FrameHardware Q	0.004	0.061	1.000	0.000	0.673
Glazer Q	2.005	3.933	17.000	0.000	458.838
SashAssembler Q	0.344	0.498	2.000	0.000	85.839
Screener Q	0.006	0.075	1.000	0.000	1.987
WeldingA/C Q	49.542	33.464	103.000	0.000	3,956.750
WeldingP/F Q	0.000	0.000	1.000	0.000	0.000

Figure 4-3. 2100 Line production information

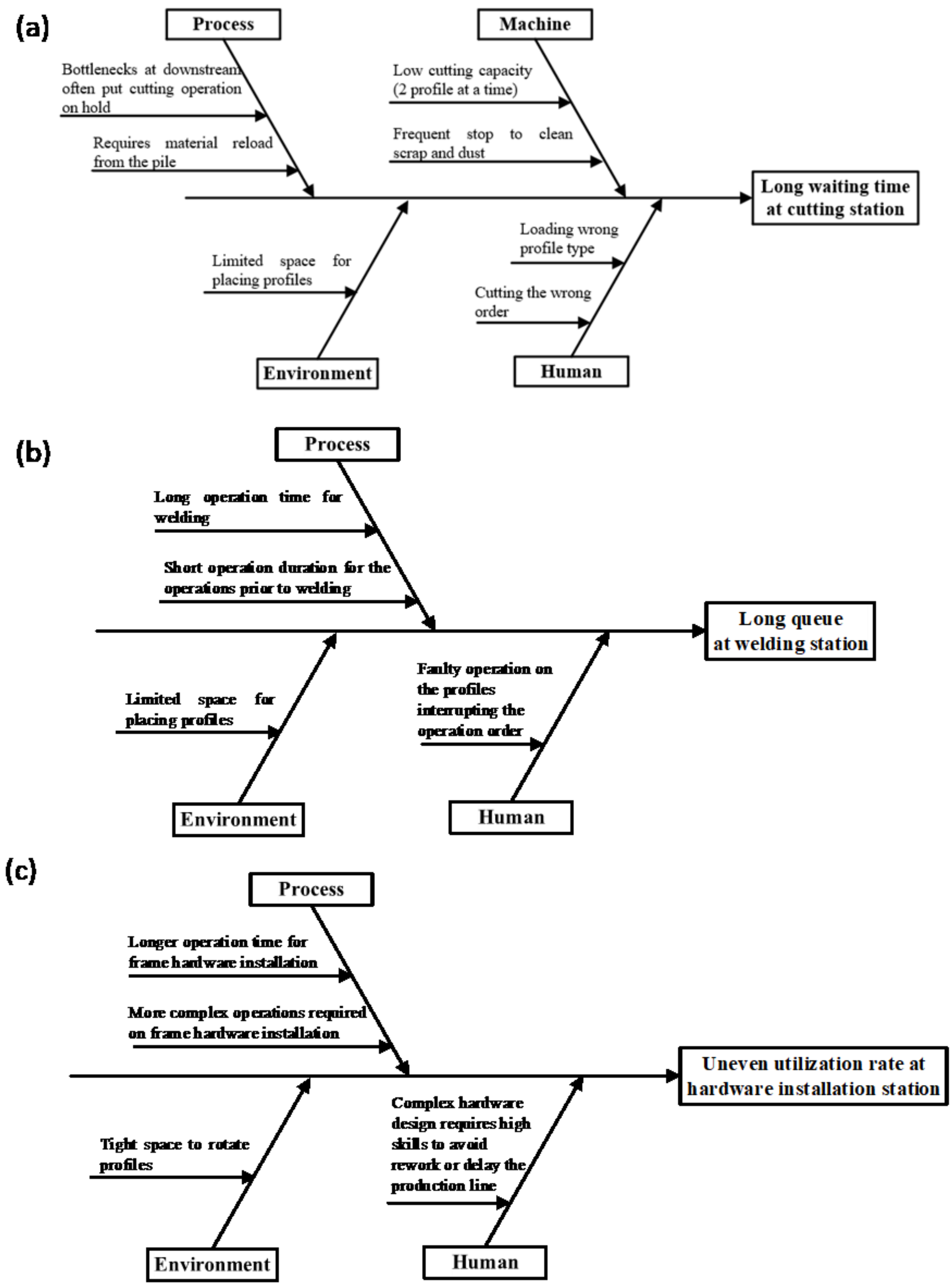


Figure 4-4. Fishbone diagrams. (a) cutting station; (b) welding station; (c) frame hardware installation station

4.2.3 Proposed operation sequence redesign

According to the bottleneck detection and the root causes analysis, the operation sequences at the profile welding, auto-corner cleaning, and frame-sash assembly workstations on the A/C line were targeted to resolve the bottleneck on the production line. To better utilize the waiting time at the profile welding station, a plan was formed, which involves reassigning much of the frame hardware and some of the sash hardware installation operations to be completed before the profile welding station. Based on the investigation of the welding and auto-corner cleaning machine specifications and on the window hardware assembly rule study, only a selection of hardware would be eligible for installation before welding the profiles (i.e., single cut profile pieces) in order to satisfy the requirement that there be a 150 mm of clearance from the welded profile corners for both machines. Eligible hardware includes casement ramp, snubber, tie bar and tie bar guide, and tie bar keeper for both awning and casement windows. The remaining hardware will be installed after the auto-corner cleaning operation at the original workstations and according to the original sequence. In the present research, the operation of installing hardware before welding will be referred to as "linear hardware installation operation". As outlined in Figure 4-5, a new workstation, named "Linear hardware installation workstation", will be added before the profile welding station so that a worker may perform linear hardware installation operation and the operation of inserting weather stripping. Physically, this floorplan can be achieved by relocating one of the three frame hardware installation worktables and one of the workers to the suggested space or by adding one additional worktable and worker to the newly designed workstation. Then, the product on the A/C line will flow from the profile cutting station to the profile routing and punching station, then to the linear hardware installation station, the next to the profile welding and auto-corner cleaning station and the remaining hardware installation station, and so on down the line until the glazing station. The new overall manufacturing sequence for the 2100 line is shown in Figure 4-6. The redesigned operation sequence includes the linear hardware installation operation, highlighted in the red box, the frame and sash profile welding operation, auto-corner cleaning operation, and the remaining hardware installation operation. As shown in Figure 4-7 (a), with an additional operation of casement ramp installation for casement window, the linear hardware installation sequence for both awning and casement windows starts with snubber installation, followed by tie bar and tie bar guide installation, and finishes with tie bar keeper installation. As for the remaining hardware installation operations, the required procedure is illustrated in Figure 4-7 (b).

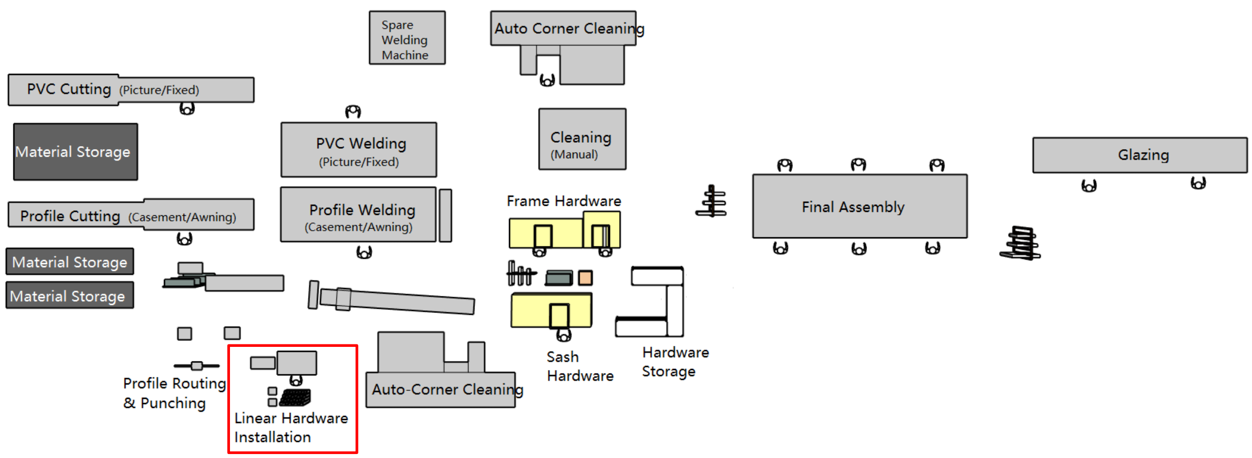


Figure 4-5. Redesigned production line workstations layout

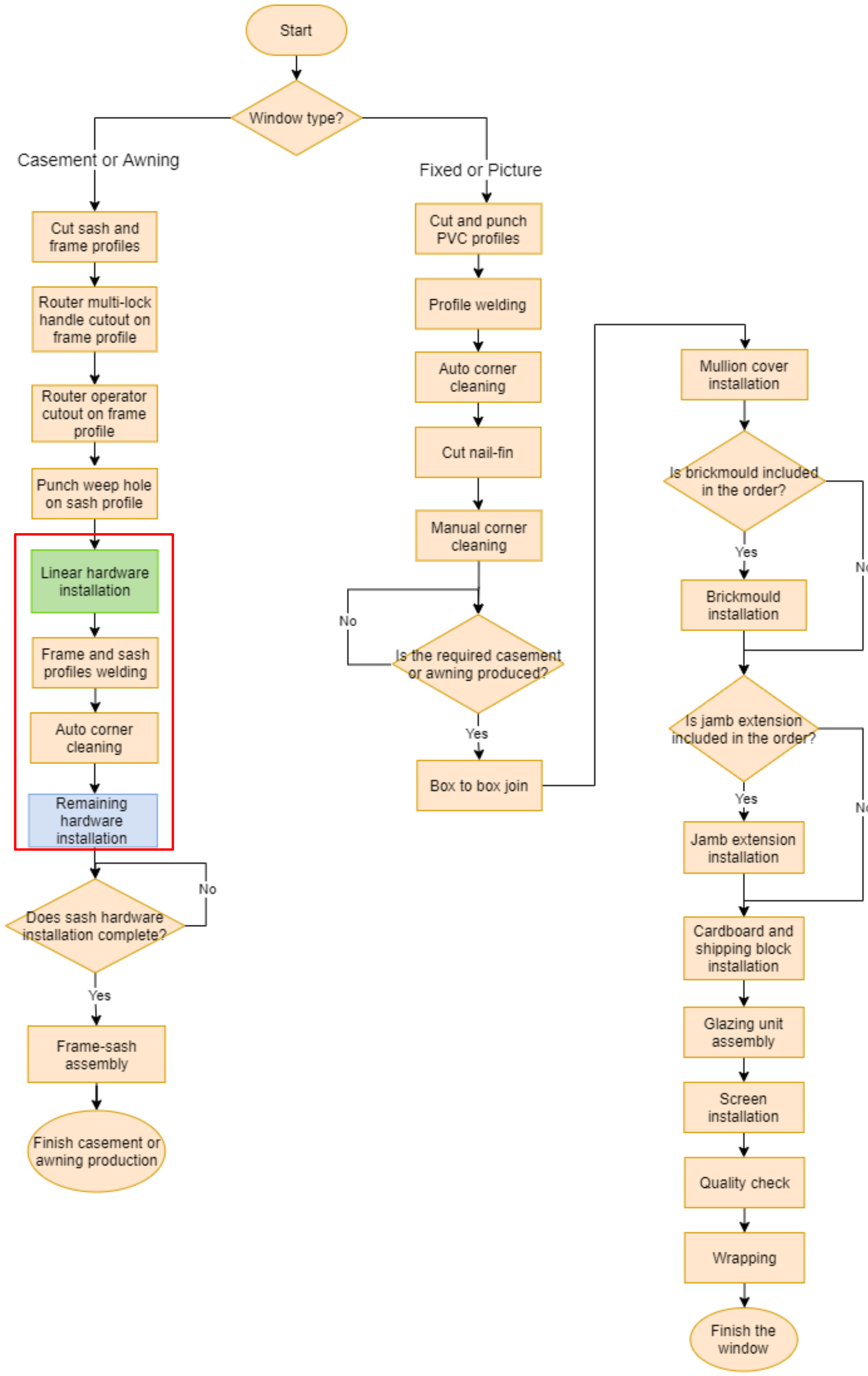


Figure 4-6. Redesigned 2100 line production sequence flow chart

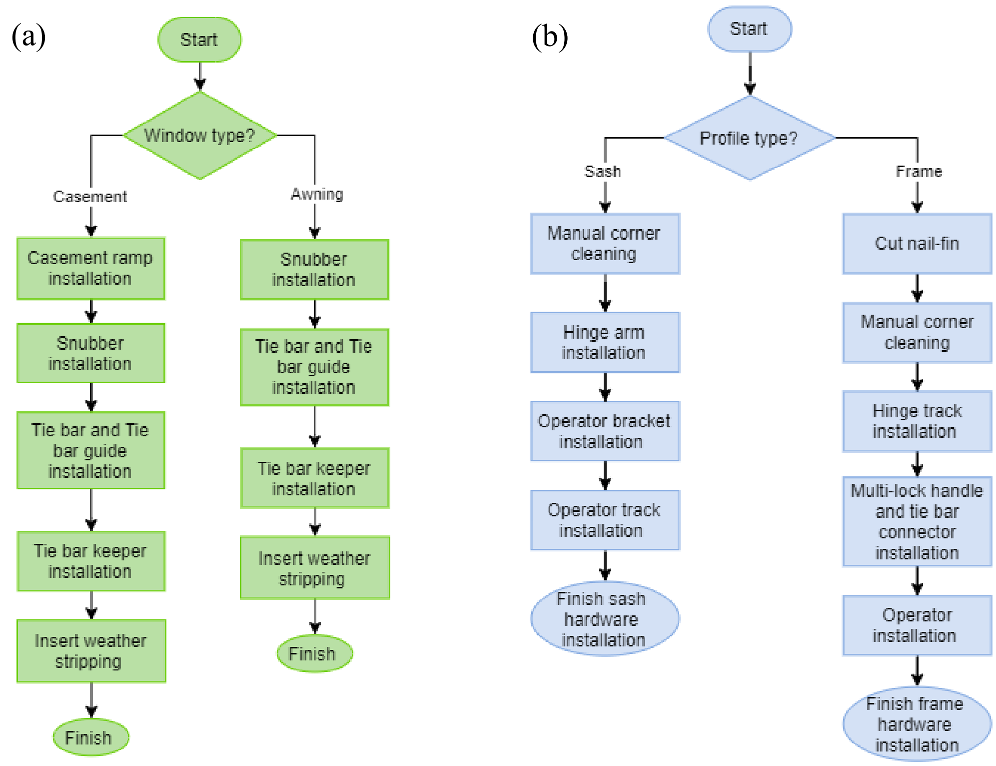
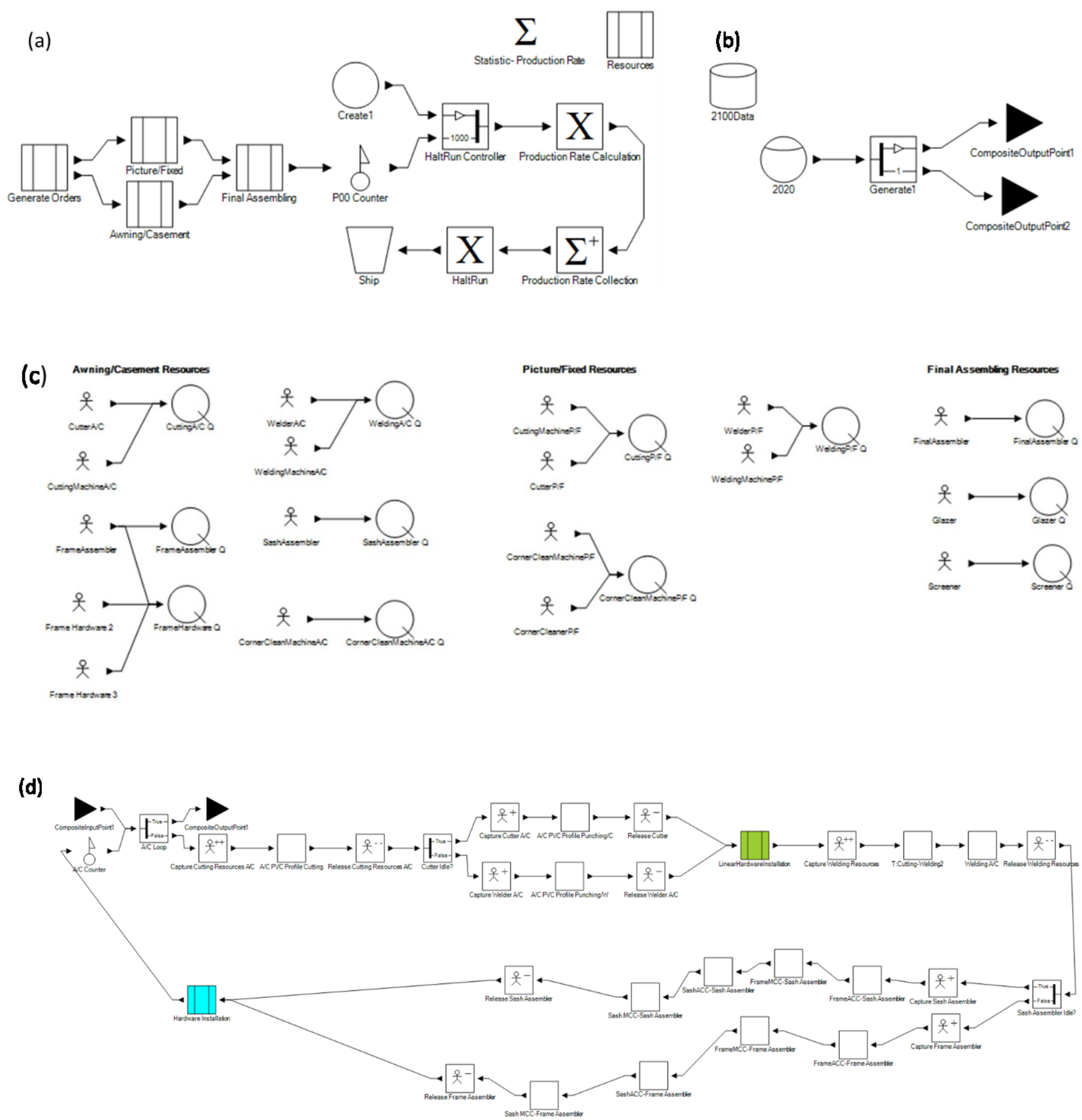


Figure 4-7. (a) Linear hardware installation workstation operation flow chart; (b) Remaining hardware installation operation flow chart

4.3 2100 line future state analysis

The current state simulation model is modified according to the proposed production sequence shown in Figures 4-6 and 4-7, with the new linear hardware installation operation added before the profile welding operation on the A/C line. This new addition results in a structure change of the simulation model, changing the simulation layers from seven to eight. Figure 4-8 shows the structure of the redesigned simulation model, in which Figure 4-8 (a), (b), (c), (g) and (h) remain the same as in the current state analysis and illustrate the process of the overall production line, order generation, resources layout, P/F production line, and the final assembly, respectively. As shown in Figure 4-8 (d), the redesigned A/C line production sequence contains the modified hardware installation operation and the linear hardware installation operation, which are highlighted by different colours and each is shown in more detail in Figure 4-8 (f) and (e). Since the only change to the model is the A/C line operation sequence, the local and global attributes remain unchanged as listed in Table 4-1 and 4-2.



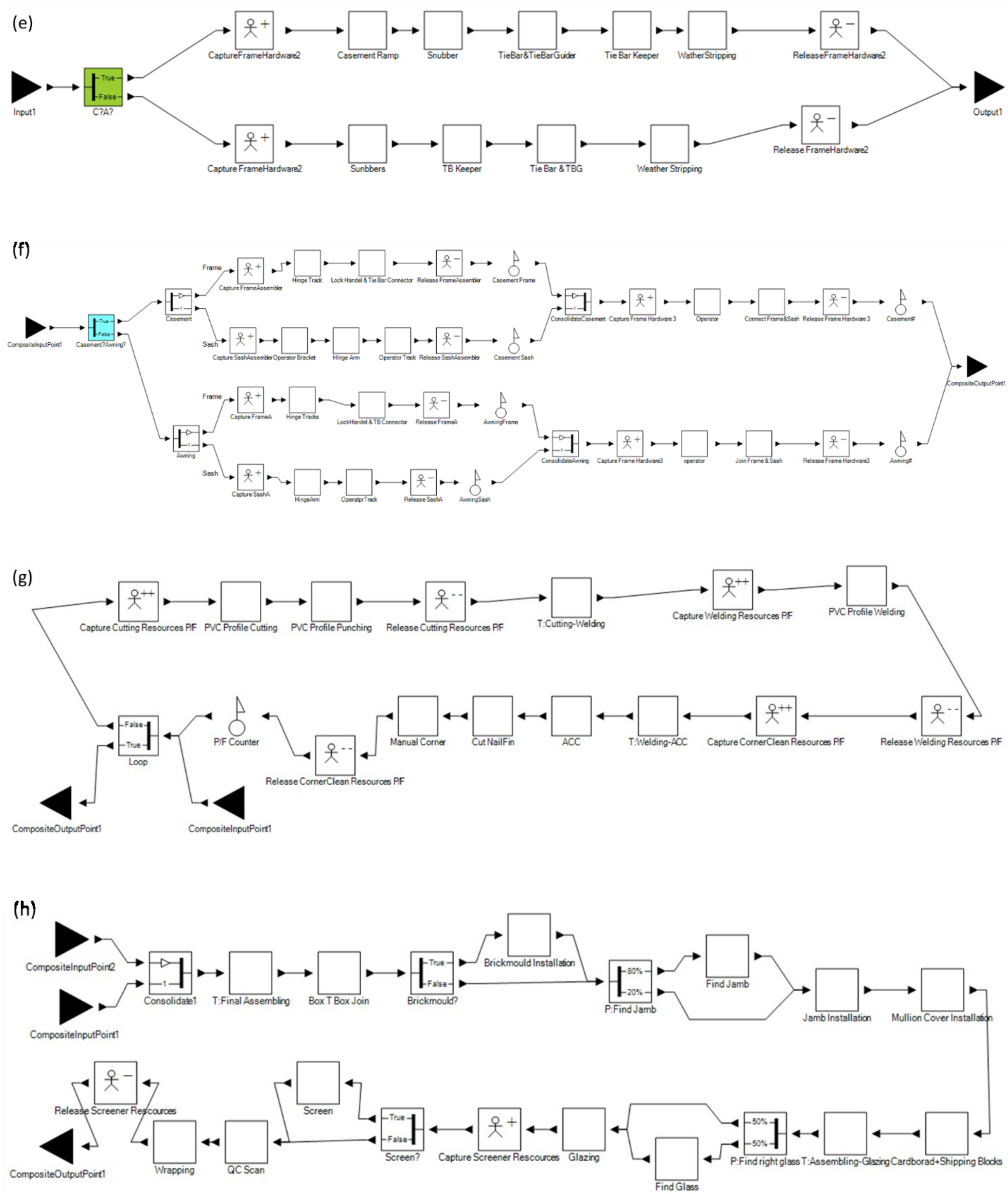


Figure 4-8. Future state simulation model structure. (a) Overall 2100 production line; (b) Order generation from database; (c) Resources layout; (d) Redesigned A/C line production process; (e)

Linear hardware installation process on the A/C line; (f) Remaining hardware installation process on the A/C line; (g) P/F line production process; (h) Final assembly production process

The future state simulation is divided into three scenarios. The first scenario is the base case scenario with the same resource layout as the current production and the same model structure as shown in Figure 4-8. The second case proposes to assign one additional worker to the linear hardware installation workstation on top of the first scenario. The third scenario involves separating the tasks for the casement windows and awning windows to the specific assigned worktable and worker by expanding the linear hardware station into two worktables with additional labour compared to the first scenario.

In order to examine the impact of the redesigned production line process, the future state simulation results will be compared to the current state simulation results, in terms of production rate and production time. Four simulation runs are simulated, and each run, 1 through 4, corresponds to a day of production that is simulated in both model environments with the number of orders set to 160, 166, 171, and 179 per day, respectively. The results of the four runs on the entire 2100 line are shown in Table 4-5 for the first scenario. On average, a 22% increase in production rate and an approximately 18% production time decrease can be observed, due to the redesign of the operation sequence. As is shown in Table 4-6, by adding one extra worker at the linear hardware installation workstation (second scenario), the production rate can be increased by 16% with an approximately 18% decrease in production time. The third scenario shows a similar trend as the other two, resulting in an approximately 22% increase in productivity and 18% decrease in production time, as shown in Table 4-7. Since the second and third scenarios are developed based on the first scenario, the first scenario is set as the reference point for comparison purposes when computing the results shown in Table 4-8. The additional labour resources employed in the second and third scenarios do not result in much improvement in terms of both production rate and production time. On average, employing one additional worker (second scenario) has a negative effect on productivity (drop of 5%) and production time (increase of 0.37%). The impact of the third scenario is almost negligible, with a 0.11% increase and a 0.09% decrease in productivity and production time, respectively. Therefore, the first scenario is considered as the optimal solution, due to less investment requirement and relatively best performance.

Table 4-5. Current state and first scenario simulation results comparison

Run No.	**Labour number**	**Order completed**	**Production rate (order completed / man-hour)**		**Production time (hours)**		**Difference in production rate**	**Difference in production time**
			Current state	First scenario	Current state	First scenario		
1	18	160	0.574	0.709	15.48	12.54	23.52%	-18.99%
2	18	166	0.576	0.696	16.00	13.26	20.83%	-17.13%
3	18	170	0.56	0.701	16.86	13.47	25.18%	-20.11%
4	18	179	0.565	0.674	17.61	14.74	19.29%	-16.30%
Average							22.21%	-18.13%

Table 4-6. Current state and second scenario simulation results comparison

Run No.	**Labour number**		**Order completed**	**Production rate (order completed / man-hour)**		**Production time (hours)**		**Difference in production rate**	**Difference in production time**
	Current state	Second scenario		Current state	Second scenario	Current state	Second scenario		
1	18	19	160	0.574	0.67	15.48	12.58	16.72%	-18.73%
2			166	0.576	0.667	16.00	13.26	15.80%	-17.13%
3			170	0.56	0.653	16.86	13.70	16.61%	-18.74%
4			179	0.565	0.642	17.61	14.66	13.63%	-16.75%
Average								15.69%	-17.84%

Table 4-7. Current state and third scenario simulation results comparison

Run No.	**Labour number**		**Order completed**	**Production rate (order completed / man-hour)**		**Production time (hours)**		**Difference in production rate**	**Difference in production time**
	Current state	Third scenario		Current state	Third scenario	Current state	Third scenario		
1	18	19	160	0.574	0.715	15.48	12.47	24.56%	-19.44%
2			166	0.576	0.691	16.00	13.34	19.97%	-16.63%

3			170	0.56	0.70	16.86	13.47	25.00%	-20.11%
4			179	0.565	0.677	17.61	14.68	19.82%	-16.64%
Average								22.34%	-18.20%

Table 4-8. Results comparison of three scenarios

Run No.	Difference in production rate (compared to first case)		Difference in production time (compared to first case)	
	Second scenario	Third scenario	Second scenario	Third scenario
1	-5.50%	0.85%	0.32%	-0.56%
2	-4.17%	-0.72%	0.00%	0.60%
3	-6.85%	-0.14%	1.71%	0.00%
4	-4.75%	0.45%	-0.54%	-0.41%
Average	-5.32%	0.11%	0.37%	-0.09%

To determine whether the bottleneck has been resolved or not, the statistics for run 2 are investigated to determine the specific changes in the resource utilization rate, the waiting times, and the waiting queue. A downward trend in the waiting time and the waiting queue of the frame hardware installation and welding stations can be observed, resulting in a 34% and 21% reduction in waiting time, respectively, which is consistent with the trend in the overall production time reduction. Furthermore, the average utilization rates among sash assembly worker, frame assembly worker, and frame hardware installation workers are more balanced than the current state, with an increase of 49.1% and 8.4% for the frame hardware installation worker 2 and 3, respectively.

By comparing the individual statistics, the impact of the redesigned production sequence on productivity improvement and production cycle time reduction can be further quantified. With the support of the simulation results, the implementation of the redesigned production line can be discussed at the management level. However, the full implementation can be costly, and may require the purchasing of new equipment, relocating or adding resources, and the time and effort to physically change the production floor setting. A two-week production trial on the redesigned production process was suggested and agreed upon by the researchers and the company. Regarding the floor plan for the production line during the trial phase, a proposed layout was designed, as shown in Figure 4-5, in which the worktable selection for the new workstation is not limited to a single type and can utilize an existing table on the production floor. To keep the cost and the changes to a minimum for the trial, one of the frame hardware installation workers can be reassigned to the new workstation. A time study will be conducted during the experiment to collect more data and increase the accuracy of the simulation model for future improvement. The updated simulation results can then be compared to the historical data for the time period of the production trial to support the final decision on the redesigned production process's full implementation. Furthermore, by improving the hardware design, the selection of hardware that is eligible to be installed before welding can be further expanded, which could relocate more tasks to before the welding operation and may completely merge the frame and sash hardware installation into one workstation and reduce the amount of floor space required.

5 CONCLUSION

5.1 Summary

This research presents a framework to improve manufacturing productivity and validate the impact of process changes by implementing production simulation with the aid of lean manufacturing concepts for manufacturers. Wastes and bottlenecks that exist on the current production line are identified by conducting a simulation-based analysis, which also facilitates the proposal of corresponding solutions. Even though the benefits of adopting LM philosophy have been proven through their application by numerous manufacturers around the world, there are still many companies that hesitate to fully commit to run their businesses in the lean way due to the risks of production interruption or investment failure. To increase the level of confidence among management personnel with respect to adopting LM philosophy for their companies, production simulation is one of the most efficient methods of quantitatively visualizing the potential impacts of the proposed changes prior to carrying out the changes.

During the solution initiation and execution phase, companies are often very conservative in their approach to the issues and changes, often only committing to small changes or being satisfied with temporarily solving issues at a particular workstation on a production line. However, in the complex manufacturing world, the causes of each of the issues are most likely related to each other or caused by the others. Thus, while considering improving the productivity or addressing the production bottlenecks, one should start by studying the whole production line and digging deep into the fundamentals of why the production line is designed to function in the current way. By redesigning the production line operations, the bottlenecks and wastes at multiple stations could be eased together in tandem. Moreover, having the support from simulation results, the risks of altering the production line can be limited to a minimal level.

In this research, a possible practical production sequence design is presented with three hypothetical scenarios each with a different resource layout, which balances the workload at each workstation. The optimal scenario is selected and visualized by simulation models for the targeted issues with the high productivity, less waiting time, and shorter waiting times for the resources (labour and equipment), forecasting an average increase of 22% in overall productivity. The implementation process is also recommended, including the solution proposal, experimental trial on the production line, experimental results analysis, and final implementation.

5.2 Research contributions

This research describes a framework to integrate lean tools with simulation analysis to support windows manufacturers to eliminate process wastes and improve the manufacturing process. The proposed framework can be generalized to other similar manufacturing setting. More specific contributions include the following:

- This research proved that segregating the hardware installation operations at post welding and post corner cleaning stage on a welded square window into linear production, has the potential of productivity improvement, reduce the footprint in the factory space and decrease in the amount of interaction between workers.
- This research demonstrated the effective utilization of the lean concept into window manufacturing utilizing value stream map as a communication tool to asses the current practice and the proposed future state.
- This research also verified the current practice and the effect of the process changes using simulation models. A minimum 20% overall production efficiency gain was observed,

based only in the reduction of the non-value added activity (rotating and flipping the welded square window profiles). However, with the consideration of the working efficiency increase by using the linear process, the overall productivity is expected to have higher productivity improvement.

The utilization of the mathematical models proved to be an effective tool to communicate the effective of the proposed changes and the acceptance of those changes by the stakeholders. The mathematical models also promoted the use of robotics and increase the level of process automation in the current practice.

5.3 Limitations

This research is subjected to the following limitations:

- Due to time constraints, the simulation model is validated by comparing only six days of productivity and production time. The result could be more accurate if the validation process is based on a larger number of production days and within a longer production period.
- Product rework can interrupt the normal production flow. According to the operation study, it occurs at a very low frequency. Thus, it was ignored during production simulation modelling. If the rework information can be added to the simulation, the model will be more realistic and deliver more precise information.
- The production order sequence could influence productivity. In the simulation model, production is executed at a fixed order sequence as defined in the database. However, on the production floor, based on worker's experience, sometimes they may not necessarily produce the windows following the strict sequence.

- In the simulation model, labour layout is determined and assigned to corresponding tasks; however, depending on the production workload on each day, the line supervisor may decide to call in another one or two workers, which is a decision based on experience. Thus, it is not reflected in the simulation model.

5.4 Recommendations for future work

In order to improve the performance of the proposed framework, the following recommendations for future work are proposed:

- With respect to the limitation from order sequencing, an algorithm can be developed to use the simulation model to determine the optimal production order sequence, to avoid production process slack or halt.
- A framework can be developed to conduct the feasibility and cost-benefit analysis for each manufacturing improvement decision. And the process may also be possibly automated using computer software and programming language.
- The hardware redesign option can be another direction for future work since less than half of the hardware can be installed before welding. With the redesigned hardware, the effect on overall productivity can be reassessed and new implementation recommendations can be made accordingly.
- Since the trend of Industry 4.0 is a dominant force in today's manufacturing industry, an application that uses the mathematical models of the window assembly rule to generate detailed shop drawings or any digital information can be explored.

REFERENCES

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. https://doi.org/10.1016/j.ijpe.2006.09.009

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.

AbouRizk, S., & Mohamed, Y. (2000). Simphony-an integrated environment for construction simulation. *Proceedings of the 2000 Winter Simulation Conference*, 1971–1977.

Andersen, B., & Fagerhaug, T. (2006). *Root cause analysis : simplified tools and techniques*. 2nd ed. Milwaukee, Wis.: ASQ Quality Press.Atieh, A. M., Kaylani, H., Almuhtady, A., & Al-Tamimi, O. (2016). A value stream mapping and simulation hybrid approach: Application to glass industry. *International Journal of Advanced Manufacturing Technology*, *84*(5–8), 1573–1586. https://doi.org/10.1007/s00170-015-7805-8

Bako, B., & Božek, P. (2016). Trends in simulation and planning of manufacturing companies. *Procedia Engineering*, *149*(June), 571–575. https://doi.org/10.1016/j.proeng.2016.06.707

Belekoukias, I., Garza-Reyes, J. A., & Kumar, V. (2014). The impact of lean methods and tools on the operational performance of manufacturing organisations. *International Journal of Production Research*, *52*(18), 5346–5366. https://doi.org/10.1080/00207543.2014.903348

Bhamu, J., & Sangwan, K. S. (2014). Lean manufacturing: Literature review and research issues. *International Journal of Operations and Production Management*, *34*(7), 876–940. https://doi.org/10.1108/IJOPM-08-2012-0315

Bhasin, S., & Burcher, P. (2006). Lean viewed as a philosophy. *Journal of Manufacturing*

Technology Management, *17*(1), 56–72. https://doi.org/10.1108/17410380610639506

Braglia, M., Carmignani, G., & Zammori, F. (2006). A new value stream mapping approach for complex production systems. *International Journal of Production Research*, *44*(18–19), 3929–3952. https://doi.org/10.1080/00207540600690545

Britannica, Encyclopedia (2014). *System | physics | Britannica*. . https://www.britannica.com/science/system-physics

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. https://doi.org/10.1108/IJPPM-09-2016-0197

Chandra, P. V. (2007). An Effort To Apply Work and Time Study Techniques in a Manufacturing Unit for Enhancing Productivity. *International Journal of Innovative Research in Science, Engineering and Technology, 2,* 4050-4058.

Chen, J. C., Li, Y., & Shady, B. D. (2010). From value stream mapping toward a lean/sigma continuous improvement process: an industrial case study. *International Journal of Production Research*, *48*(4), 1069–1086. https://doi.org/10.1080/00207540802484911

Chung, C. A. (2004). *Simulation modeling handbook: A practical approach*. Boca Raton, Fla.: 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. https://doi.org/10.1080/002075400189509

Diaz-Elsayed, N., Jondral, A., Greinacher, S., Dornfeld, D., & Lanza, G. (2013). Assessment of lean and green strategies by simulation of manufacturing systems in discrete production environments. *CIRP Annals - Manufacturing Technology*, *62*(1), 475–478.

https://doi.org/10.1016/j.cirp.2013.03.066

Esfandyari, A., Osman, M. R., Ismail, N., & Tahriri, F. (2011). Application of value stream mapping using simulation to decrease production lead time: A Malaysian manufacturing case. *International Journal of Industrial and Systems Engineering*, *8*(2), 230–250. https://doi.org/10.1504/IJISE.2011.041371

Goienetxea Uriarte, A., Ng, A. H. C., & Urenda Moris, M. (2020). Bringing together Lean and simulation: a comprehensive review. *International Journal of Production Research*, *58*(1), 87–117. https://doi.org/10.1080/00207543.2019.1643512

Government of Canada (2020). *Manufacturing sector gateway*. https://www.ic.gc.ca/eic/site/mfg-fab.nsf/eng/home

Guner Goren, H. (2017). Value stream mapping and simulation for lean manufacturing: A case study in furniture industry. *Pamukkale University Journal of Engineering Sciences*, *23*(4), 462–469. https://doi.org/10.5505/pajes.2016.59251

Gupta, S., & Jain, S. K. (2013). A literature review of lean manufacturing. *International Journal of Management Science and Engineering Management*, *8*(4), 241–249. https://doi.org/10.1080/17509653.2013.825074

Halpin, D. W. (1973). An investigation of the use of simulation network for modeling construction operations. [Doctoral dissertation, University of Illinois, Urbana-Champaign]. http://search.proquest.com/docview/302647102?accountid=13552

Hines, P., Holweg, M. and Rich, N. (2004), "Learning to evolve: A review of contemporary lean thinking", *International Journal of Operations & Production Management*, Vol. 24 No. 10, pp. 994-1011. https://doi.org/10.1108/01443570410558049

Holweg, M. (2007). The genealogy of lean production. *Journal of Operations Management*, *25*(2), 420–437. https://doi.org/10.1016/j.jom.2006.04.001

Jarkko, E., Lu, W., Lars, S., & Thomas, O. (2013). Discrete event simulation enhanced value stream mapping: An industrialized construction case study. *Lean Construction Journal*, *2013*(November 2014), 47–65.

Jasti, N. V. K., & Sharma, A. (2015). Lean manufacturing implementation using value stream mapping as a tool a case study from auto components industry. *International Journal of Lean Six Sigma*, *5*(1), 89–116. https://doi.org/10.1108/IJLSS-04-2012-0002

Kulkarni, P. P., Kshire, S. S., & Chandratre, K. V. (2014). Productivity improvement through lean deployment & work study methods. *International Journal of Research in Engineering and Technology*, *03*(02), 429–434. https://doi.org/10.15623/ijret.2014.0302076

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. https://doi.org/10.1080/00207540600791590

Marvel, J. H., & Standridge, C. R. (2009). A simulation-enhanced lean design process. *Journal of Industrial Engineering and Management*, *2*(1), 90–113. https://doi.org/10.3926/jiem.2009.v2n1.p90-113

McLaughlin, P., & Durazo-Cardenas, I. (2013). Cellular manufacturing applications in MRO operations. *Procedia CIRP*, *11*(May), 254–259. https://doi.org/10.1016/j.procir.2013.07.077

Melton, T. (2005). The benefits of lean manufacturing: What lean thinking has to offer the process industries. *Chemical Engineering Research and Design*, *83*(6 A), 662–673. https://doi.org/10.1205/cherd.04351

Mourtzis, D., Doukas, M., & Bernidaki, D. (2014). Simulation in manufacturing: Review and challenges. *Procedia CIRP*, *25*(C), 213–229. https://doi.org/10.1016/j.procir.2014.10.032

Moyano-Fuentes, J., & Sacristán-Díaz, M. (2012). Learning on lean: A review of thinking and research. *International Journal of Operations and Production Management*, *32*(5), 551–582. https://doi.org/10.1108/01443571211226498

Nash, M. A., & Poling, S. R. (2008). *Mapping the total value stream : a comprehensive guide for production and transactional processes*. Boca Raton: CRC Press.

Omogbai, O., & Salonitis, K. (2016). Manufacturing system lean improvement design using discrete event simulation. *Procedia CIRP*, *57*, 195–200. https://doi.org/10.1016/j.procir.2016.11.034

Paniquar De Souto, A. (2020). *Simulation-based approach to improving Overall Equipment Effectiveness analysis in construction manufacturing*. [Master's thesis, University of Alberta]. https://doi.org/10.7939/r3-zte9-xj59

Pettersen, J. (2009). Defining lean production: Some conceptual and practical issues. *TQM Journal*, *21*(2), 127–142. https://doi.org/10.1108/17542730910938137

Rohani, J. M., & Zahraee, S. M. (2015). Production line analysis via value stream mapping: A lean manufacturing process of color industry. *Procedia Manufacturing*, *2*(February), 6–10. https://doi.org/10.1016/j.promfg.2015.07.002

Rose, A. N. M., Deros, B. M., & Rahman, M. N. A. (2009). A review on lean manufacturing practices in small and medium enterprises. *AMReG*, *29 Juy*, 1–15.

Rother, M., & Shook, J. (2003). Learning to see value stream mapping to create value and eliminate muda. *Lean Enterprise Institute Brookline*, 102. https://doi.org/10.1109/6.490058

Sabaghi, M., Rostamzadeh, R., & Mascle, C. (2015). Kanban and value stream mapping analysis in lean manufacturing philosophy via simulation: A plastic fabrication (case study). *International Journal of Services and Operations Management*, *20*(1), 118–140.

https://doi.org/10.1504/IJSOM.2015.065977

Sargent, R. G. (2013). Verification and validation of simulation models. *Journal of Simulation*, *7*(1), 12–24. https://doi.org/10.1057/jos.2012.20

Sundar, R., Balaji, A. N., & Satheesh Kumar, R. M. (2014). A review on lean manufacturing implementation techniques. *Procedia Engineering*, *97*, 1875–1885. https://doi.org/10.1016/j.proeng.2014.12.341

Tyagi, S., Choudhary, A., Cai, X., & Yang, K. (2015). Value stream mapping to reduce the lead-time of a product development process. *International Journal of Production Economics*, *160*, 202–212. https://doi.org/10.1016/j.ijpe.2014.11.002

Venkataraman, K., Ramnath, B. V., Kumar, V. M., & Elanchezhian, C. (2014). Application of value stream mapping for reduction of cycle time in a machining process. *Procedia Materials Science*, *6*(Icmpc), 1187–1196. https://doi.org/10.1016/j.mspro.2014.07.192

Wang, Y. (2019). *Integrated lean and simulation for productivity improvement for windows manufacturing*. [Master's thesis, University of Alberta]. https://doi.org/10.7939/r3-gqak-cd28

Wanitwattanakosol, J., & Sopadang, A. (2012). A framework for implementing lean manufacturing system in small and medium enterprises. *Applied Mechanics and Materials*, *110–116*, 3997–4003. https://doi.org/10.4028/www.scientific.net/AMM.110-116.3997

Womack, J. P. (1991). The Machine that changed the world: based on the Massachusetts Institute of Technology 5-million-dollar 5-year study on the future of the automobile. In *Choice Reviews Online* (Vol. 28, Issue 08). Rawson Associates,. https://doi.org/10.5860/choice.28-4589

Xia, W., & Sun, J. (2013). Simulation guided value stream mapping and lean improvement: A case study of a tubular machining facility. *Journal of Industrial Engineering and Management*, *6*(2), 456–476. https://doi.org/10.3926/jiem.532

APPENDIX A: TIME STUDY DATA EXAMPLE

Table A-1. Time study data example on A/C line

Operations	Unit	Time 1	Time 2	Time 3
Cut sash and frame profiles	sec	51.88	48.15	52.98
Router multi-lock handle cutout	sec	23	25.2	25.5
Router operator cutout	sec	27.5	28.84	29.87
Punch weep hole	sec	15.69	16	17.75
Insert weather stripping	sec	25	33	26.48
Frame and sash profiles welding	sec	130	131	137
Auto corner cleaning	sec	68	80	77
Cut nail-fin	sec	25	20	22
Manual corner cleaning on frame	sec	41.81	46.53	42.46
Hinge track installation	sec	22.5	24.5	27
Casement ramp installation	sec	5.3	6.2	7.1
Snubber installation	sec	32	27	30
Multi-lock handle and tie bar connector installation	sec	17	16	19
Tie bar and Tie bar guide installation	sec	19.5	17.5	19
Operator installation	sec	51	60	58
Manual corner cleaning on sash	sec	39	41	40
Tie bar keeper installation	sec	50	45	55
Hinge arm installation	sec	45	52	54
Operator bracket installation	sec	37	39	46
Operator track installation	sec	18	19	22
Frame-sash assembly	sec	38	45	35

Table A-2. Time study data example on P/F line

Operations	Unit	Time 1	Time 2	Time 3
Cut and punch PVC profiles	sec	112	94	104
PVC profiles punching	sec	16	17	14
Profile welding	sec	123	117	108
Auto corner cleaning	sec	93	86	76
Cut nail-fin	sec	39	58	56
Manual corner cleaning	sec	42	47	45

Table A-3. Time study data example on joining line

Operations	Unit	Time 1	Time 2	Time 3
Box to box join	sec	94	78	89
Mullion cover installation	sec	76	51	28
Brickmould installation	sec	167	216	180
Jamb extension installation	sec	327	318	422
Cardboard and shipping block installation	sec	68	82	55
Glazing unit assembly	sec	1065	705	919
Screen installation	sec	30	35	33
Quality check:	sec	20	28	32
Wrapping	sec	105	105	239

APPENDIX B: ORDER INFORMATION DATABASE EXAMPLE

ID	Traveller Number	Screen	Operation Venting	Fixed	Picture	Casement	Awning	Mullion	Short Description	Height	Width	Perimeter	Startseq	SU	JE	BM	Sash	Cut Nail Fin
1	157	0	A	0	0	0	1	0	2100 Awning SINGLE A 35 7/16X35 7/16 NoBM PVC \	900	900	3600	1	1	1	0	1	0
2	173	0	L	0	0	1	0	0	2100 Casement SINGLE L 31 1/2x47 1/4 NoBM PVC \	1200	800	4000	5	1	11	0	1	0
3	171	0	R	0	0	1	0	0	2100 Casement SINGLE R 29 9/16X47 1/4 NoBM PV(	1200	750	3900	6	1	1	0	1	0
4	172	0	L	0	0	1	0	0	2100 Casement SINGLE L 31 1/2x47 1/4 NoBM PVC \	1200	800	4000	7	1	1	0	1	0
5	175	1	F-A	1	0	0	1	1	2100 1Wx2H F-A 20 3/4X56 3/4 NoBM NoJamb	1441	527	3936	8	2	0	0	1	1
6	174	1	F-A	1	0	0	1	1	2100 1Wx2H F-A 22 1/2X33 1/8 NoBM NoJamb	841	572	2826	9	2	0	0	1	1
7	180	0	L-P	0	1	1	0	1	2100 2W L-P 47 1/2X59 1/16 NoBM PVC Whit	1500	1205	5410	11	2	1	0	1	1
8	191	0	L	0	0	1	0	0	2100 Casement SINGLE L 23 5/8X59 1/16 NoBM PVC	1500	600	4200	13	1	1	0	1	0
9	186	0	A	0	0	0	1	0	2100 Awning SINGLE A 39 3/8x39 3/8 NoBM PVC Wh	1000	1000	4000	14	1	1	0	1	0
10	182	0	L	0	0	1	0	0	2100 Casement SINGLE L 23 5/8X59 1/16 NoBM PVC	1500	600	4200	15	1	1	0	1	0
11	192	0	A	0	0	0	1	0	2100 Awning SINGLE A 23 5/8X29 9/16 NoBM PVC W	750	600	2700	16	1	1	0	1	0
12	210	0	L-P	0	1	1	0	1	2100 2W L-P 47 1/2X59 1/16 NoBM PVC Whit	1500	1205	5410	18	2	1	0	1	1
13	104	0	p	0	1	0	0	0	2100 Picture SINGLE P 29X59 NoBM PVC White/Whi	1499	737	4472	20	1	1	0	0	0
14	146	1	R	0	0	1	0	0	2100 Casement SINGLE R 29 9/16X35 7/16 NoBM P\	900	750	3300	21	1	1	0	1	0
15	169	1	A	0	0	0	1	0	2100 Awning SINGLE A 42X26 NoBM PVC White/Wh	660	1067	3454	22	1	1	0	1	0
16	144	1	L	0	0	1	0	0	2100 Casement SINGLE L 27 9/16X47 1/4 NoBM PVC	1200	700	3800	23	1	1	0	1	0
17	152	1	L	0	0	1	0	0	2100 Casement SINGLE L 29X59 3/4 NoBM PVC Whi	1518	737	4510	24	1	1	0	1	0
18	148	1	l	0	0	1	0	0	2100 Casement SINGLE L 29 9/16X39 3/8 NoBM PVC	1000	750	3500	25	1	1	0	1	0
19	39	1	L-F-F	2	0	1	0	1	2100 3W L-F-F 113 1/16X61 3/16 2RV2 PVC	1554	2872	8852	26	3	1	1	1	1
20	13	1	L-P-R	0	1	2	0	1	6100 3W L-P-R 89 11/16X70 7/8 NoBM PVC B	1800	2277	8154	27	3	1	0	2	1
21	83	1	L-P-R\P-P-P	0	4	2	0	1	2100 3Wx2H L-P-R\P-P-P 95X59 NoBM PVC Wh	1499	2413	7824	28	6	1	0	2	1
22	35	1	L-P\P	0	2	1	0	1	6100 2W+1WR L-P\P 48X72 NoBM PVC Black/W	1827	1218	6090	29	3	1	0	1	1
23	34	1	P-L-P BB	0	2	1	0	1	2100 3WBAY P-L-P BB 59 1/16x41 NoBM NoJa	1041	1500	5082	31	3	0	0	1	1
24	4	0	L-P	0	1	1	0	1	2100 2W L-P 59 3/16X35 7/16 NoBM PVC Whi	900	1503	4806	32	2	1	0	1	1
25	14	1	L-P	0	1	1	0	1	6100 2W L-P 59 5/16X70 7/8 NoBM PVC Blac	1800	1505	6610	35	2	1	0	1	1
26	15	0	L-P	0	1	1	0	1	2100 2W L-P 59 3/16x35 7/16 NoBM PVC Whi	900	1503	4806	36	2	1	0	1	1
27	16	1	L-P	0	1	1	0	1	6100 2W L-P 59 5/16X47 1/4 NoBM PVC Blac	1200	1500	5400	37	2	1	0	1	1
28	8	0	P-P-R	0	2	1	0	1	6100 3W P-P-R 89X47 1/4 NoBM PVC Black/W	1200	2260	6920	38	3	1	0	1	1
29	17	0	L-P	0	1	1	0	1	2100 2W L-P 59 3/16x35 7/16 NoBM PVC Whi	900	1503	4806	41	2	1	0	1	1
30	110	0	P-P-P	0	3	0	0	1	2100 3W P-P-P 89X70 7/8 NoBM PVC White/W	1800	2261	8122	42	3	1	0	0	1
31	114	1	R	0	0	1	0	0	2100 Casement SINGLE R 23 3/4x70 3/4 112RV2 PVC	1797	603	4800	43	1	1	1	1	0
32	119	1	P-R	0	1	1	0	1	2100 2W P-R 38 3/16X46 7/16 2RV2 PVC Wh	1180	986	4332	44	2	1	1	1	1
33	123	0	P	0	1	0	0	0	2100 Picture SINGLE P 23 5/8X23 5/8 NoBM PVC Wh	600	600	2400	45	1	1	0	0	0
34	122	0	P	0	1	0	0	0	2100 Picture SINGLE P 23 5/8X23 5/8 NoBM PVC Wh	600	600	2400	46	1	1	0	0	0
35	131	0	L-P	0	1	1	0	1	2100 2W L-P 59 3/16x35 7/16 NoBM PVC Whi	900	1503	4806	54	2	1	0	1	1
36	147	0	L-P	0	1	1	0	1	2100 2W L-P 59 3/16x35 7/16 NoBM PVC Whi	900	1503	4806	59	2	1	0	1	1
37	117	1	P-R	0	1	1	0	1	2100 2W P-R 38 13/16X46 7/16 2RV2 PVC Wh	1180	986	4332	60	2	1	1	1	1
38	152	0	L-P	0	1	1	0	1	2100 2W L-P 59 3/16x35 7/16 NoBM PVC Whi	900	1503	4806	61	2	1	0	1	1
39	160	1	A	0	0	0	1	0	2100 Awning SINGLE A 39 13/16x39 13/16 2RV2 PVC	1011	1011	4044	62	1	1	1	1	0
40	158	0	L-P	0	1	1	0	1	2100 2W L-P 59 3/16x35 7/16 NoBM PVC Whi	900	1503	4806	67	2	1	0	1	1
41	72	1	A	0	0	0	1	0	2100 Awning SINGLE A 17 3/4X17 3/4 NoBM NoJam	450	450	1800	68	1	0	0	1	0
42	48	1	R	0	0	1	0	0	2100 Casement SINGLE R 23X35 NoBM PVC White/\	889	584	2946	70	1	1	0	1	0
43	121	0	P-P-R	0	2	1	0	1	2100 3W P-P-R 94 15/16X70 7/8 NoBM PVC W	1800	2410	8420	72	3	1	0	1	1
44	163	0	L-P	0	1	1	0	1	2100 2W L-P 59 3/16x35 7/16 NoBM PVC Whi	900	1503	4806	73	2	1	0	1	1