Addis Ababa University

College of Technology and Built Environment

School of Civil and Environmental Engineering

(Construction Technology and Management)

Value Stream Mapping Integrated with Discrete Event Simulation for Productivity Improvement of Aluminum Window and Door Production

By

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A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirements for the Master of Science Degree in Civil Engineering (Construction Technology and Management)

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DECLARATION

I hereby declare that the work which is being presented in this thesis entitle “Value Stream Mapping Integrated with Discrete Event Simulation for Productivity Improvement of Aluminum Window and Door Production” is my own original work, has not been presented for a degree of any other university and all sources of materials used for the thesis have been duly acknowledged and referenced in accordance with academic standards.

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ABSTRACT

Aluminum window and door manufacturing sector in Ethiopia plays a critical role in supporting the country's construction and infrastructure development. However, this sector faces several productivity challenges, including long lead times, inefficient resource use, unbalanced workloads, equipment downtime, and limited adoption of modern tools and methods. This research investigates the integration of Value Stream Mapping (VSM) with Discrete Event Simulation (DES) to identify and mitigate these inefficiencies in a real-world manufacturing setting.

A case study was conducted at Vision Aluminum Manufacturing PLC located in Sululta, Ethiopia. The current state production process was mapped using VSM to visualize material and information flow, identify wastes, and propose improvement alternatives. Simphony CYCLONE was used to develop and validate a DES model, which simulated proposed changes before physical implementation. Three improvement scenarios were tested: (1) application of lean tools such as Kanban, 5S, TPM, and cellular manufacturing; (2) strategic upgrades like CNC machine repair and using cutting optimization software; and (3) labor optimization to balance production lines.

Simulation results revealed that Scenario 1 improved productivity by 22.11%, Scenario 2 raised it to 31.96%, and Scenario 3 added a 5.8% gain by optimizing bottlenecks. Combined, the improvements enhanced overall productivity by 49.87%, reducing production time from 6,670.02 to 3,333.51 minutes, increasing the production rate from 0.222 m^2/min to 0.386 m^2/min, and enhancing labor productivity from 0.579 m^2/man-hour to 1.287 m^2/man-hour. The study demonstrates that integrating VSM with DES provides a practical, data-driven framework for continuous improvement in aluminum window/door manufacturing. It enables manufacturers to make evidence-based decisions, reduce waste, and optimize operations efficiently.

Keywords: Productivity, Productivity Improvement, Lean Manufacturing, Value Stream Mapping, Discrete Event Simulation

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Table of Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CSM	Current State Mapping/Map
CT	Cycle Time
DES	Discrete Event Simulation
FSM	Future State Mapping/Map
JIT	Just-In-Time
LT	Lead Time
NVAA	Non-Value-Adding Activities
TPS	Toyota Production System
VAA	Value-Adding Activities
VSM	Value Stream Mapping
WOS	Workplace Organization and Standardization

CHAPTER ONE: INTRODUCTION

1.1 Background

The construction industry in Ethiopia plays a vital role in the country's economic development, contributing significantly to GDP and employment. Despite its importance, the sector faces numerous challenges that hinder its productivity, including inefficient project management, limited technological advancement, shortage of skilled labor, and inadequate infrastructure (Amanuel, 2016; FurtherAfrica, 2024). As Ethiopia experiences rapid urbanization and a growing demand for infrastructure, addressing these productivity issues is crucial for sustainable development (FurtherAfrica, 2024).

Productivity in the construction industry is a critical factor that determines the success of projects and the overall performance of the sector. However, studies indicate that the Ethiopian construction industry lags behind in productivity compared to global standards. This productivity gap is attributed to various factors, such as the reliance on traditional construction methods, lack of training and development programs for workers, and poor project planning and execution (Amanuel, 2016).

The construction manufacturing industry plays a critical role in supporting the construction sector by providing essential materials, products, and prefabricated components. This industry significantly influences the efficiency, quality, and cost-effectiveness of construction projects. However, productivity within the construction manufacturing industry has become a critical concern in recent years. Various studies highlight that, despite technological advancements and modern manufacturing techniques, the industry still faces productivity challenges that hinder its potential growth (Ofori et al., 2022).

Several factors contribute to the productivity issues within the construction manufacturing industry, including traditional production methods, inadequate investment in technology, and a lack of skilled labor (Amanuel, 2016). The reliance on traditional manufacturing processes limits the industry's ability to meet the growing demands of the construction sector. Furthermore, the integration of automation and digital technologies, which have the potential to enhance productivity, remains low in many sectors (Ghobakhloo, 2020).

Improving productivity in the construction manufacturing industry is crucial not only for enhancing the performance of individual companies but also for the overall efficiency of the construction sector. This requires a comprehensive approach that includes adopting advanced manufacturing technologies, investing in workforce development, and implementing best practices in production management (Ghobakhloo, 2020). Addressing these challenges will enable the construction manufacturing industry to better support the construction sector's needs and contribute to sustainable economic growth.

The aluminum window and door manufacturing industry play a vital role in the construction sector, providing essential building components for residential, commercial, and industrial structures. However, the industry faces numerous challenges in improving productivity, reducing lead times, and enhancing overall operational efficiency. Complex production processes, fluctuating demand, resource constraints, and inefficient workflow contribute to suboptimal productivity levels (Jadhav et al., 2014).

To address these challenges, organizations in various industries have adopted lean manufacturing principles, which focus on eliminating waste, optimizing processes, and improving overall efficiency (Jones, n.d.). Lean manufacturing has been successful in enhancing productivity and reducing costs in many sectors. However, its application in the aluminum window and door manufacturing industry is relatively limited, and there is a lack of comprehensive studies on its integration with advanced techniques like discrete event simulation (Sharma & Kulkarni, 2020).

Discrete event simulation is a powerful tool used to model complex systems and analyze their behavior under different scenarios (Banks et al., 2010). By integrating lean principles with discrete event simulation, manufacturers can gain insights into process optimization, identify bottlenecks, and evaluate the impact of potential improvements before implementing changes in the real production environment (Abdulmalek & Rajgopal, 2007a). This integrated approach has the potential to transform the aluminum window and door manufacturing industry by providing a systematic and data-driven methodology for productivity improvement.

Given the potential benefits and limited research on the adoption and implementation of lean principles integrated with discrete event simulation in the context of aluminum window and door manufacturing, this research aims to link the gap in existing literature and provide valuable insights for industry practitioners and researchers. By conducting a comprehensive analysis of the current manufacturing processes, identifying improvement opportunities, developing a lean implementation plan, and utilizing discrete event simulation, this research seeks to contribute to the knowledge and understanding of how these methodologies can be effectively applied to enhance productivity in aluminum window and door manufacturing industry.

1.2 Problem Statement

The aluminum window and door manufacturing sector in Ethiopia plays a vital role in the construction industry, yet it remains significantly constrained by low productivity, inefficient workflows, prolonged lead times, and poor utilization of resources. These inefficiencies are further aggravated by the high customization demands of products, inconsistent work standards, and inadequate use of modern process improvement tools (Tadesse, 2022). Despite widespread recognition of lean methodologies such as Value Stream Mapping (VSM) to visualize and reduce waste, these tools lack the ability to dynamically model complex interactions, uncertainties, and resource constraints inherent in real-world production systems (Ramesh & Kodali, 2012).

On the other hand, Discrete Event Simulation (DES) offers powerful capabilities to analyze system behavior under various operational scenarios, yet it is often applied in isolation without the strategic perception offered by lean tools. The lack of an integrated VSM–DES framework has left many small and medium scale manufacturers without a structured, data-driven approach to identify inefficiencies and simulate performance enhancement (Almanei et al., 2017). This gap is particularly evident in the Ethiopian context, where empirical studies applying lack of such integrated techniques are virtually, and decision-making often relies on trial-and-error approaches.

Hence, this study aims to address this critical problem by developing and applying a comprehensive VSM-DES integration framework tailored to the aluminum window and door manufacturing industry. Through a case study approach, the research will map current processes, identify value-adding and non-value-adding activities, simulate alternative scenarios, and propose practical improvements grounded in both lean principles and simulation analysis.

1.3. Objectives

1.3.1 General objective

The general objective of this research is to improve productivity of aluminum window and door production through the integrated application of lean manufacturing tool (Value Stream Mapping) and Discrete Event Simulation Modelling.

1.3.2 Specific objectives

- To analyze the current production processes of aluminum window and door manufacturing.
- To identify the waste and inefficiencies in the production process using value stream mapping (VSM).
- To perform root cause analysis and suggest solutions to problems using lean tools.
- To develop a DES model based on VSM findings to evaluate scenarios and analyze the productivity gains and lean manufacturing improvements.
- To measure and compare the improvements in overall productivity before and after the implementation of the VSM-DES approach.

1.4. Research Questions

- What are the existing conditions and workflows in the current aluminum window and door manufacturing processes
- What are the current inefficiencies and waste in the aluminum window and door manufacturing process that hinder productivity improvement?
- What are the root causes for wastes (NVAA) and probable solutions?
- How can Discrete Event Simulation (DES) be utilized to model the manufacturing process and evaluate the impact of identified inefficiencies?
- To what extent does the integrated VSM–DES approach improve overall productivity?

1.5. Scope and Limitation of the Research

Scope of the Research

This research focuses on the implementation of lean manufacturing tools (Value Stream Mapping) (VSM) integrated with Discrete Event Simulation (DES) to improve productivity in aluminum window and door manufacturing. The study is focused on a case study conducted in vision aluminum manufacturing plc located in Sululta, Ethiopia. The scope includes:

- Process Analysis: The study analyzed the current manufacturing processes using Value Stream Mapping (VSM) to identify inefficiencies and bottlenecks.
- Simulation Modeling: A Discrete Event Simulation (DES) model developed based on the VSM findings to simulate various scenarios and evaluate their impact on the production process.
- Implementation: The research focused on the implementation of the integrated VSM-DES approach in the case study company, observing its effects on productivity.
- Productivity Metrics: The study measured improvements in key performance indicators, such as lead time, resource utilization, and overall productivity

Limitations of the Research

- Case Study Limitation: The research is limited to a single aluminum manufacturing company (Vision Aluminum Manufacturing plc) located in Sululta, Ethiopia. As such, the findings may not be directly generalizable to all aluminum window and door manufacturing companies, especially those in different regions or operating under different conditions.
- The average cycle time in the value stream mapping may not be representative of all units due to the highly customized nature of each order, resulting in significant variations in processing times for each windows and doors.
- Implementation Challenges: The study's implementation phase may face practical challenges, such as resistance to change or limited resources, which could impact the effectiveness of the VSM-DES approach.

- Time Constraints: The research is conducted within a limited time frame, which may restrict the depth of analysis and the ability to observe long-term impacts of the VSM-DES implementation.
- The study focuses only on the workshop prosses. It does not cover the site installation activities.

1.6 Significance of the Research

This study provides a practical and structured framework by integrating Value Stream Mapping (VSM) with Discrete Event Simulation (DES) to improve productivity in aluminum window and door manufacturing. It enables manufacturing managers to identify inefficiencies, simulate process changes, and make data-driven decisions without interrupting actual operations.

The findings offer actionable insights for practitioners, particularly small and medium manufacturers, by demonstrating how the VSM-DES approach can reduce lead times, eliminate waste, and enhance resource utilization. The case study serves as a replicable model for similar industries seeking to improve performance through lean practices. Academically, the study fills a research gap by applying the integrated VSM–DES method in a context with limited empirical studies. It contributes to lean manufacturing literature and provides a foundation for future research in process improvement across developing industrial sectors.

1.7. Research Organization

This research is organized into five fundamental chapters. The first chapter, Introduction, begins with an initial background of the subject, followed by the problem statement, research objectives (both general and specific), research questions, scope and limitations of the study, and the significance of the research.

Chapter Two: Literature Review presents the theoretical foundation of the study. It covers the history and principles of lean manufacturing, key tools and techniques, and its application across industries, including construction. The chapter also reviews lean wastes, modeling and simulation, Discrete Event Simulation (DES), and the integration of VSM with DES. It concludes with an empirical review and identification of research gaps.

Chapter Three: Research Methodology describes the research design, data collection and analysis methods, the development of a lean implementation plan, simulation modeling, and the evaluation metrics used.

Chapter Four: Analysis and Discussion begins with the current state analysis of aluminum window and door manufacturing, identifying value-added and non-value-added activities, bottlenecks, and performance metrics. It then outlines the lean implementation plan, including VSM, lean tool selection, and improvement strategies. The chapter also details DES model development and presents the results and their implications in relation to the study's objectives and existing literature.

Finally, chapter five, Conclusion and Recommendations, summarizes the key findings of the research, offers conclusions, and provides recommendations for future practice and research.

CHAPTER TWO: LITERATURE REVIEW

2.1 Definition of Key Terms

Lean Manufacturing*:* A systematic approach to identifying and eliminating waste through continuous improvement, aiming to deliver value to the customer with minimal resources.

Value: Any action or process that a customer is willing to pay for, and that directly transforms a product or service to meet customer needs. In lean thinking, value is always defined from the customer's perspective.

Value Stream Mapping (VSM)*:* A lean tool used to visualize and analyze the flow of materials and information required to bring a product or service to the customer. It helps identify value-added and non-value-added activities.

Simulation Modeling: The creation of digital models that imitate real-world processes or systems to study performance, identify inefficiencies, and test improvement scenarios without disrupting actual operations.

Discrete Event Simulation (DES)*:* A computer-based modeling technique that represents a system as a series of discrete events in time. It is used to simulate complex and dynamic processes to assess system performance under different scenarios.

Waste (Muda)*:* Any activity that consumes resources but does not add value from the customer's perspective. Common types include overproduction, waiting, transportation, over-processing, excess inventory, motion, and defects.

Productivity*:* A measure of output relative to input, often expressed as units produced per labor hour, or value added per unit of resource used.

Lean Tools*:* Techniques used within lean manufacturing to identify and eliminate waste, such as 5S, Kaizen, Kanban, Poka-Yoke, and root cause analysis.

Kaizen: A lean philosophy that promotes continuous, incremental improvement involving all employees.

Lead Time: The total time from the initiation of a process (e.g., customer order) to its completion. It reflects the speed of the entire production or delivery system.

Cycle Time: The total time taken to complete one unit of product from start to finish within a process or workstation. It includes both processing and waiting times.

Value-Adding Activity (VAA): An activity that transforms the product or service in a way that the customer is willing to pay for.

Non-Value-Adding Activity (NVAA): Any activity that consumes time or resources but does not directly contribute to meeting customer requirements.

Takt Time: The maximum amount of time allowed to produce a product based on customer demand. It helps align production pace with demand.

Work-in-Progress (WIP): Items that are in production but not yet completed. Excessive WIP is considered a form of waste in lean manufacturing.

Bottleneck: The slowest part of a production system that limits overall throughput and causes delays in the flow.

Root Cause Analysis (RCA): A structured problem-solving method used to identify the fundamental cause of a problem rather than just addressing its symptoms.

Kanban: A visual scheduling system used in lean manufacturing to control the flow of materials and information based on demand, helping prevent overproduction and reduce inventory.

5S: A workplace organization method that includes Sort, Set in order, Shine, Standardize, and Sustain to improve efficiency and safety.

Poka-Yoke: A lean technique used to prevent errors by designing fail-safe mechanisms or visual controls in the production process.

2.2 Overview of Lean Manufacturing

Lean manufacturing is a revolutionary way of production management that came into being as the production system developed by Toyota in Japan during the mid-20th century. The origins of Lean manufacturing date back to the post-World War II years when the company, Toyota, faced the daunting task of bringing solutions toward increasing production efficiency as well as product quality. This system, afterwards known as Lean manufacturing, was designed to counter those challenges of maximizing value and minimizing waste (Ohno, 1988).

Lean manufacturing emerged from what may be called the production philosophy of the so-called Toyota production system (TPS), influenced heavily with those earlier production and management philosophies, e.g., by Frederick Taylor's scientific management and Henry Ford's assembly lines. However, Toyota production system introduced some concepts that differentiate it from its predecessors. The creation of TPS was under the much prestigious leadership of Taiichi

Ohno and Eiji Toyoda, who attempted to create a flexible and efficient production system quickly convertible to market demands (Liker, 2004).

An important tenet of the TPS was the elimination of waste defined by Ohno as any activity that requires resources but creates no value for the customer. Such an approach to waste reduction provided the impetus for the development of the various Lean tools and techniques like Just-In-Time production which aims at producing only what is needed as well as Jidoka which implies automating processes with human oversight to ensure quality (Ohno, 1988).

2.2.1 The goal of lean manufacturing

The primary objective of lean manufacturing is to meet customer demands while producing as little waste as possible. This entails producing the product as cheaply and efficiently as possible while delivering it on schedule (Bhamu & Sangwan, 2014). Policies, design, and operational processes all contain waste, which can take any shape and happen during any activity at any time (Seth & Gupta, 2005). Russell and Taylor, (2011) define waste as anything that exceeds the bare minimum of resources considered necessary to enhance the product's value. Defects, overproduction, waiting, transportation, inventory, over processing, and motion are the seven categories of waste that lead to non-value-added activities (Melton, 2005). Lean production holds that a product's value is determined by how customers view it, and that the production flow should correspond with when the customer requires it (Sundar et al., 2014). Lean manufacturing also aims to continuously eliminate waste in the production process by separating value-added from non-value-added operations.

Since lean manufacturing has developed over the past few decades, there may be additional lean manufacturing goals in many fields of study in addition to the most widely recognized one mentioned above (Bhamu & Sangwan, 2014). The following are some of the most often mentioned objectives while using lean (Liker, 2004):

- Continuously improve the flow of production
- Minimize the inventory
- Reduce cost
- Reduce lead time
- Perform quantity check in the production processes to reduce rework

- Raise the understandings of the process
- Improve productivity and quality

2.2.2 Lean manufacturing wastes

As previously mentioned, reducing or eliminating waste is a key priority. Anything that doesn't improve the quality of the good or service is considered a waste. Since these wastes don't benefit the client or the product/service, they are referred to as non-value adding activities. According to Sundar et al., (2014), the non-value-adding tasks that are the focus of lean manufacturing are as follows:

- Overproduction
- Defects
- Waiting
- Transportation
- Inventory
- Motion
- Over-processing
- Non-utilized talent

1. **Overproduction**

Overproduction occurs when more is produced or done earlier than is necessary. Because we are utilizing these resources to create parts that are not yet needed, it is not only a waste but also the primary cause of other wastes like rework and extra time (Rother & Shook, 1999). According to (Ohno, 1988), as cited in Koskela et al., (2013), overproduction is the main waste that fuels other wastes in a vicious cycle of waste generation. However, the assertion that overproduction is the primary waste of building cannot be supported because construction is often a produce-to-order process, which contrasts with the circumstances of mass production (Koskela et al., 2013)

2. **Defects**

Defects occur when products fail to meet up to quality standards. Some of the potential causes include poor design and specification, inadequate planning and control, inadequate workgroup qualification, and a lack of synergy between design and production. It happens when the finished or partially processed products don't meet quality standards. Rework or the addition of inferior or unnecessary materials to the building could result from flaws. According to Amanuel, (2016), rework is among the top ten issues affecting worker productivity in Ethiopia. The best product costs the same as a product that is considered to be flawed. Other than the losses, there are numerous different costs connected to rejecting, that make this an especially imperative Classification of waste to minimize or eliminate. In addition to the losses, rejecting has many other expenses, which makes it a particularly important waste type to reduce or eliminate.

3. Inventory

Stockpiling excess raw materials, work-in-progress, or completed commodities raises holding costs and increases the risk of obsolescence (Womack & Jones, 1996). By using techniques like Just-In-Time (JIT) and Kanban systems, which support the maintenance of ideal inventory levels and carrying costs, lean manufacturing minimizes inventory waste (Ohno, 1988).

4. Waiting

Waiting is associated with idleness, which is mostly brought on by inadequate synchronization, uneven material flow, and the speed at which some pieces of equipment or groups operate. Additionally, waiting happens while goods are not being moved or processed. Waiting for engineering, maintenance, raw materials, designing, quality assurance results, inspections, confirmation orders, and so on may be the cause of the idleness. By integrating the operations and maintaining their flow, waiting-related waste can be significantly decreased (Ayalew et al., 2018).

5. Transportation

Moving materials or equipment inside an organization where a poorly designed workspace or a lack of process flow causes several stops and starts in a production cycle is known as transportation (material/equipment movement). One of the main causes of needless transportation may be the working conditions at construction sites. This kind of waste can also be caused by improper handling, the use of subpar equipment, or damaged channels. It is important to remember that every relocation should have a purpose because moving items always comes with a price. Interruptions to work process flow might raise transportation expenses considerably (Sahlu, 2017). These wastes include wasted labor hours, wasted space on the job site, wasted energy, and the possibility of material waste during transit. It has been shown that properly rearranging the machines in an industrial facility from a functional to a cellular layout helps to decrease waiting times and work in progress (WIP) in addition to transportation-related waste. This also holds true for the construction sector, where a well-designed site layout can reduce needless material transit.

6. Motion

All situations involving lifting, walking, and reaching include motion, which is linked to ergonomics. The unneeded or ineffective movements that employees make while at work are the focus of motion-generated waste. This waste could be the result of inadequate work practices, a lack of tools, or a poorly organized workspace. Additionally, a lengthy commute that needs to be made within a workplace in order to complete tasks is regarded as a waste of time and energy. Superfluous movements have the potential to cause or worsen accidents, injuries, and the associated expenses. Lean thinking aims to reduce unkempt workspaces, disorganized work areas, poorly designed machinery, and ineffective or inconsistent work practices. Therefore, when a work area is properly laid up, workers' needless or ineffective movements are reduced, which lowers expenses. Therefore, in order to reduce motion and the expenses that come with it, jobs or activities that need needless motions should be reviewed and altered (Sahlu, 2017).

7. Over-processing

Over processing happens when conversion or processing operations don't improve the product or service from the standpoint of the customer. This is continuously produced by the work's poor quality. Rework pertaining to surface finishes or other works is the most obvious instance of over processing. Changing the technologies used in construction is another way to prevent this waste.

8. Non-Utilized Talent

This is the only lean manufacturing waste that is not specific to a particular manufacturing process. When management in a production setting does not make sure that all of the potential employee talent is being used, manufacturing waste of this kind results. In order for enterprises to incorporate staff development into the lean ecosystem, this waste was added. It's a waste because it could lead to workers being given incorrect or improperly trained tasks. It might also be the consequence of inadequate communication management.

Overall operational performance is increased through involving employees, including their ideas, offering training and growth opportunities, and allowing them to contribute to the development of process changes that consider their abilities and the reality they experience (https://www.machinemetrics. com /blog/8-wastes-of-lean-manufacturing)

Some examples of *Non-Utilized Talent*:

- Poor communication
- Failure to involve people in workplace design and development
- Lack of or inappropriate policies
- Incomplete measures
- Poor management
- Lack of team training

Based on site observations of randomly chosen job items, Ayalew et al., (2018) found that NVAA takes up more than half of working hours. According to Sahlu, (2017) analysis on various case studies in Addis Ababa construction sites, waiting time accounts for the largest portion of working hours on NVAA. On the other hand, Ayalew et al., (2018) found that the most common wastes in Ethiopian building construction projects were overproduction, over processing, and transportation waste. This indicates that distinct activities display and are characterized by wastes that differ from those of other processes. Lean construction approaches may eliminate the majority of waste causes; the only time waste that the techniques cannot eliminate is that which results from erratic cash flows (Polat & Ballard, 2004).

2.2.3 Lean manufacturing principles

According to Forbes & Ahmed, (2011), lean thinking may be summed up in the following five principles, which are the fundamental ideas of lean production.

1) Value

Value specification is the first stage in lean thinking. Value is meant to be communicated through a particular product and the attributes that the consumer defines for it. From the perspective of the client, the producer is accountable for fulfilling the exact specifications provided by the "voice of the customer" with relation to particular product features like price and delivery time. Something that the buyer can use right now is valuable to them. Identifying the final consumer must come first. The producer then has the responsibility of allowing the consumer to identify those characteristics that provide him with the information (Womack & Jones, 2003). A tight relationship between the manufacturer and the consumer is necessary. This particular way of thinking is based on the idea of the client. Waste is the opposite of value. Lean aims to reduce and eliminate waste while increasing value (Womack & Jones, 2003).

2) **Value stream**

Identifying the value stream, or the entire set of steps necessary to create a particular product (whether a thing, a service, or a combination of both), is the second lean thinking principle (Liker, 2004; Womack & Jones, 2003). It is an activity that is used in all three of a business's primary duties, Value stream research, according to Friedrich Rodewohl, (2014), reveals three different kinds of actions taking place along the value stream:

i. Solving problems: From conception to engineering and technical design to manufacturing launch
ii. Tasks related to information management: order taking, thorough scheduling, and delivery
iii. Physical transformation task: transforming a raw material into a final product that the consumer can hold.

Examining each product's whole value stream, from the initial supplier to the final consumer, is the fundamental objective of value stream analysis. Analyzing the complete value chain offers a comprehensive perspective that extends beyond a particular organization and offers the chance to enhance the whole rather than focusing only on one's own operations, thus eliminating waste. According to (Womack & Jones, 2003), this organizational strategy is frequently referred to as the lean enterprise. New methods of involving suppliers and partners are necessary to create a lean enterprise; these methods of coordinating are founded on straightforward ideas. in order to make the value stream transparent and control partner behavior.

- Value adding activities (VA): Assembling, cutting frame
- Non-value adding (NVA): activities that add no value and to be eliminated instantly

3) **Flow**

Creating a continuous flow of value-creating steps is the third lean thinking principle. This is a crucial phase in the entire lean implementation process. This phase necessitates a shift in perspective and a new method of operation that is entirely distinct from batch thinking (Christoph Friedrich Rodewohl, 2014). Redefining the work of departments, firms, and functions to positively contribute to value creation and to address the actual needs of employees at every stage of the process so that value flow is actually in their best interests is the foundation of the flow principle (Womack & Jones, 2003). Focusing on the product and further developing a lean enterprise for each product, together with rethinking traditional boundaries of careers, departments, functions, and organizations, will enable effective achievement of this goal. Managers may use flow strategies in any activity once they understand flow thinking, because the flow principle is always the same. The last lean principle, perfection, puts the entire system in a constant state of creative strain on behalf of every employee, making it difficult to create and maintain continuous flow (Womack & Jones, 2003).

4) Pull production

The fourth lean thinking principle focuses on more than just when and how to provide customer-focused goods. Toyota uses pull, which means that manufacturing doesn't begin until a consumer places an order. In order to get to the initial stage of production, the client order is pushed backward (using Kanban) in the production process (Christoph Friedrich Rodewohl, 2014). According to Womack and Jones, the pull principle needs to be used throughout the value stream. A good or service shouldn't be produced by one upstream party unless a downstream customer request it. Pull is a basic technique that eliminates the backlog of inventory by allowing the client to pull the goods from your business rather than pushing it toward them (Christoph Friedrich Rodewohl, 2014). In their comparative analysis of automakers, Womack et al., (1990) noted that Toyota Takoka's facility could only hold an hour's worth of inventory and had no space for inventory. By scheduling materials using pull rather than push, the pull system transforms production into a just-in-time operation (Karlsson & Ahlstrom, 1996). According to (Womack & Jones, 2003), pull cuts throughput times by "half in product development, 75 percent in order processing, and 90 percent in physical production." Because customers are aware that "they can get what they want and whenever they want," this fosters stability (Womack & Jones, 2003). Therefore, the entire system is set up so that work is done in tiny batches and supplies are ordered right away from the next level. Kanban and Just in Time (JIT) are two widely used techniques for pull management. Shingo, (1985) asserts that just-in-time production necessitates equal orders since it maintains a zero finished product stock. In practice, this guideline is more difficult to follow and takes time for businesses to grasp. According to data on inventories at every given level of economic activity, Europe, the United States, and even Japan have insufficiently low stocks. Pull is more commonly used in Just in Time supply than Just in Time production. As a result, it appears that businesses have embraced the concept more in supply than in production. As a result, all that has occurred is a push back toward upstream processes and raw materials for inventories of the same size (Womack & Jones, 2003).

5) Perfection

These four principles further guide the system toward the final lean thinking principle, "Perfection," which serves as a reminder that there is no end to the process of reducing effort, time, space, cost, and mistakes while providing a product that is increasingly closer to what the customer actually wants. This occurs as organizations start to accurately specify value, identify the entire value stream, make continuous flow of value creating steps, and let the customer pull the value (Womack & Jones, 2003). Improvements in any one of the first four principles result in improvements in the others because they interact in a positive feedback loop. Among the other ways that contribute in this context are new production technologies and procedures. In this way, value is increased and waste is completely eliminated, resulting in perfection. Of sure, "it provides inspiration and direction essential to making progress in the right direction," but it is difficult to imagine perfection (Womack & Jones, 2003). Transparency is the most important stimulus to perfection; it makes the entire value stream visible to all parties, including suppliers, subcontractors, distributors, assemblers, customers, and employees. This makes it easier to find ways to prevent waste and create value. Visual control boards, which give workers immediate feedback on changes achieved and encourage them to keep making improvements, are frequently utilized in production and close to assembly lines in lean organizations (Womack & Jones, 2003).

2.2.4 Lean Tools and Techniques

Koskela, (2000) asserts that concepts and principles form the foundation of practical approaches. The building process and its performance can be enhanced by utilizing a variety of lean tools and approaches.

Process mapping, visual management, PDCA, Kaizen, value stream mapping (VSM), Last Planner, 5s, Kanban, work structuring, Hejunka, and Kanban are a few of the frequently utilized tools, according to (Koladiya, 2017). In order to help businesses, take corrective action to eradicate waste once they have identified the primary causes of it, the researcher focuses on discussing the VSM tool and a few other useful strategies used for this study, such as Cellular Manufacturing, Just-in-Time Manufacturing, Continuous Improvement, Kanban, and others. The following sections provide a brief description of these tools.

1. **Value stream mapping (VSM)**

Value stream mapping, according to Womack & Jones, (2003), is the process of observing resource and information flows, summarizing and analyzing them, and then developing a more effective future state. Three steps make up VSM, a tool for mapping out the whole process flow. Following the product from the outbound all the way back to the inbound is the first stage in the current state mapping process. VSM iconography is used to map the information and resource flow during the production process. Finding the underlying causes, removing the waste, and identifying the nonvalue-added activities constitute the second step. At this step, a "future state map" is also made. Applying the modifications to enhance output is the last phase (Gahagan, 2007). Takt time can be used to identify the bottleneck cycle time since VSM can visually depict the inventory, lead time, cycle time, waiting time, and production flow (Sundar et al., 2014). Companies' internal and external production processes can be graphically represented by the current state mapping, which can also be used as a jumping off point for methodical production process analysis and waste detection. Finding waste in the production process and taking steps to remove it are the primary objectives of VSM (Rohani & Zahraee, 2015).

2. **Cellular Manufacturing**

The activities of cellular manufacturing are grouped together. A few adjacent workstations where tasks are carried out on comparable machinery, equipment, and raw materials should be included in each group (Hyer & Wemmerlov, 2001). Cellular manufacturing can increase production lines' continuous performance by placing the resources needed to process related items nearby. Businesses have claimed improvements in productivity, lead time, quality, space usage, and cycle time following the implementation of cellular manufacturing (McLaughlin & Durazo-Cardenas, 2013). Social systems, like staff training and job satisfaction surveys, must keep up with technical systems, such physical layout and workflow sequence design, in order to maximize the benefits of the manufacturing system (Huber & Brown, 1991). The effective application of cellular manufacturing can also be aided by additional line approaches like flow manufacturing, line balancing, and U-shaped manufacturing layout (Sundar et al., 2014).

One essential component of becoming lean is cellular manufacturing. The idea behind cellular manufacturing is to produce a wider variety of goods with the least amount of waste. A cell is made up of workstations and equipment that are positioned to ensure that materials and components move through the process smoothly. Additionally, it has trained and competent operators assigned to that cell (Abdullah, 1996).

When it comes to reaching lean objectives, there are several benefits to organizing personnel and equipment into cells. The one-piece flow idea, which holds that each product passes through the process one unit at a time without abrupt interruption and at a rate dictated by the needs of the customer, is one benefit of cells. Cellular manufacturing also has the advantage of expanding the product mix. The method should be flexible enough to meet the expectations of clients who want a wide range of products and quicker delivery times.

By assembling related items into families that can be processed in the same order on the same machinery, this flexibility can be attained. Additionally, this will reduce the amount of time needed to switch between items, which will promote smaller-batch production. According to Abdullah, (1996) Additional advantages of cellular manufacturing include:

- Inventory (especially WIP) reduction
- Reduced transport and material handling
- Better space utilization
- Lead time reduction
- Identification of causes of defects and machine problems
- Improved productivity
- Enhanced teamwork and communication
- Enhanced flexibility and visibility

3. Pull Scheduling

Because push scheduling is a production method where each operation aims to generate the largest number of units possible (demand forecast), it results in incredibly long lead times. Pull scheduling, on the other hand, is a production system where each operation only produces what the subsequent one needs (real demand). The goal of a pulling system, according to Arbulu & Harper, (2003), is to create only what is required, when required, and in the appropriate amounts. It guarantees upstream and downstream tasks are coordinated exactly in time. It is necessary to work backwards from the finish date when using the pull scheduling strategy. Its foundation is the idea that upstream should wait for downstream to request production (Womack & Jones, 1996, as cited in Nikakhtar et al., 2015). This approach reduces on-site storage expenses, material holding costs, and idle man and equipment hours by enforcing JIT material delivery (Arbulu & Harper, 2003). Pull and flow lean principles, as defined by Picchi and Granja (2004), are considered the fundamental elements of lean thinking and serve as the foundation for waste reduction. Smaller buffers, quicker project completion, and higher production are the advantages when done correctly (Ballard & Howell, 2003). Because fewer pieces need to be trashed or changed during manufacturing, there is a lower work-in-progress (WIP), less working capital commitment, and a lower cost of design modifications. Pulling, or just-in-time material supply, reduces overproduction in reinforcing operations significantly (Nikakhtar et al., 2015).

4. Work Structuring

The Lean Construction Institute (LCI) created the term "work structuring" to describe how operations and process design are developed in accordance with product design, supply chain structure, resource allocation, and potential modularization opportunities (Ballard & Howell, 2003). Work structure aims to increase workflow efficiency and dependability while providing value to the client. Reducing the number of handovers (work structure) and using multitasking workers can both reduce the overall lead time (Rother & Shook, 1999). Work structuring is consistent with one of the eleven Koskela principles, which is to simplify by reducing the number of stages and pieces. Simplification, according to Koskela, (1999), is the process of lowering the number of steps in a material or information flow. By reorganizing work and enhancing operational reliability through job standardization, Yu et al. were able to save three workdays of lead time in a study to design a lean model for home construction. In a simulation of lean improvement for residential buildings, Esquenazi A. & Sacks, (2006) found that multiskilling had the greatest impact on improving labor utilization rates because it eliminated the production rate imbalance that causes teams to have to wait for work to be ready by previous teams.

5. Kanban

The Japanese word for "signboard" is Kanban. It serves as a signal system to make sure that suppliers only provide materials in response to requests from the following work center (Melton, 2005). One method to guarantee just-in-time production is Kanban. Kanban can address some of the issues with inventory level and material flow design since all requirements are only retrieved when necessary. A seamless workflow depends on the Kanban system's ability to offer appropriate buffers between activities when demand is unpredictable. According to Sundar et al., (2014), the Kanban method can help with mixed model production and inventory optimization, which can shorten lead times for product delivery and boost the rate at which resources (such as labor and machinery) are used.

6. Employee perception

The success of implementing a lean transition can be influenced by employee perception. The changes that lean production brings about on the floor are frequently the subject of intense discussion. Lean implementation typically entails resource reallocation and modifications to operating practices. In general, employees feel differently about it. Even after the benefits of lean production have been demonstrated, employees may experience stress and anxiety when they leave their comfort zones and established practices, which could lead to an increase in workload (Neirotti, 2018). According to a survey, there are two categories of factors that affect employees' beliefs about the success of the lean transformation: critical intrinsic factors (commitment, lean belief) and external factors (work method, communication) (Losonci et al., 2011). Better employee perspective can be fostered by staff training, and awareness can be increased by updating standard operating procedure (SOP) manuals or outlining the road map in order to guarantee the best possible outcome of lean (Mahfouz et al., 2011).

7. Kaizen (Continuous Improvement)

"Kai" means "change" and "zen" means "better" in Japanese. Kaizen is a technique for ongoing development. Two categories can be used to classify kaizen. The first is flow kaizen, which concentrates on the movement of information and materials along the entire production line; the second is process kaizen, which only concentrates on improving each individual workstation. In addition to identifying existing waste and designing a system with zero waste, kaizen methods are utilized to discover the underlying cause of inefficiency (Sundar et al., 2014). Three organizational competencies are thought to be necessary for the effective application of Kaizen. Employee initiative to research and enhance the work process is the first; barrier-free cross-functional communication inside the organization is the second; and the capacity to discipline employees to ensure they follow instructions is the third (Chan & Tay, 2018). Kaizen aims to remove waste and create greater value. Data collection is typically the first step in implementing Kaizen, which is frequently utilized as a springboard for significant changes.

8. 5S Workplace organization

5S is one of the best tools for continuous improvement and the cornerstone of a successful lean company. 5S is the first modular step toward a significant reduction in waste. Seiri (sort), Seiton (straighten), Seiso (sweep and clean), Seiketsu (systemize), and Shitsuke (standardize) are the Japanese words that make up 5S. Finding waste and attempting to reduce it is the fundamental idea behind 5S. Scrap, flaws, surplus raw materials, unnecessary things, old, broken tools, and outdated jigs and fittings are all examples of waste (Monden, 1998).

The first S, Seiri, is focused on keeping items that aren't being used often apart from those that are (like those that won't be utilized for a month or so). Fled, (2000) asserts that moving those things and discarding superfluous stuff will make it easier for employees to move and work.

Seiton is about placing the appropriate items in the appropriate locations. A venue must be free of items that are inappropriate for that area. It is necessary to identify and place the appropriate tools for a given workspace. The unlabeled commodities will be easier to remove from that area as a result. They will become visible, recognizable, and easy to utilize with the right tool, jig, fixture, and resource location (Fled, 2000).

Seiso takes a thorough method for cleaning and sweeping the office. The work area should be neat, clean, and ready for the next shift. The workstation needs to be maintained on a regular basis, such as every day. All supplies and equipment should be in their correct places, and nothing should be missing. A clean workplace creates a healthy working atmosphere (Fled, 2000).

Seiketsu is maintaining a high standard of housekeeping and organization in the workplace. Regular audits and scoring of areas of responsibility are necessary. If a specific person is allocated to each area, then everyone has a responsibility to maintain a high quality of cleanliness and housekeeping (Fled, 2000).

Shitsuke's is the duty of training employees to follow housekeeping guidelines as the management. Management should implement the housekeeping rules such that the public will accept them. It is advised that management do a tour of the work floor, clarify expectations, congratulate compliance, and offer advice to noncompliant employees (Fled, 2000).

Five S's represent improved cleaning and order of the workplace. Kaizen techniques, such as 5S, not only increase a company's profitability but also allow it to showcase previously unrealized potential strengths and capabilities. According to Cox, (2002), the use of 5S has had favorable results. The benefits of implementing 5S will also be covered later.

9. Just-In-Time (JIT)

Since just-in-time manufacturing is a management concept that aims to eliminate production waste causes by creating the appropriate part in the right place at the right time, it has a strong connection to lean manufacturing. This tackle wastes such work-in-process materials, flaws, and inadequate part supply schedule, claims (Nahmias, 1997). In general, inventory and material flow systems can be divided into two categories: push (conventional) and pull (just-in-time). Both techniques are driven by customer desire. The primary distinctions, however, are seen in how each system reacts to customer demand. Just-in-time manufacturing enables a business's internal procedures to adapt to sudden shifts in the demand pattern by producing the right product in the right quantities at the right times (Monden, 1998). Just-in-time is also a crucial tool for overseeing a company's external activities, like purchasing and distribution. One may think of JIT purchasing, JIT distribution, and JIT production as its three constituents. Further details on each are given in the following sections.

Just-In-Time Production. Eliminating waste wherever it exists is the goal of lean production. JIT is one of the most crucial phases in putting lean manufacturing into practice. JIT production, according to Monden, (1998) and Levy, (1997), is the foundation of lean manufacturing. Not having more raw materials, work-in-progress, or finished goods than are necessary for efficient operation is the goal of just-in-time production. A "pull system" is what JIT makes use of. Production receives the first signal from customer demand, which is the source of the order. The product is thus removed from the assembly process. Pulling or withdrawing the required pieces in the required quantity at the required time, the final assembly line proceeds to the previous procedure (Monden, 1998). As each phase pulls the necessary components from the previous process further upstream, the process continues. A Kanban system is used to organize the entire operation.

JIT shipments are made in frequent, small batches. These shipments are managed using a Kanban. An information system called Kanban is utilized to manage how many pieces need to be made in each phase (Monden, 1998). The two most popular kinds of Kanban's are the production Kanban, which indicates how much the previous process must generate, and the withdrawal Kanban, which indicates how much the next step should take from the previous process (Monden, 1998).

Just-In-Time Distribution. Having a strategic alliance between suppliers and buyers is crucial to JIT effectiveness. Businesses can concentrate on their core skills and areas of expertise by using a third-party logistics distributor, leaving the logistical capability to logistics firms (Quinn & F.G. Hilmer, 1994; Simchi-Levi et al., 2000). Using an outside entity to handle all or a portion of the company's product distribution and materials management tasks is known as third-party logistics, or 3PL (Simchi-Levi et al., 2000). Just-in-time distribution (JITD) can be supported by 3PL by offering distributors or clients on-time delivery, technology flexibility like EDI, and geographic flexibility (Simchi-Levi et al., 2000).

Because the transportation of inbound and outbound material can significantly impact production in the absence of buffer inventory, JITD necessitates the frequent exchange of small lots of goods between suppliers and customers. It also requires an efficient transportation management system (Simchi-Levi et al., 2000) . Because smaller lots are delivered frequently under JITD, it might occasionally be challenging to have a complete truckload, which raises the cost of transportation. To overcome the issue, Monden, (1998) claims that a mixed loading strategy allows for full truckloads and more deliveries because it eliminates the need for single-part loading.

EDI is another crucial component that is necessary for JITD. An EDI system is necessary for efficient product deliveries between suppliers and their distributors or clients. Suppliers in the conventional product delivery system are always required to maintain completed goods inventories or modify their production schedules in response to spikes in demand. Suppliers can alter their production plan by reviewing all shipment and inventory data under EDI (Simchi-Levi et al., 2000). Since suppliers can modify their production plans and delivery windows as additional product data becomes available to them, information sharing throughout the supply chain is crucial to being competitive under JITD.

Just-In-Time Purchasing. Just-in-time (JITP) purchasing is defined by Gunasekaran, (1999) as the acquisition of products so that their delivery occurs immediately before their demand or as needed. Traditional purchasing methods, which bring items well in advance of their need, are in opposition to the JITP concept. JITP processes including product development, supplier selection, and production lot sizing become crucial.

Relationships between suppliers and customers are a crucial component of JITP. A limited number of qualified suppliers are required under JITP. When suppliers are quality-certified, the quality inspection and piece-by-piece counting of components are moved to the supplier's location, where the supplier is responsible for ensuring that the parts are free of defects prior to being shipped to the manufacturer's facility. Product development is another crucial component of JITP. Suppliers and buyers need to establish a "Black Box" relationship in which suppliers play a significant role in design and development. A reduction in the cost of purchased materials, an improvement in the quality of purchased materials, a reduction in development time and expense as well as manufacturing costs, and an increase in the technology levels of the final product are all advantages of sharing new product development and design innovation (Simchi-Levi et al., 2000).

Under JITP, EDI is crucial. JITP's ultimate objective is to ensure that, from the receipt of raw materials to the delivery of completed goods, production is as close to a continuous process as feasible (Gunasekaran, 1999). By cutting down on transaction processing time and assisting purchasers in coordinating their material movement with their suppliers, EDI can promote JITP. The cost of executing a purchase order and the cost of maintaining inventory are reduced with JITP, which offsets the increased carrying cost of materials caused by frequent small quantities.

10. Takt time

The manufacturing rate at which goods should be made in order to satisfy consumer demand is known as the Takt time. According to Zahraee et al., (2014), the Takt time is often computed by dividing the effective working time for production by the necessary unit of production. Takt time is a crucial component in manufacturing systems. It reflects the needs of the customer regarding when manufacturing should begin. Takt time can be used to estimate the minimal batch sizes in changeovers and to gauge the production speed of machines (Rohani & Zahraee, 2015).

11. Line balancing

When planning the process, line balance is a crucial factor to consider. Production line imbalance is caused by a variety of circumstances. For instance, rework, transportation between processes, machine cycle time instability, and labor productivity fluctuations. Changeover may also contribute to line imbalance in the mixed model line since it causes variations in machine cycle time (Sundar et al., 2014). One lean technique for leveling production is line balancing. In order to achieve the quickest cycle time possible, line balancing is utilized to investigate the best resource allocation at each workstation. By leveling the workload, it can also decrease the number of workstations in a particular cycle time (Sundar et al., 2014).

12. Workplace Organization/Standardization

Standardizing workplace is a key component of waste removal. In essence, standardized work guarantees that every task is planned and completed as efficiently as possible. The same degree of quality should be attained regardless of who is performing the work. Every employee at Toyota consistently adheres to the same processing stages. This covers the amount of time required to complete a task, the sequence in which each task should be completed, and the available pieces. This guarantees the achievement of line balancing, the reduction of unnecessary work-in-process inventories, and the elimination of non-value-added activities. The so-called "takt" time is a tool used to standardize work. Takt time, which means "rhythm" or "beat" in German, describes how frequently a portion of a product family should be produced in accordance with actual client demand. Producing at a rate that doesn't exceed the takt time is the goal (Mid-America Manufacturing Technology Center news release, 2000). Takt time is computed using the formula below (Fled, 2000):

$$\text{Takt time} = \frac{\text{Available work time per day}}{\text{Customer demand per day}}$$

According to Koladiya, (2017) defined the following sub-principles for workplace standardization and organization:

- Providing visual management devices.
- Creating defined work processes for repetitive tasks.
- Encouraging workplace organization and use of the 5s.
- Implementing error-proofing devices.
- Creating logistic, material movement and storage plans that adapt to changes in workplace configuration.

Yu et al., (2009) were able to enhance project performance by implementing work reorganization and enhancing operational reliability through work standardization. Similar to this, Esquenazi A. & Sacks, (2006) discovered that multiskilling had the greatest impact on increasing labor utilization rates in a simulation of lean improvement for residential buildings because it eliminated the production rate imbalance that causes teams to have to wait for work to be prepared by earlier teams. By using the mistake-proofing of processes idea, (Nikakhtar et al., and 2015) were able to drastically reduce the quantity of defects and rework time.

13. Total Productive Maintenance

One of the most significant problems that shop floor workers worry about is machine failure. The shop floor's equipment dependability is crucial because a single malfunction might bring down the entire manufacturing line. Total productive maintenance is a crucial instrument that is required to account for unexpected machine failures. A complete productive maintenance program is crucial in practically any lean scenario (Abdullah, 1996).

A comprehensive productive maintenance program consists of three primary parts: maintenance prevention, corrective maintenance, and preventive maintenance. Regular planned maintenance on all equipment, as opposed to sporadic inspections, is the focus of preventive maintenance. Employees must do routine equipment maintenance in order to identify any irregularities as soon as they arise. By doing this, unexpected machine failure can be avoided, improving each machine's throughput (Fled, 2000).

Making decisions like whether to repair or purchase new equipment is the focus of corrective maintenance. It is preferable to replace a machine's parts with newer models if it is constantly malfunctioning and its parts are breaking down. The machine will live longer and have a greater uptime as a result. Purchasing the correct machine is the key to preventing maintenance. A significant amount of money will be lost if workers are unwilling to do routine maintenance on a machine that is difficult to maintain (for example, difficult to grease or bolts difficult to tighten) (Abdullah, 1996).

14. Poya-Yoke

Poka-yoke, or mistake-proofing, is a term used in the Japanese production business. By removing errors before they arise rather than identifying and fixing them, which only classify them as "rework," the goal was to remove or reduce the need for inspection, which is seen as waste in lean philosophy (Nikakhtar et al., 2015). Individual worker participation in process issue solving and product inspection is emphasized by (Shingo, 1986, as referenced in (Bertelsen & L. Koskela, 2002). Poka yoke is a tool for enhancing productivity. This might be seen as the understanding that the process is not entirely predictable and organized, and that collaboration and education are the best ways to deal with this. According to (Nikakhtar et al., 2015), processes that are mistake-proof greatly reduce the quantity of defects and rework time.

15. Gemba Walk

The Gemba Walk is a lean management practice where leaders and managers go to the "Gemba," or the actual place where work is done, to observe processes, engage with employees, and identify opportunities for improvement. The Gemba Walk encourages management to gain firsthand insights into the challenges faced by workers and the inefficiencies in the production process (Liker, 2004). By seeing the work environment directly, leaders can make more informed decisions and foster a culture of continuous improvement.

2.2.5 Root cause analysis tools (problem solving tools)

When problems or errors that could impact a program's, completion need to be fixed, these techniques are employed as a collaborative approach. Problems may arise with cost, quality, safety, or productivity, and the objective is to identify the underlying cause in order to do the assignment in the most efficient manner feasible.

a. Plan-Do-Check-Act.

An improvement cycle is another name for the Plan-Do-Act-Act (PDCA) cycle. It is a method of process improvement that is symbolized by an unending circle that represents the cycle of repetition (Koladiya, 2017). According to Liker, (2004), as mentioned in Goodwin & Pantzar (2017), the PDCA cycle, which stands for Plan-Do-Check-Act, is a popular tool for implementing continuous improvements. There are four steps in the tool: Plan, which include recognizing the issue, establishing a goal for the modifications, and devising a strategy for putting the adjustments into action; Do, which is carrying out the modifications in accordance with the strategy suggested in the preceding phase; Check is interested in the outcome of the modifications that were done. Proceed to the next stage if the aim is accomplished; if not, return to Plan. Act involves standardizing the solution. (Koskela, 1999) Maintaining and raising working standards via incremental enhancements is a fundamental principle.

b. Fishbone Analysis.

Fishbone analysis, sometimes called an Ishikawa diagram, is a root cause analysis technique that sorts ideas into meaningful categories to determine the most likely sources of the issue. One organized method for determining the fundamental reasons of a negative issue is root cause analysis. According to Aziz, Qasim, & Wajdi, (2017), there are numerous limitations and their reasons. A typical template of a fishbone structure is employed in this kind of diagram. Under the headings of material, person, method, environment, or person, the problem and its likely causes are listed at the top of a fish. The four W's are "What," which refers to questions about things like materials and machinery; "Why," which answers questions about working conditions like the availability of labor; "When," which refers to issues with the order of time in operation; and "Where," which addresses effects related to the location, production line, area, and so forth.

c. 5 Whys

Until the root cause or causes are identified, the "5 whys" technique is employed to continuously asking "why." The practice and development of this scientific method served as the foundation for the Toyota Production System, as noted by Ohno, (1988). "Why is this problem occurring?" would be the first question the problem-solver would ask. He or she would have determined a cause for the observed effect after responding to it. In order to find a deeper reason, the problem-solver repeats the same inquiries with the goal of converting the cause into an effect. Until the root reason can be investigated, the problem-solver keeps asking this question. After completing, the problem-solver has a cause-and-effect chain that is clear and cohesive, indicating a thorough comprehension of the issue in context and highlighting the connection between the observed phenomena and the root cause (Sobek & Smalley, 2008). Implement countermeasures at the most profound level of the cause that is practical and that will stop the issue from happening again. According to Sobek & Smalley, (2008), organized tests or experiments can be used to rule out potential causes in situations when the fundamental cause cannot be determined using the 5-why techniques. This is especially true for issues pertaining to organizational processes.

2.3 Application of Lean in Discrete Industry

Many businesses in the discrete manufacturing sector have adopted lean practices to cut costs through waste reduction and continuous improvement as a result of the Toyota production system's success. Nowadays, component assembly operations across a range of industries, including automotive, electronics, and photography, frequently employ the lean manufacturing philosophy. Lean manufacturing methods and processes have been adopted by numerous other companies in the United States, especially those in the discrete industry. These include sectors such as computer part assembly, office furniture, appliances, telecommunications equipment, and shipbuilding. Motorcycles and scooters, apparel, amusement park equipment, vacuum pump construction, automobile air conditioning systems, and bicycle parts are other industries that have adopted lean manufacturing, especially in Europe (Panizzolo, 1998).

2.4 Lean Thinking in Construction Industry

2.4.1 Application of Lean in the Construction Industry

As the idea continues to develop, lean construction has been characterized in a number of ways. Antillon, (2010) defines lean construction as a new production philosophy that applies and adapts the fundamental ideas and methods of lean manufacturing to the building industry. This production approach has been adopted by the industry as a way to boost productivity and cut down on waste, which is common in the construction sector. Less waste, more value for the owners, and ongoing development are the main goals of lean production. Effective lean construction tools have been developed from the successful implementation of some of these lean production concepts and practices in the construction sector (Antillon, 2010).

"The continuous process of eliminating waste, meeting or exceeding all owner requirements, focusing on the entire value stream, and pursuing perfection in the execution of a constructed project" is how the Construction Industry Institute (CII) defines lean construction (CII Lean Principles in Construction Project Team, PT 191). Lean construction is "a way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum amount of value for the customer (both internal and external)," according to (Bertelsen & L. Koskela, 2002).

(Bertelsen & L. Koskela, 2002) added the concepts of construction as a complex system, construction as cooperation, and construction as one-of-a-kind production to the lean manufacturing model. In their work "What Kind of Production is Construction," Ballard & Howell, (2003) explain the distinctions between construction and manufacturing. The "Rethinking Construction" (The Egan Report), created by the Construction Task Force in the United Kingdom, applies the lessons learned from the manufacturing revolution to the country's building industry. The creation of the Last Planner (Ballard 2000a), which prioritizes dependability in the planning function, was another advancement in the application of lean theory to construction.

The Lean Construction Institute (LCI) was established in the United States in August 1997 by Glenn Ballard and Greg Howell (Lean Construction Institute, 2010). Through research, LCI hopes to advance our understanding of project-based production management in capital facility design, engineering, and construction.

According to Koskela, (2000), and Ballard & Howell, (2003), traditional project management techniques and construction methods are inadequate for addressing the issues facing the sector. However, the foundations for reducing or eliminating the waste that the industry faces are provided by lean manufacturing concepts and practices. Lean construction has embraced the idea of flow and value generation, challenging the conventional understanding of labor flow and work flow reliability, which were thought to be the most important factors influencing building projects. In essence, lean construction seeks to minimize workflow wastes that traditional approaches cannot effectively eradicate.

According to Koskela, (2000), there is a discrepancy between the conceptual models of project management and the actual situation. This demonstrates how weak the current management concepts are, which is why production theory in construction is necessary. To maximize project performance, this new strategy must be based on the enlarged Transformation (T), Flow (F), and Value generating (V) foundation.

Among other things, LC practice differs from traditional project management in three ways, specifically: a) LC focuses on reducing waste in building operations; b) LC aims to reduce variability and irregularity so that information and materials flow through processes uninterrupted; and c) LC uses pull system: materials for construction is expected to be delivered on site just when it is required or needed (Abdul et al., 2012).

2.4.2 Lean Tools Usable in the Construction Industry

Lean tools are adapted to suit the dynamic and temporary nature of construction projects. The following are key lean tools that have proven effective in the industry (Koskela, 1999):

- Last Planner System (LPS): Improves workflow reliability and production planning by incorporating short-term commitments from those performing the work.
- 5S (Sort, Set in Order, Shine, Standardize, Sustain): Enhances site cleanliness, orderliness, and safety, leading to better productivity.
- Just-In-Time (JIT): Reduces material handling and on-site inventory by ensuring materials arrive only when needed.
- Kaizen: Encourages continuous improvement through small, incremental changes driven by team members.
- Visual Management: Uses visual cues such as charts, signs, and floor markings to enhance communication and workflow transparency.
- Standard Work: Establishes best practices for frequently performed tasks, ensuring consistency and quality.

These tools support efficient project delivery by streamlining workflows, improving communication, and reducing waste.

2.4.3 Construction Waste

Construction waste encompasses any activity or resource that does not add value from the client's perspective. This includes both physical waste (e.g., excess materials, off-cuts) and process waste (e.g., waiting time, rework, over processing). The impact of construction waste is significant, often accounting for 25% to 30% of total project costs (Koskela et al., 2013). Process waste in particular is often overlooked but has substantial effects on project timelines and budgets. Delays due to poor scheduling, unbalanced workflows, and idle labor or equipment contribute to inefficiencies that lean construction aims to eliminate. Identifying and mitigating waste is a foundational step in lean implementation.

Numerous factors contribute to waste generation in construction. These can be grouped into the following categories (Polat & Ballard, 2004):

- Design-related causes: Late design changes, inadequate detailing, and unclear specifications lead to rework and delays.
- Supply-chain and site management causes: Inaccurate material deliveries, poor logistics, and ineffective coordination among subcontractors result in material waste and idle time.
- Operational causes: Low skill levels, inadequate supervision, and equipment breakdowns contribute to inefficiencies and increased costs (Faniran & Caban, 1998).

Addressing these causes involves the adoption of lean tools that promote better planning, resource allocation, and stakeholder engagement.

2.4.4 Barriers to Implementing Lean Construction

Despite the potential benefits of lean construction, several barriers limit its widespread adoption (Nikakhtar et al., 2015):

- Cultural resistance: Traditional hierarchical management styles can hinder the collaborative ethos required for lean practices.
- Lack of training and awareness: Many construction professionals are unfamiliar with lean principles and tools.
- Fragmented project delivery systems: Multiple subcontractors and lack of integrated project delivery approaches lead to poor communication.
- Short-term focus: Construction firms often prioritize immediate project outcomes over long-term process improvements.
- Limited client involvement: Without client support, lean initiatives may not be sustained or fully implemented.

Overcoming these barriers requires strong leadership, education, and a strategic shift towards long-term thinking.

2.5 Value Stream Mapping

According to Rother & Shook, (1999), a value stream is a collection of all value-added and non-value-added activities necessary to move a product or a group of products that share resources through the primary flows, from raw materials to the hands of consumers. These activities are part of the supply chain as a whole, which includes the information and operation flow that are essential to any effective lean operation. Value stream mapping is an enterprise improvement tool that helps visualize the movement of information and materials throughout the whole manufacturing process.

The goal is to identify all types of waste in the value stream and to take steps to try and eliminate them (Rother & Shook, 1999). Taking the value stream viewpoint means working on the big picture and not individual processes, and improving the whole flow and not just optimizing the pieces. It creates a common language for production process, thus facilitating more thoughtful decisions to improve the value stream (McDonald et al., 2002).

Value stream mapping can serve as a good starting point for any enterprise that wants to be lean. Rother & Shook, (1999) summarize other benefits of value stream mapping as follows:

- It helps you visualize more than just the single process level (e.g., assembly, welding) in production. Enable to see the entire flow.
- Mapping helps not only see the waste but also its source in the value stream.
- It provides a common language for talking about manufacturing processes.
- It ties together lean concepts and techniques, which helps to avoid "cherry picking."
- It forms the basis for an implementation plan. By helping the design how the whole door-to-door flow should operate a missing piece in so many lean efforts value stream maps become a blueprint for lean implementation.

A predetermined collection of icons is used to construct value stream mapping, a pencil and paper tool (see figure below). Value stream maps created by hand using paper and pencil have many advantages. Instead of being limited to a computer, manual mapping allows us to understand what is truly occurring on a shop floor value stream. Additionally, rapidly sketching and redrawing a map serves as a cycle of plan-do-check-act that enhances our comprehension of the entire flow of value or lack thereof.

VSM consists of two parts, a map of the current state, and a map of the future state. Data must be gathered by documentation and observation in order to create the current state map. To illustrate and elucidate the various flows and timelines, the map uses standardized figures (Nash & Poling, 2011). Refer to Figure below for an explanation of the figures.

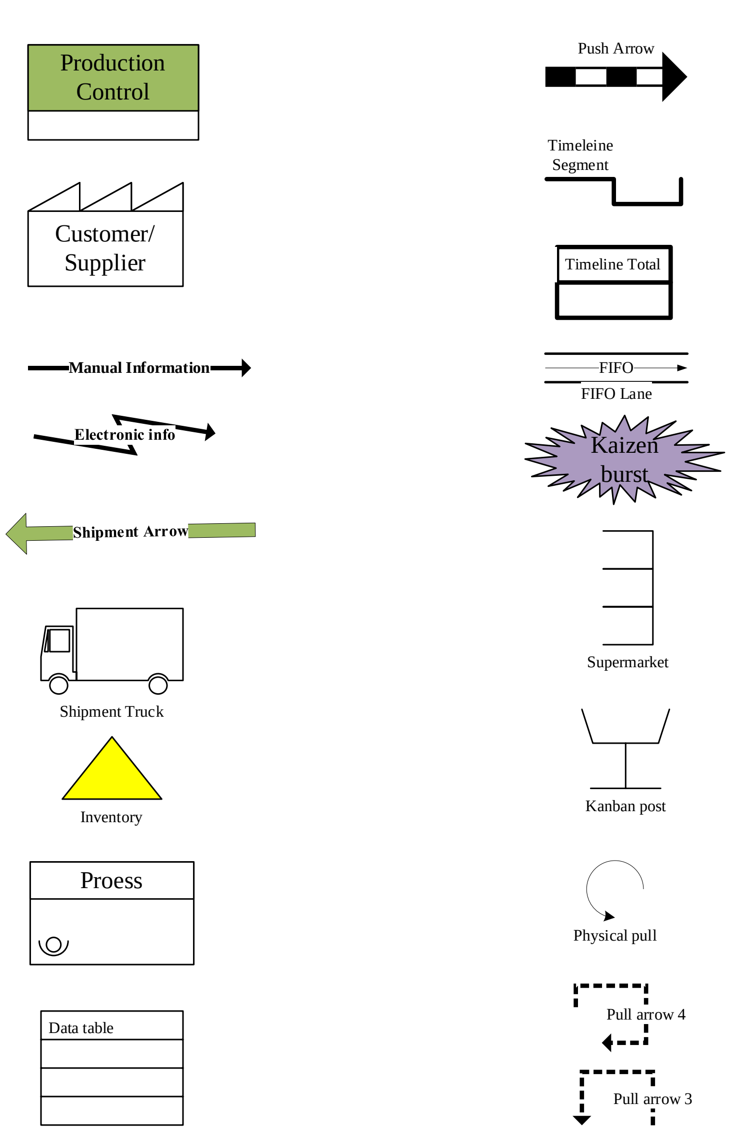


Figure 1. Icon used for value stream mapping (Microsoft visio)

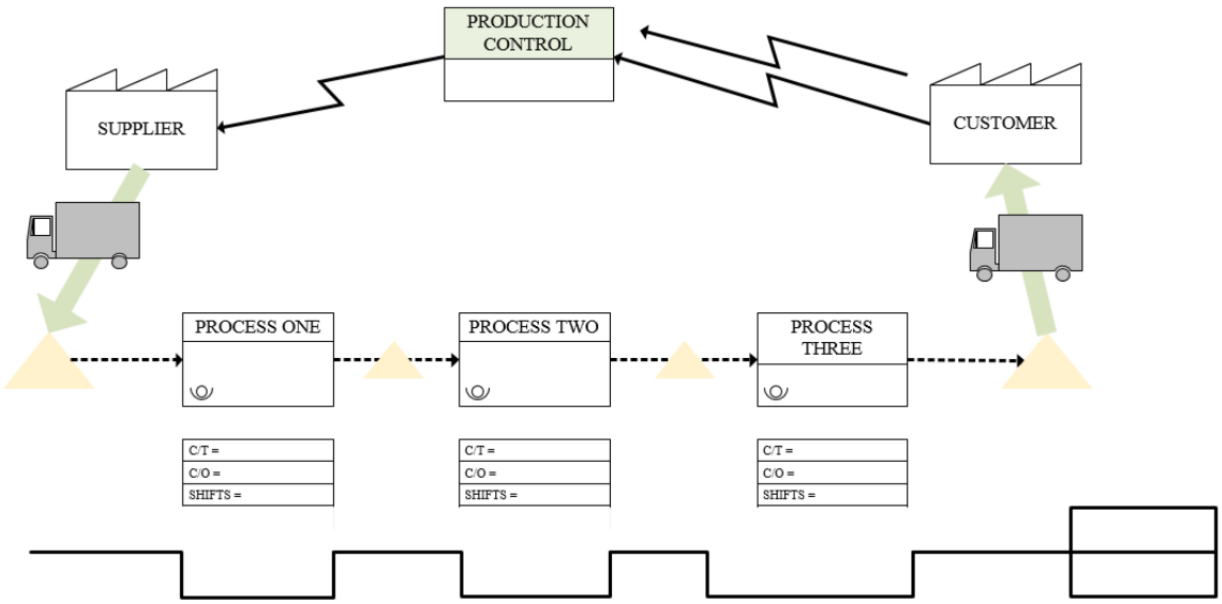


Figure 2. Example of a value stream map (Abdulmalek & Rajgopal, 2007)

Product Family: Selecting a product family as the improvement target is the first stage in value stream mapping. Since customers are primarily interested in their products and not all products, it is impractical to map every item that moves through the store. It would be extremely complicated to draw every product flow in a single organization. Either selecting items with the largest volume or classifying similar process steps for various products using the product and process matrix are two methods for identifying a product family.

Current State Map: Drawing a current state map is the next step after selecting a product family in order to capture the present state of operations. This is carried out while strolling along the real routes taken during the manufacturing process. The process most closely related to the clients, usually the shipping department, should always be the first to be drawn on the present state map when illustrating material flow. From there, one should work their way up to the upstream processes. The map's lower section depicts the material flow. Every important detail, such as lead time, cycle time, changeover time, inventory levels, etc., is recorded at every stage of the process. Since it's crucial to use actual numbers rather than historical averages supplied by the business, the inventory levels on the map should reflect levels at the time of the actual mapping rather than the average.

Information Flow: The information flow, which shows how each process will know what to make, is the second feature of the current state map. The map's upper section depicts the information flow. Connected to the previously drawn material flow, the information flow is depicted on the map from right to left. Once the map is finished, a timeline is created beneath the process boxes to show the production lead-time (the amount of time a certain product is on the shop floor from the time it is delivered until it is finished). The value-added time is then added as a second time. The total processing time for all processes is represented by this time.

Future Stata Map: Making the future state map is the third phase in value stream mapping. Value stream mapping aims to draw attention to waste causes and assist in highlighting areas that need improvement. Simply put, the future state map is an implementation strategy that identifies the types of lean tools required to remove waste and their locations within the product value stream. In order to create a future state map, a series of questions about technical implementation connected to the usage of lean tools and challenges related to future state map construction must be answered. One should directly indicate the future state concepts on the future state map based on the responses to these questions. Following the creation of the future state map, the final stage is to try to apply the various concepts it has produced to the real value stream.

2.6 Simulation and Modeling

2.6.1 Simulation Definitions

"The use of a computer to represent the dynamic responses of one system by the behavior of another system modelled after it. A simulation uses a mathematical description, or model, of a real system in the form of a computer program. This model is composed of equations that duplicate the functional relationships within the real system. When the program is run, the resulting mathematical dynamics form an analog of the behavior of the real system, with the results presented in the form of data."(AbouRizk et al., 2016)

"The use of computer software (e.g., Simphony) to represent the dynamic responses of a construction system by the behavior of a model made to represent it. A simulation uses mathematical descriptions, graphical constructs, computer algorithms (as well as other means) that are generally encapsulated in a simulation software model to represent the real system." (AbouRizk et al., 2016)

2.6.2 Types of Simulation

There are many types of simulations that are encountered in construction. The simulation models can be classified as either static or dynamic depending on whether they require time as an input. Dynamic simulation can be further divided into discrete simulation, where outputs only change at specific times, and continuous simulation, where system outputs are continuously monitored over time. Time-stepped and event-driven are two further subcategories of discrete simulation. In event-driven simulation, changes take place when an entity goes through a programmed event, and the duration of each event may be unique, whereas in time-stepped simulation, the output changes after a predetermined amount of time (Mourtzis et al., 2014).

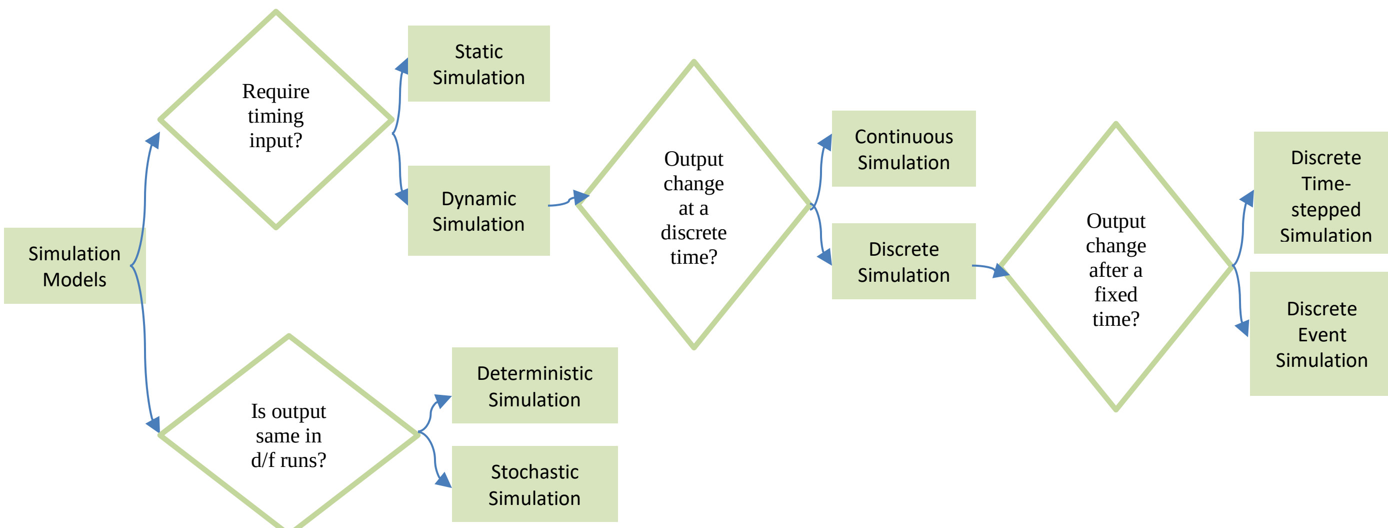


Figure 3. Classification of Simulation Models (Wang, 2019)

Static Simulation Models

Simulation models that are static don't change over time. Formulations of a system component that do not change throughout time are known as static simulation models. When Monte Carlo simulation is used in building, these models are generally helpful. A Monte Carlo simulation of a project estimate, for instance, is a total of all project expenses as well as the risk events that might occur during project execution (together with their implications and probabilities). After that, a simulation is conducted repeatedly, with random numbers generated from each distribution in each iteration (AbouRizk et al., 2016)

Dynamic Simulation Models

The goal of dynamic simulation models is to simulate a system that undergoes changes throughout time. One example of a dynamic simulation system is a model that depicts the tunnel's manufacturing process. The model would probably explain how the crane, rail system, construction workers, and tunnel boring machine work together to create the tunnel one meter at a time. The term "dynamic model" refers to the way the model will evolve over time (AbouRizk et al., 2016).

Deterministic Simulation Models

Elements that remain constant during the simulation make up deterministic simulation models. Usually not helpful for making decisions, these models can be quite helpful for debugging and model verification.

Stochastic/Monte Carlo Simulation Models

Monte Carlo simulation uses uncertainty models, which do not require temporal representation, to convey its gambling resemblance. A scenario where a challenging non-probabilistic problem is resolved by creating a stochastic process that meets the deterministic problem's relations was initially described by this term (Aziz, Qasim, & Wajdi S., 2017). According to a more current definition, Monte Carlo is the technique of repeated trials.

Continuous Change Models

According to Aziz et al., (2017), continuous simulation makes use of equational models, frequently of physical systems, which fail to accurately depict the time and state interactions that lead to discontinuities. State and temporal relationships do not need to be explicitly represented for studies employing such models to achieve their goals. Ecological modeling, ballistic reentry, and large-scale economic models are a few examples of these systems.

Discrete Event Simulation Models

One kind of dynamic simulation model is the discrete event simulation model. In order to analyze (computer-simulate) these models, time is advanced in discrete segments according to significant events that occur in the model. Typically, the simulation model begins with a certain event that sets off other events until a termination point is reached. The model is discrete since it tracks different events and their chronological processing, simulating the real world when processed (AbouRizk et al., 2016).

2.6.3 Modelling Systems

Although there are numerous approaches to modeling a system, one of the most practical is to first consider abstracting the key components and then utilizing a computer to represent those components in some way. Understanding the problem, considering it a system, drawing boundaries, and attempting to split it up into smaller parts are all necessary steps in abstracting the system. These parts must then be entered into a computer using a particular language and system. Spreadsheets, computer programs, Simphony General Purpose, Simphony Special Purpose, AnyLogic, SLAM, and other computer systems are a few examples of computer systems that are used for modeling (AbouRizk et al., 2016).

2.6.4 Simulation Software

Today, there are numerous commercial and academic simulation software programs available. Here are a few instances of simulation software created in educational settings (AbouRizk et al., 2016):

- Simphony (AbouRizk & Hajjar, 1998),
- Micro CYCLONE (Halpin, 1973),
- STROBOSCOPE (Martinez, 1996),
- ABC (Approximate Bayesian Computation) (Beaumont, Zhang, & Balding, 2002), and
- SLAM (a hybrid developed at Purdue University, which then became a fairly well-known commercial system) (Pritsker, O’Reilly, & Laval, 1997).

2.6.5 Developing Simulation Models

For simulation model development to be successful, a methodical approach must be followed. The figure below shows a high-level strategy that can be used.

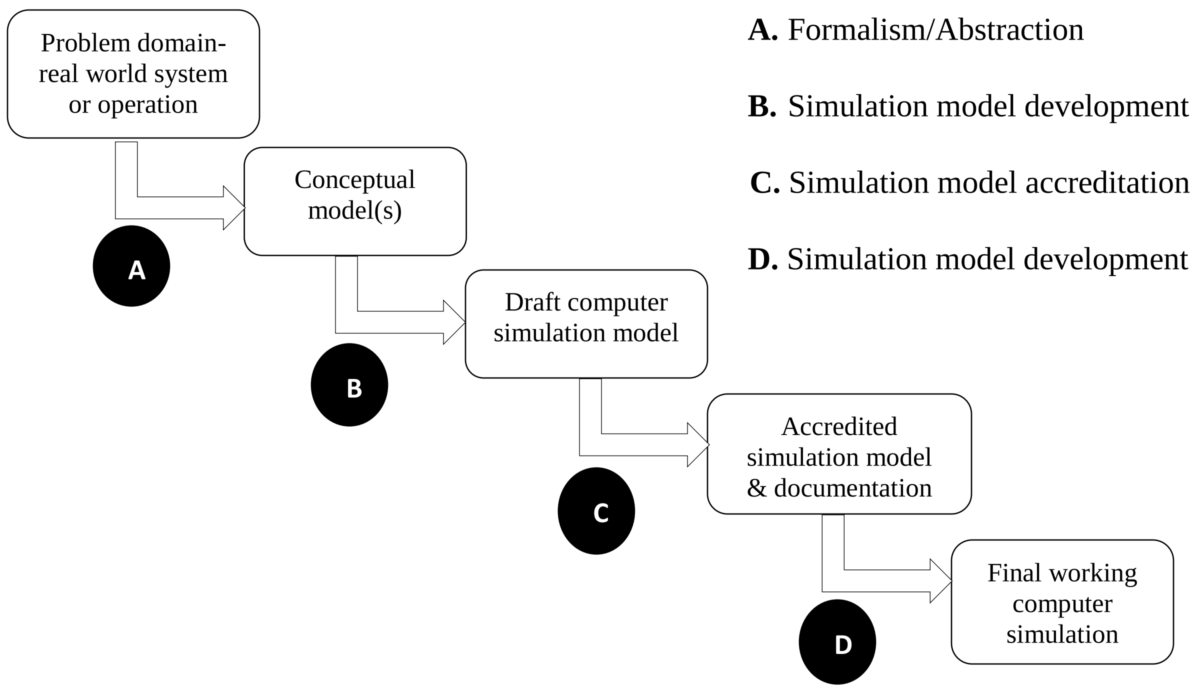


Figure 4. A Schematic Layout of a Typical Simulation Model Development Process (AbouRizk et al., 2016)

2.6.6 Applications of Simulation in Construction

One effective method of decision support for construction management is simulation. According to AbouRizk & Mohamed, (2000), precise models of construction processes can help with optimization and the creation of superior alternatives. For 1) project planning, 2) locating operational bottlenecks, 3) analyzing productivity gains and resource optimization, and 4) rapidly comparing different construction scenarios, various simulation tools can be used in construction projects (Ruwanpura Arachchige, 2001). Applications for simulation are numerous.

2.6.7 Discrete event simulation in construction

Since Halpin, (1977) released the first construction simulation tool, CYCLONE, discrete event simulation has been effectively used to model construction processes as an effective tool to support decision-making in a wide range of operations in the construction industry (AbouRizk et al., 2016). Later, numerous more simulation programs were created to mimic other construction procedures, including Simphony (AbouRizk & Hajjar, 1998).

With the help of these tools, users can simulate a range of construction processes with varying resource combinations and limits. Examples of how these systems are used in tunnel construction include CYCLONE(Touran & Toshiyuki, 1987) for tunnel advance rate prediction in soft rock, Simphony (Ruwanpura Arachchige, 2001) for forecasting soil types and soil families along a tunnel path, and Simphony.NET 3.5 (Al-Bataineh, 2008) for tunnel construction planning by modeling various construction scenarios. Nevertheless, these models' effectiveness and applicability are limited to working on clearly defined tasks that don't take place in a collaborative setting (AbouRizk et al., 2009). These construction simulation tools only enable the creation and execution of a simulation model within a particular environment, like Simphony, on a stand-alone computer; model developers are required to gather and configure all model inputs.

Since materials only change after passing a work center and each operation may be viewed as an event in the simulation model, this research model's production processes using discrete event simulation, which best mimics real production. Any production system with a process flow and where system events take place in a chronological order can be modeled using discrete event simulation software (Omogbai & Salonitis, 2016). A product moving through a production system is a common example. Production systems' performance can be enhanced by discrete event simulation in the following ways:

- Verifying the payback of changes before actual implementation;
- Reducing the cost of production line planning;
- Detecting and eliminating potential problems before actual production; and,
- Testing out the what-if scenarios to reach the best resource allocation.

The Simphony CYCLONE template is the simulation tool utilized in this study to represent the manufacturing process. The modeling environment of Microsoft Windows is the foundation of the software Simphony. Simphony is a framework for modeling industrial processes that is founded on modular and hierarchical concepts. Simphony offers collections of modeling elements, or templates, such as CYCLONE, that are intended to represent real-life problems. These templates, in addition to the general-purpose template, which is a collection of high-level elements that can be used to develop simulation models, facilitate and expedite the modeling process (AbouRizk et al., 2016).

2.6.8 Modelling with CYCLONE

Halpin first presented CYCLONE, an acronym for CYCLic Operations Network, as a construction simulation language in 1977. The foundation of Halpin's methodology is the idea that construction processes can be abstracted as cyclic networks of modeling elements that depict the movement of resources between two states: an idle state and an active state. Simply consider a resource as a virtual entity that is being processed in the network through a number of modeling elements in order to develop a CYCLONE model (AbouRizk et al., 2016).

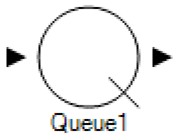
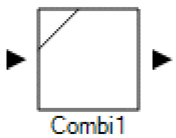
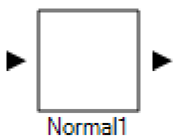
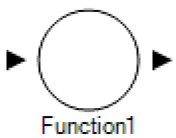
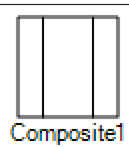
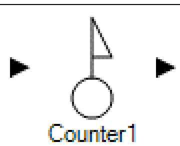
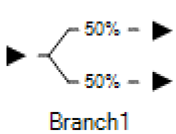
- Models are made up of virtual entities and modeling pieces that move between each other until the simulation is finished (a specific condition is satisfied to end the simulation).
- By following the virtual entities' path between the modeling parts, we attempt to develop a model that describes the real-world systems they represent.
- As the virtual entities arrive, they are processed by the modeling components, which then release them to later elements when they are finished.

A task element and a queue element are the two fundamental components of CYCLONE. A resource's active state is represented by the Task element, which can be either unconstrained, where resources flow through it without obstruction, or limited, requiring a combination of resources before enabling resources to flow to the next element (referred to as a Combi). The resource's idle status is represented by the Queue element. Resources that are unable to move on to other elements wait there. The model has additional components to control the resource flow. These consist of the following:

- Queue element (Queue), Combination task (Combi),
- Normal task (Normal),
- Production counter,
- Function, and
- Probabilistic branch (not an original CYCLONE element).

Entities (abstract elements) and arrows, which link elements and specify the direction of flow for entities originating from the element, are also included in models.

Table 1. Simphony CYCLONE Simulation Modelling Elements

Element Name	Symbol	Description	Properties
Queue		Provide a location where the entities wait for a resource	The priority of the file
Combi		The combi element Represents a constrained activity.	1) The duration of the activities. 2) The number of workers and machines required. .
Normal		Represents unconstrained task	The duration of the task.
Create		Introduces entities into the simulation model	1) The number of entities to create. 2) The simulation time at which the first entity will be created. 3) The time interval between entities.
Composite		Contains elements for sub-models	None
Counter		Tracks the number of entities passing through	None
Probabilistic Branch		Directs entities to different paths based on the probability	1) The probability for each branch.

2.6.9 Input Modelling

When examining any real-world issue, the analyst frequently faces the challenge of gathering and modeling data. According to Banks et al., (2010), even if the model structure is sound, the simulation's output data will be deceptive and potentially harmful if the input data are improperly gathered, improperly evaluated, or not reflective of the environment. (AbouRizk & Hajjar, (1998) briefly discuss the impact of employing various distribution models on the simulation output for three construction-operation models. They argue that, as long as the statistical input models utilized have the same mean value, the mean values of system-related parameters that are indicative of a system's throughput are insensitive to the type of model used. However, depending on the characteristics of the input model utilized, the mean value of resource-related parameters varied significantly and was sensitive to the input distributions used (AbouRizk & Hajjar, 1998).

In a building simulation experiment, duration input (the most important type of input in construction models) is often treated by fitting a statistical distribution to a sample of observations that has been gathered. Any of the classical statistical distributions can be fitted to the observational sample by the analyst. Regardless, a goodness of t test has to be carried out. Statistical goodness-of-fit tests, such as the chi-square test, the Kolmogbrov-Smirnov (K-S) test, Q-Q plots, and visual evaluation of the quality of fit between the fitted (theoretical) CDF and the empirical cumulative distribution function (CDF), are frequently used to accomplish this. Visual examination of the sample data's histogram and theoretical probability density function (PDF) is another option (AbouRizk et al., 2016)

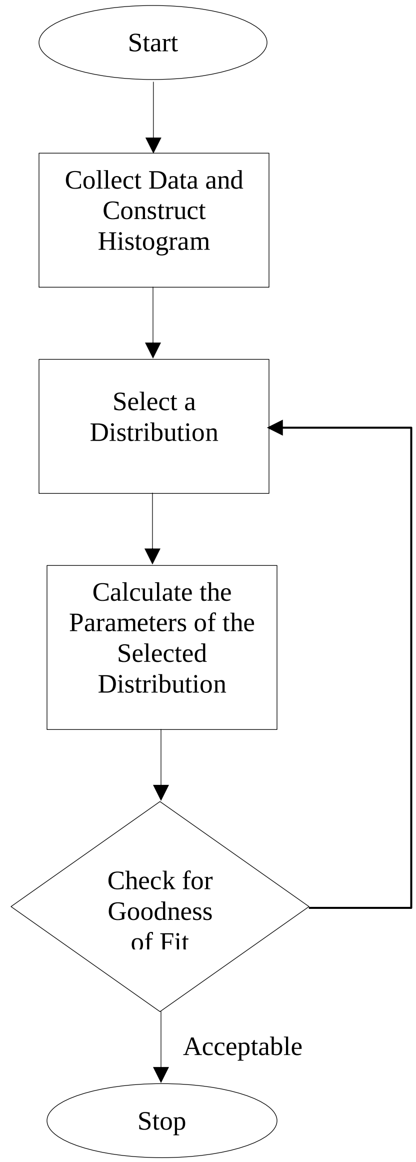


Figure 5. Input Modelling Steps for a Simulation Experiment (AbouRizk et al., 2016)

2.6.10 Verification and Validation

Typically, simulation models are created to aid in decision-making. Therefore, it is essential that the simulation model accurately depicts the desired real world and that the outcomes are reliable. In this manner, the decision-maker may trust them to make choices. The model building methodology must be used methodically in order to create accurate models and gain the confidence of users. This is because many mistakes can occur during the simulation model creation process. Whitner & Balci, (1989) state that these mistakes usually result from one or more of the following sources:

- The conceptual model,
- Input data,
- The simulation model (its implementation), and
- The simulation model development environment.

A simulation model verification and validation procedure can be used to identify and correct these errors.

Simulation Model Verification

Verification of simulation models is a procedure used to make sure the model implementation is accurate. To finish this, Sargent, (2007) recommends: 1) Verification of the specifications to ensure that they are implemented satisfactorily on the designated simulated environment. 2) Verification of implementation to ensure that the simulation model has been applied in accordance with the model's specifications. Error detection during model construction is the primary objective of simulation model implementation verification. These errors include:

- Data errors,
- Syntax errors,
- Logical errors,
- Experimental errors, and
- Bugs within the simulation environment.

Simulation Model Validation

Sargent, (2003) defines validation as, "the substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model."

The purpose of a computer simulation model is to create a virtual environment that accurately and convincingly mimics a real-world system. Analysts can experiment in this virtual environment without interfering with the real-world system. Validation is necessary to ensure a computer simulation model's accuracy and reliability. It is crucial to remember that simulation models cannot precisely replicate a real-world system. Nonetheless, the goal is to create a model that closely resembles reality, meaning it must be realistic and believable enough for the decision maker to find it easier to make wise choices. Based on (Sargent, 2003), the following important validation techniques are applicable to management simulation modeling and construction engineering applications:

- Face validity: Face validation is the process by which model users and domain experts assess the accuracy of the model's output. By allowing users to participate in the model construction and validation process, this kind of validation has the benefit of accelerating the users' process of developing confidence (Banks et al., 2010).
- Historical data validation: Part of the data is used to develop the model, and the remaining data is used to ascertain (test) whether the model behaves as the system does, provided historical data is available (or if data is gathered on a system for building or testing a model).
- Comparison to other models: The outputs and other outcomes of the simulation model under validation are contrasted with those of other (valid) models. For instance, the simulation model is compared to other simulation models that have been verified for simpler circumstances, or it is compared to known outcomes of analytical models such as a queuing model in basic cases.
- Event validity: To ascertain whether the "events" of the simulation model's occurrences are comparable to those of the actual system, they are compared.

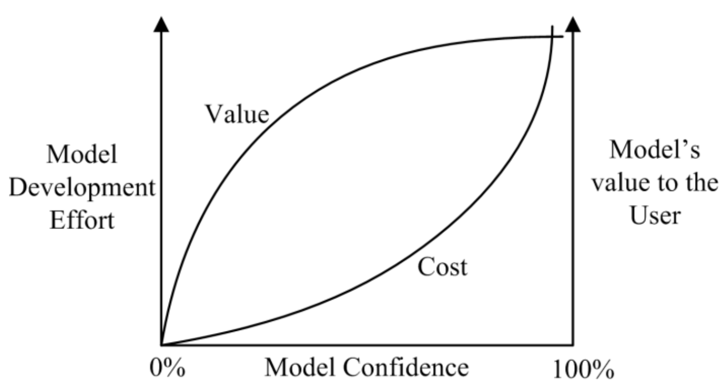


Figure 6. Decision Variables for Model Validation (Sargent, 2007)

2.7 Value Stream Mapping and Discrete Event Simulation Integration

The combined application of VSM and DES is a means to further process improvement in manufacturing. While VSM creates the high-level view of the production process and points to places for needed improvement, DES goes ahead with detailed analysis to test and verify those improvements. Together, they allow manufacturers to develop an identification of waste and then develop and introduce effective solutions. One of the key advantages of integrating VSM and DES Making the switch to lean manufacturing is difficult, particularly for businesses that depend on conventional manufacturing techniques (Abdullah, 1996).

The distinctions between lean manufacturing and traditional manufacturing methods in a variety of areas, such as production control, inventory management, labor management, and raw material procurement, make it challenging. Traditional manufacturers face challenges in implementing lean because of their unique requirements, which make it difficult to forecast the size of the gains that may be made. Because of this, the choice to adopt lean manufacturing is frequently based on personal beliefs, the outcomes of other people who have done so, and general guidelines for projected payback. This is insufficient justification for many businesses to support the adoption of lean (Detty & J.C. Yingling, 2000)This leads us to the next question how could value stream mapping be made a more practical tool?

Evaluation of the future state map can be done easily in many cases, but it may be challenging in many others. For instance, using a future state map alone is insufficient to forecast inventory levels during the production process because a static model does not allow one to see how inventory levels would change under various conditions (McDonald et al., 2002). To assist a company, think about using lean methods. It is necessary to have an additional value stream mapping tool that can measure the benefits in the early phases of planning and evaluation. This tool is simulation, which may produce performance metrics and resource requirements while maintaining organizational flexibility.

By using simulation, one may lower uncertainty and generate dynamic views of the process's machine utilization, lead times, and inventory levels for a specific future state. This allows the payback from applying lean manufacturing techniques and their effect on the entire system to be quantified. Simulation can also be used to investigate potential future state maps that are produced by various answers to design questions. It can also help companies thinking about lean manufacturing measure the advantages of implementing lean manufacturing during the planning and assessment phases. Simulation can produce resource requirements and performance statistics for both the current operation and the suggested future state map, and it can be tailored to the unique circumstances of the company. Management would be able to evaluate the lean system's performance using the simulation's data, both in absolute terms and most importantly in comparison to the established system that it is intended to replace (Detty & J.C. Yingling, 2000).

Applying the lean manufacturing principles of continuous flow, just-in-time inventory management, total preventive maintenance, setup reduction, and level production scheduling can result in performance improvements that can be measured through simulation. It can show the benefits of lean manufacturing across the board, including WIP and warehousing levels, transportation and conveyance needs, production control efficacy, and system responsiveness to market changes. However, some of the most significant advantages of implementing lean manufacturing principles, such as those resulting from 5S, continuous improvement, and employee empowerment, do not easily lend themselves to simulation(Abdullah, 1996).

Discrete event simulation has been applied in a lean manufacturing setting by numerous researchers. For example, there is only one publication in the literature about using simulation to enhance value stream mapping. McDonald et al., (2002) showed how simulation can be an extremely important tool in evaluating various future state maps by using it for a high-performance motion control product manufacturing system. They show that in addition to the possibilities derived from future state mapping, simulation may offer and analyze alternative situations.

2.8 Summary of Literature and Gap Identification

Several articles and books were examined in order to meet the requirements of this thesis's objectives. This chapter included a brief discussion of the history of lean production, the spread of lean concepts, lean in construction, lean production tools & principles, waste in lean construction, modeling & simulation, simulation classification, Discrete-Event Simulation, and Integration of VSM and DES.

It is clear that lean manufacturing is an effective technique that, when used, may produce better operational and financial outcomes. However, because of the unique features of the process industry, managers have been hesitant to apply lean manufacturing principles to this sector. According to the literature analysis above, certain process facilities have implemented JIT and kanban techniques, with positive outcomes documented. However, it appears from the literature that no one has thoroughly investigated the application of lean manufacturing methods and technologies at a process facility. Additionally, the literature indicates that value stream mapping, which identifies wastes in the value stream, is a useful initial tool for businesses looking to become lean. By forecasting the outcomes prior to implementing lean, simulation can assist value stream mapping for businesses seeking to achieve lean.

One must carefully analyze various aspects of lean manufacturing tools and create a methodical plan to make the most of them at a process facility in order to apply them to the process sector. The core focus of manufacturing is, on eliminating inefficiencies and boosting productivity by making processes more streamlined and effective. This approach relies heavily on a technique called Value Stream Mapping (VSM) a method for assessing and refining the flow of materials and information within production systems. Research indicates that VSM is successful in pinpoint plant bottlenecks, time reductions and productivity increase across sectors such, as construction and metalworking industries. Nevertheless, its utilization, in settings with production output, like the manufacturing of aluminum windows and doors has not been fully investigated.

In the way Discrete Event Simulation (DES) is a used method, for simulating and improving intricate manufacturing systems effectively. Through enabling manufacturers to test scenarios DES aids in pinpointing inefficiencies in processes optimizing resource distribution. Enhancing system efficiency without causing disruptions to real world activities. Numerous scholars have combined DES with VSM to elevate decision making in manufacturing. Nevertheless the majority of these investigations concentrate on settings, with production volumes, where operations repetitive and standardized. Limited focus has been given to combining VSM and DES in sectors, like aluminum window and door production that have diverse product ranges.

The Ethiopian aluminum window and door manufacturing sector faces several challenges, including high variability in order types, inefficient workflows, and limited adoption of lean and simulation tools. While previous studies on lean manufacturing in Ethiopia have primarily focused on construction and general manufacturing industries, there is a lack of research specifically addressing productivity improvement in the aluminum manufacturing sector. Additionally, simulation-based decision-making is rarely implemented in Ethiopian manufacturing, with most companies relying on traditional, experience-based problem-solving approaches. Furthermore, the absence of accurate production data and the lack of a standardized framework for integrating VSM and DES pose additional challenges for implementing lean and simulation-based improvements.

Based on these gaps, this research aims to develop a structured VSM-DES implementation framework tailored for aluminum window and door manufacturing. The study will address cycle time variability in customized production settings and provide data-driven solutions for improving productivity. By bridging the gap in Ethiopian lean and simulation research, this study will offer practical insights for manufacturers and policymakers, enabling a more systematic approach to productivity enhancement in the industry.

Despite the extensive research on Value Stream Mapping (VSM) and Discrete Event Simulation (DES) individually, there remains a notable scarcity of studies that explore their integration specifically within the context of aluminum window and door manufacturing. Existing literature predominantly addresses VSM and DES as separate tools for productivity improvement, but fails to adequately investigate their combined application in this specialized sector.

- Limited Case Studies in Specific Manufacturing Contexts**:** Most case studies focus on broad applications of VSM and DES in various industries, such as automotive or electronics, rather than specifically addressing the aluminum window and door manufacturing sector. This gap suggests a need for empirical research examining the practical benefits and challenges of integrating these tools within this niche industry (Smith, 2020).
- Insufficient Analysis of Integration Benefits**:** While individual benefits of VSM and DES are well-documented, there is a scarcity of comprehensive analysis on how their integration could amplify productivity improvements specifically in aluminum window and door manufacturing. Current research often overlooks the synergistic effects that could arise from their combined use (Brown & Wang, 2021).

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 Description of Study Sample Company

This research employs a case study research design to explore the implementation of Value Stream Mapping (VSM) integrated with Discrete Event Simulation (DES) as a strategy for productivity improvement. The selected case is Vision Aluminum Manufacturing PLC, a company engaged in the production of aluminum windows and doors located Sululta, Sheger Sub-City, Ethiopia.

Vision Aluminum Manufacturing Plc which is one of the MIDROC Investment Group Company. It was established on December 3, 2007 G.C and has been in operation for over 18 years which has a fully-fledged manufacturing workshop setup located at Sululta on 20,700m2 area. The Factory is fully equipped unit & technically advanced and capable to match the requirements of any level to execute any size of the projects and to achieve fast and efficient manufacturing process. Advanced Machineries are bought and installed in this workshop. The production line produces different kinds of units.

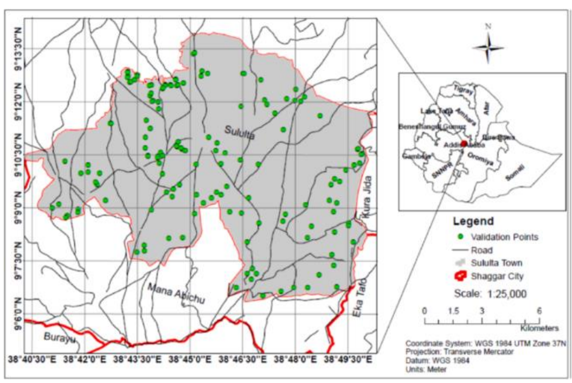


Figure 7. Location Map of the Study Area – Sululta, Ethiopia: Ethio-GIS (2023)

3.2 Research methods

3.2.1 Research Processes

This study will use the methodology shown in Figure 8 in order to accomplish its objectives. A time study of the Vision Aluminum Manufacturing Company's workshop was conducted. Raw data is gathered over a number of times for each individual operation. Additionally, a process analysis is conducted at this stage, wherein the resource layout and operational sequence are examined. Additionally, documented are the order details and actual productivity. Waste in the production process is found using lean manufacturing techniques, specifically value stream mapping. The root cause analysis of current non-value-added procedures is part of this study, and solutions are suggested accordingly. Future state analysis in simulation is required prior to putting strategy changes into action. Data from the time study and process studies were used to create simulation models. Current resource allocation and actual production data are used to validate the models. To confirm the model's accuracy, the actual production rate and the simulated production rate (completed unit/man-hour) are compared. The next step is simulation analysis, when production is simulated under strategic changes using simulation models. The most profitable strategy adjustments are chosen. Following the implementation of modifications, simulation is utilized to pinpoint the production bottleneck and provide the optimal scenario for resource allocation.

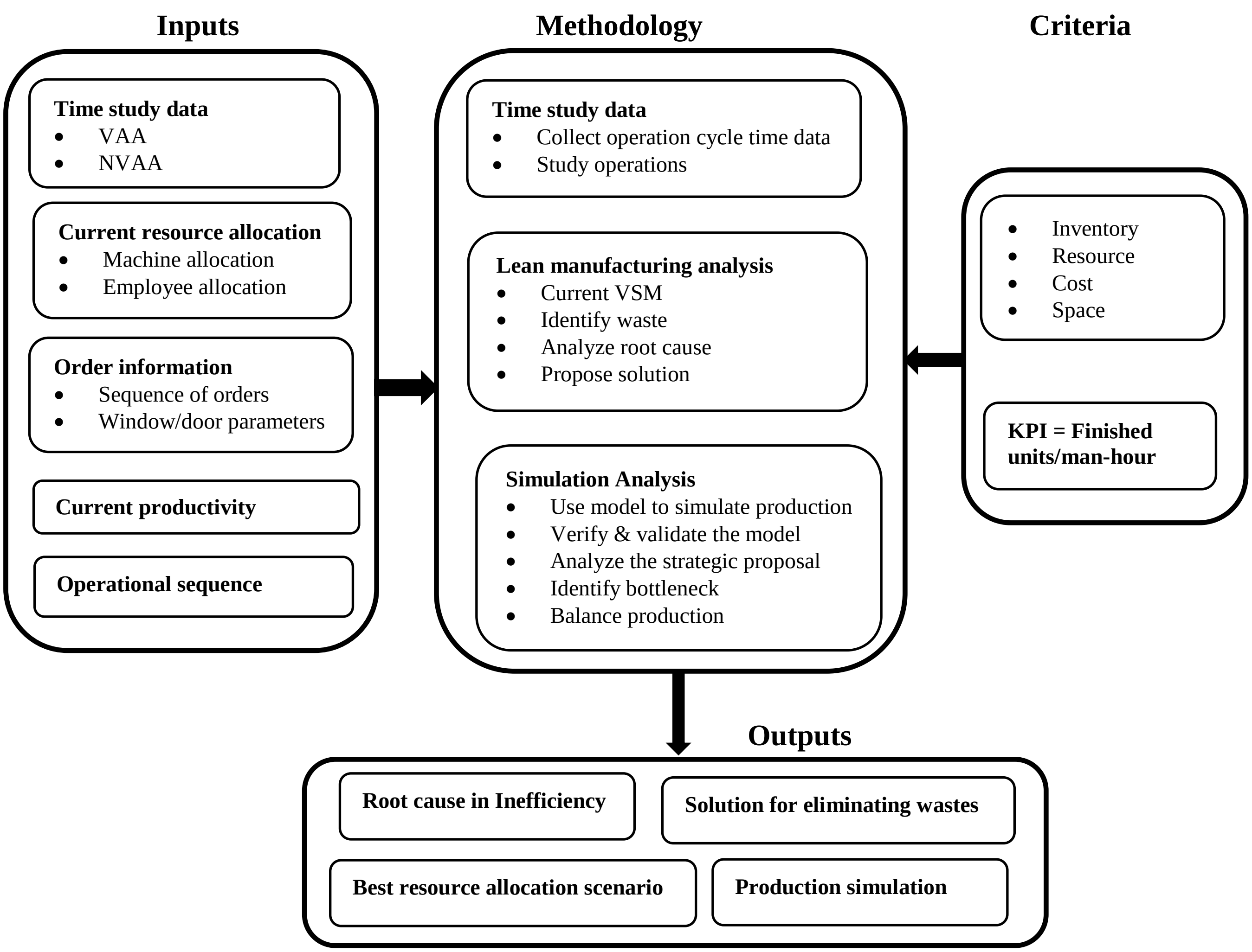


Figure 8. Research Process

3.2.2 Research Design

This research adopts a case study design, on an aluminum window and door manufacturing company. Case study research provides a deep understanding of contemporary real-life phenomena in their natural settings, which makes it ideal for exploring the implementation of Lean manufacturing integrated with Discrete Event Simulation (DES). According to Yin, (2018), case studies allow researchers to explore the complexities of specific systems. This research design is selected due to the complex nature of combining Lean principles with DES in an industrial setting. The case study allows for detailed documentation and evaluation of the existing production process, identifying inefficiencies and assessing potential solutions for productivity improvement.

The main purpose of this research is to identify, analyze, and solve problems related to inefficiency and waste within the production process, by developing value stream mapping and discrete-event simulation model, to carry out waste identification, optimization analysis, and to develop improvement strategies that improve the overall system production of aluminum window/door manufacturing operations. The study follows problem-solving research frame work, where the primary objective is to identify, analyze, and solve problems related to inefficiency and waste within the production process. This approach aligns with the goal of lean manufacturing and discrete event simulation, both of which focus on optimizing system performance by eliminating NVAA and improving overall productivity.

3.2.3 Research Purpose and Approach

A case study approach was deemed appropriate because it allows for an in-depth investigation of complex production processes and contextual factors affecting performance within a real-life setting. By focusing on a single organization, the study captures detailed insights into the workflow, cycle times, resource utilization, and areas of inefficiency that may not be visible in broader surveys or experimental research.

Through direct observation, interviews with key personnel, review of production records, and time studies of manufacturing activities, the case study provides a comprehensive understanding of the current state production. This enables the development of a Value Stream Map and the structure of a DES model using Simphony CYCLONE to simulate potential improvements. Ultimately, the case study approach supports the validation of lean and simulation-based interventions in a practical context, offering actionable recommendations tailored to the operational realities of Vision Aluminum Manufacturing PLC.

Few studies have been done in this field, hence the goal of the research is to combine VSM and DES to determine the potential of lean production principles in increasing overall productivity in the aluminum manufacturing industry. Because exploratory studies are conducted while little is known about the topic at hand, the purpose of the research is exploratory. When there is doubt about the exact nature of a problem and a need to clarify understanding, exploratory research is very helpful (Yin, 2018). Quantitative data is required for simulation, and qualitative data is required for VSM. As a result, a mixed research approach must be used simultaneously.

3.2.4 Sampling Technique

Sample company selection

Since purposive or judgmental sampling allows the use of judgment to choose sample that will best be able to answer the research questions and meet the desired objectives, non-probability purposive typical case sampling is used to choose a company (Yin, 2018). The company was chosen that offer an ideal choice for applying lean tools & principles and DES by considering:

- Its alignment with the research objectives
- The company willingness to collaborate on data sharing and site access
- Its operational scale and complexity

Data Sample Size Determination

Determining the sample size for the study period is crucial for ensuring statistical accuracy after the activity categories have been established. Because only a certain number of observations may be made each day, the sample size determines how long the investigation will take. According to research, each study should last at least one to three weeks in order to produce significant and representative data (Guide to Activity Analysis, 2010).

To ensure the accuracy of an activity analysis study, the right sample size must be chosen. More samples are collected, which lowers sampling error and improves the accuracy of the results. Nonetheless, the expense of sample collection and statistical accuracy must be balanced. A 95% confidence level and a ±5 percent margin of error is deemed acceptable in most industries. Determining the time period over which this statistical precision should be applicable is also very important. The sample size requirements are usually computed for a duration of one hour. However, collecting the required samples in an hour on a single day can be difficult for one observer (Guide to Activity Analysis, 2010). The table below provides a quick reference for determining the minimum sample size required for a study interval based on the number of craft workers. This sample size has been calculated to achieve a typical margin of error of ±5 percent at a 95 % confidence level.

Table 2. Minimum Sample Size per Hour According to Number of Craft Workers in Study (Guide to Activity Analysis, 2010)

Number of Craft Workers	Minimum Sample Size per Hour
0-50	46
51-100	84
101-150	116
151-200	144
201-250	168
251-300	189
301-350	208
351-400	225
401-450	240
450-500	253
501-550	265
551-600	276
601-650	286
651-700	296
701-750	304
751-800	312
801-850	319
851-900	326
901-950	332
951-1000	338

The number of craft workers of the selected case study company is on the range of (0-50) workers. According to Guide to Activity Analysis, (n.d.) the minimum requires observation is 46 observations per hour. An adjusted sample size of 50 observations per hour is proposed for 8 hours work shift of this study. The total sample size shall be 50*8hrs = 400 observations for each activity. Since the study was conducted for a month period, data collection was evenly distributed over a month and the result is summed after all sampling is complete.

3.2.5 Data Collection

Both quantitative and some qualitative data were used in this exploratory research. It is essential to use both primary and secondary data in order to fully achieve the study's goal. As a result, data triangulation from different sources, including documents, interviews, and direct observation, was used to address data validity. Simulation results will be used to address internal validity, whereas analytical generalization is linked to external validity.

a. **Primary data collection**

Direct observation: The main source of data for this research, the collected data through observation technique is reliable since the data are recorded by observation from the manufacturing workstation. The flow of materials, machine configurations, changeover time, and worker-equipment interactions are the main subjects of systematic observations made on the factory floor. Value-adding time, non-value-adding time (over processing time, waiting time, inventories generated, unnecessary transportation time, defect, over production, rework), cycle times, lead times, material flow, information flow, employee involvement, idle times, and other aspects are all documented using a structured observation framework. These aspects are all crucial inputs for the DES model. Moreover, the observations aid in locating obvious wastes such excessive motion, waiting times, and overproduction (Ohno, 1988). The following variations may cause highly varying the operation time for the same procedure to vary:

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

Semi-structured Interviews: The system cannot be fully understood by observation alone. Therefore, it is necessary to question those who are familiar with the system (Banks et al., 2010). Consequently, interviews were used. Interviews are conducted with the key personals, including production supervisor, quality control, inventory manager, machine operators, and other technicians. These interviews conducted in order to gather information such as: production process, challenges on the production workshop, bottlenecks, current system efficiency.

b. Secondary Data

The secondary data was collected from the company records including production records, order arrival rate, inventory, productivity, and other historical data. Secondary data which involves information from published text such as books, academics periodicals, research journals, proceeding and conference report.

3.3 Data analysis and Implementation strategy for VSM & DES

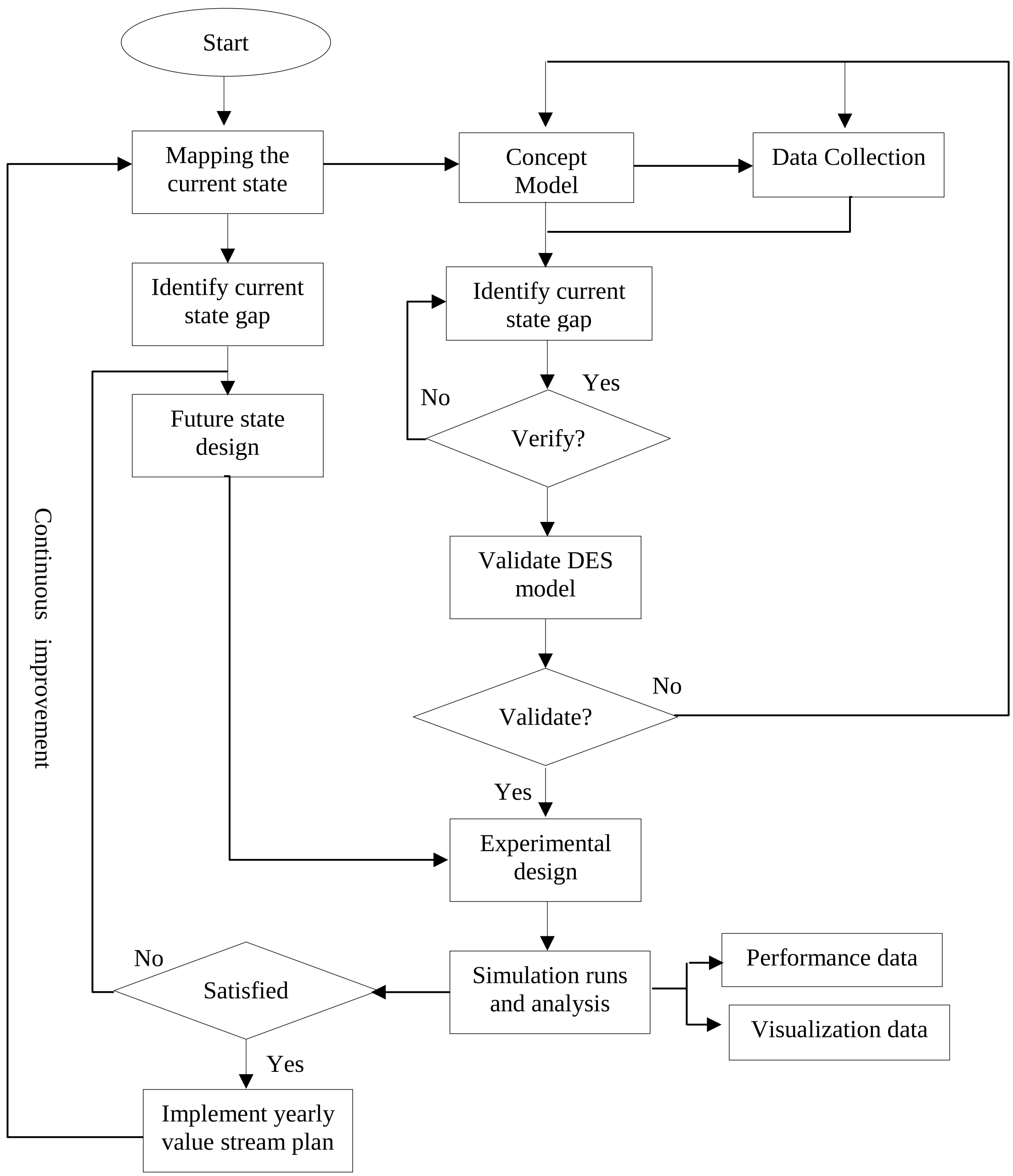


Figure 9. Data analysis and Implementation strategy for VSM & DES (Abdullah, 1996)

3.3.1 VSM analysis and Implementation strategy

Gemba walk and process study: Gemba walk was utilized to classify and identify VAA and NVAA and their effects. It entails looking for proof of the previously indicated wastes in the literature. The Gemba walk is a representation of the walk's managers take to track the location of production tasks and watch them unfold. A set of inquiries designed to collect background data on the process flow; specific details about the process concerning its suppliers, clients, and operational steps in order to gain a better understanding; and general data for a section like working days, working hours, and workforce.

Data collection: Depending on the kind of operations (subprocesses), data collecting sheets were prepared. Data for key sub processes in aluminum manufacturing process such as cutting frame, assembly, drilling, data was collected. Following the data collection for DES, input modeling was carried out using the previously described data that was required to create.

Current state mapping: A detailed VSM of the current production process is developed, highlighting the cycle times, and lead times. Build a visual map that illustrates the flow of materials and information across the production floor, marking areas of both value-added and non-value-added activities. Finding the muda (waste) in the value stream, figuring out the underlying causes and ways to get rid of it.

Analyzing the current state: Examine the map to identify sources of inefficiency. Common wastes in aluminum manufacturing which include excess inventory, long waiting times, and rework caused by quality defects. Focus on bottlenecks such as the time-consuming process. Use lean tools to determine the underlying causes of identified wastes.

Root Cause Analysis and Changes Proposal: There are various ways to identify the waste on the production line. This study used the 5 Whys technique to identify the underlying cause of waste. The most popular method for figuring out the underlying causes is the 5 Whys technique. As a lean manufacturing tool, asking "Why?" five times enables us to delve deeper into an issue and gain a better understanding of its nature; hence, "five whys" can lead to "one how" (Ohno, 1988). The cost of reallocating resources, buying new equipment, altering the manufacturing process, etc., is expensive in the majority of manufacturing company. The workshop typically undergoes significant changes as a result of the strategic solutions. When future paybacks are not sufficiently justified, managers are typically hesitant to implement lean analysis. Usually, further analysis is required before making strategic adjustments. Generally speaking, simulation is a technique that can measure benefits and highlight them early in the planning process. Managers may be able to compare the possible future performance of modifications to the current system using the statistical analysis provided by simulation tools. Before being implemented, the suggested solutions in this study must undergo simulation analysis in order to statistically examine the gains.

Developing future state map: The next future state is designed after determining the feasible improvements, following the parallel sketching of the draft and probable future state with the existing state. After that, a value stream with the identified issues of the present state fixed is depicted in the future state design.

3.3.2 DES analysis and Implementation strategy

Data collection: Without interfering with the employees' regular work schedule, the time elapsed that for each operation's procedure was measured and documented while they were working. Additionally, time-lapse images and video recordings of the primary sub processes were captured for in-depth examination. Following a comparison of the gathered data with a variety of continuous distribution functions, the best match was determined by goodness-of-fit tests. Whether sufficient samples had been collected or if additional samples would be required was indicated by the continuous similarity of best fit results.

Developing simulation model: This study models the window/door manufacturing processes using discrete event simulation (DES). The modeling tool is Simphony CYCLONE, a simulation program created at the University of Alberta. The data gathered from the time study, process study, and resource allocation study is used to build the draft computer simulation model.

Simulation validation and verification: The data and observations from the actual system are used to create simulation models. Simulation models will be employed in this study to examine the what-if scenarios and assist in decision-making. It is crucial to validate and verify the models to ensure it accurately reflect the real system they mimic because it is expensive for window manufacturing companies to reallocate resources, buy new equipment, and alter the manufacturing process. Historical data validation is the validation approach employed during the validation stage.

The entities in the model are chosen to get the order information of the windows/doors for two production days. The model will be verified in this study using real production inputs, and the correctness of the model will be assessed by comparing the simulated and real productivity.

Scenario Development & Analysis: Examine several improvement possibilities found using the VSM map for the future state. To forecast how modifications would affect the overall performance of the system, run simulations for each scenario. In order to estimate the effects of various Lean interventions on production efficiency, scenario analysis is made possible by the DES model. Examine the simulation's output, paying particular attention to two important metrics: machine utilization and cycle time.

Proposed changes analysis: When the payback isn't well explained, managers are frequently hesitant to implement strategic changes. This study will employ simulation to statistically analyze the impact of strategic adjustments in order to mitigate this issue. The suggested modifications will be incorporated into the simulation models' input. Two performance metrics of the suggested modifications will be generally contrasted with the output as is: 1) how many completed units are made each day, 2) how productive the line is. A positive change should ideally be able to raise productivity in addition to increasing the quantity of finished units produced.

Bottleneck identification**:** All of the resources' utilization rates are computed following the simulation. When a workstation has a higher burden than usual, it may constitute a bottleneck. In this study, a workstation is deemed to be a possible bottleneck if its utilization rate exceeds 90%. The following test was carried out to ascertain whether a workstation is a bottleneck:

- To check a workstation's maximum capacities, run a simulation model that only targets that one workstation. If it approaches the quantity of windows created each day, then:
- Increase the resources in the bottleneck in the original model to see if there is a noticeable increase in overall productivity. If so, the workstation is regarded as a production bottleneck.

Line balancing: The objective is to achieve evened utilization rates in each workstation by reallocating the number of resources in each workstation, based on the previously determined bottleneck and the validated original model. More employees will be assigned to workstations with high utilization rates. By doing this, lower workstation utilization rates can be increased in addition to the bottleneck's utilization rate being decreased. By altering the resource structure and monitoring the rate of resource use, line balancing analysis is accomplished.

3.3.3 Improvement Implementation

Further simulation analysis is needed for those enhancements that needs a strategic modification will also be implemented if the simulation analysis demonstrates a notable improvement in overall productivity. Simulation will be utilized once more to locate production bottlenecks after the modifications to line manufacturing are put into place. The ideal resource allocation for a balanced production line will be tested by reallocating personnel and machines in the simulation model based on the observed bottleneck. After then, a new resource arrangement will be put into place.

CHAPTER 4: ANALYSIS AND DISCUSSION

4.1 Overview of Aluminum Window and Door Manufacturing Processes

4.1.1 Case Study Overview

The case study for this research was carried out at Vision Aluminum Manufacturing PLC. This company was selected due to its alignment with the research objectives, the company willingness to collaborate on data sharing and site access, its operational scale and complexity offer an ideal choice for applying lean tools and principles. Vision Aluminum is among one of the MIDROC ETHIOPIA group companies, it was established in December 3, 2007 G.C, engaged in Aluminum works on a building. its head office is located in Addis Ababa Nifas Silk Lafto Sub City, Mekanisa Abo, Agresefet Compound and 20,700 m2 manufacturing plant in Sululta. It has 139 well trained and experienced staff, in addition, extraordinary manufacturing and installation machinery including CNC machines.

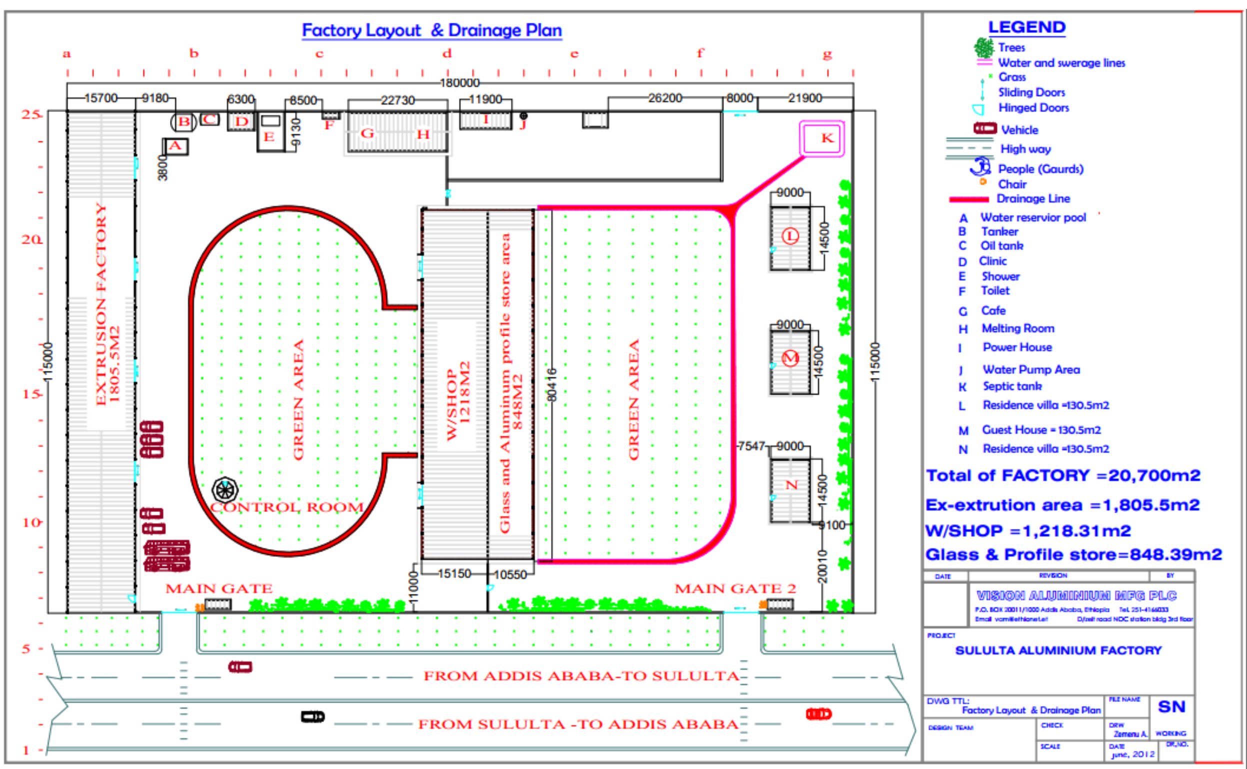


Figure 10. Factory Layout, Drainage Plan

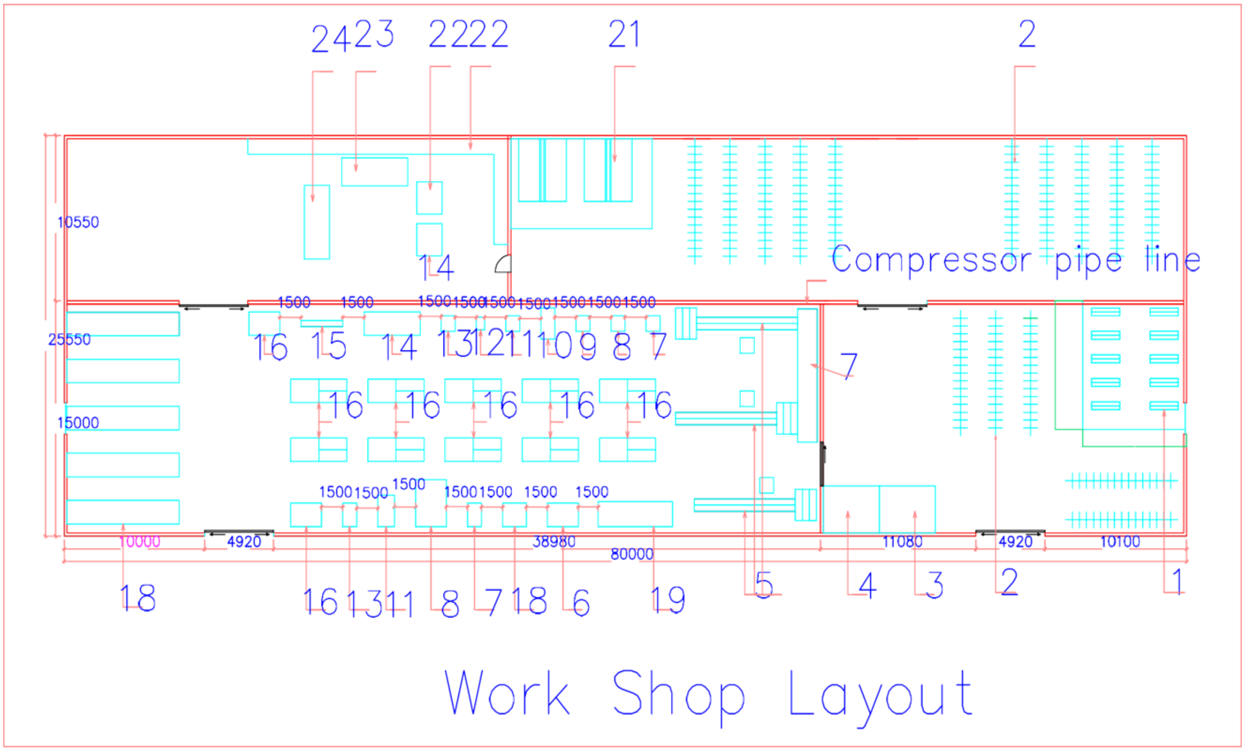


Figure 11. Workshop Layout

Aluminum product range

The company specialized in the fabrication and installation of the following architectural products:

- Window and door Systems with steel RHS sub-frame
- Curtain Walling Systems
- Aluminum Composite Panel Cladding
- Skylights with laminated safety glass
- Aluminum or glass handrails and balustrades
- Spider Glass system
- Aluminum louvers
- Internal Partition work

This research was conducted on window/door manufacturing product family. This product family is selected because, based on the historical data of the company their maximum and repetitive orders from different clients is windows and doors. Therefore, the research is interested to conduct the study on this product family.

Window/door category and components

The company produces different kinds of units: An awning is a window with a sash hinged on top that can swing outwards; a casement is a window with a sash attached to a frame by a hinge on one side, and the sash can swing outwards like a door; a picture is a window without a sash; and a casement is a window with a sash attached to a frame by a hinge on one side. A picture window maximizes the glass surface because its profile is less than that of a fixed window.

- Window and door Systems & Categories:
  - ✓ Fixed window
  - ✓ Window with; sliding opening
  - ✓ Window with; French opening
  - ✓ Window with; Casement
  - ✓ Window with; Awning
  - ✓ Hinged door with inward or outward opening
  - ✓ Sliding doors
  - ✓ French doors
  - ✓ Automatic doors
- Aluminum Window Types

Fixed Casement Awuning Sliding

Window Catalogue

▪ Aluminum Dooor Types

Hinged *Sliding* *French*

Figure 12. Window and Door Catalogue

The majority of windows/doors are a combination of individual pieces. One window/door can be created by combining different components. A window with more units usually takes longer to create. Figure 3-2 provides some of common window/door combinations. A window is made up of several parts. Figure 3-3 shows the anatomy of a typical window.

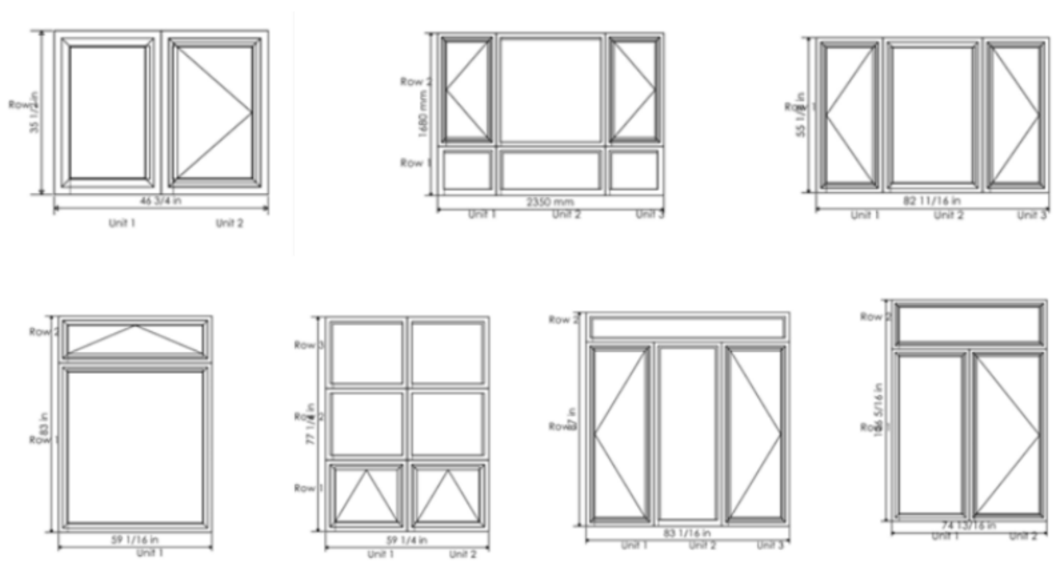
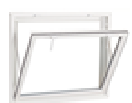
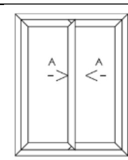
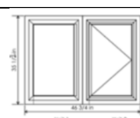
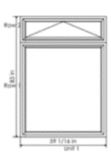
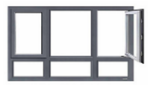
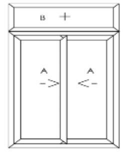


Figure 13. Combination of individual piece

Table 3. Window/Door types and order probability

Window/Door Type			Description	Picture	Common Uses	Profile Type Combination	Accessories & Hardware	Order Probability (%)
Windows	W1	Fixed/ Picture Window	Does not open, used for aesthetics and lighting.		High-rise buildings	4 (L or U) - Profiles, 4 Glass stop (Ferma)	4 Connectors	9%
	W2	Casement Window	Hinged on the side, opens outward like a door.		Residential homes	4 L-Profile, 4Z-Profile, 4 Glass stop (Ferma) Profiles	2 Hinges, 1 Handle,1 Lock, 8 Rubber Gasket, 8 Connectors	18%
		Awning, and Hopper Window	Hinged at the top or bottom opens inward or outward.	 	Bathrooms, kitchens, Basements, small spaces	4L-Profiles, 4Z-Profile, 4 Ferma	2 Top or bottom Hinges, 1 Locking Handle, 1` Lock, 8 Rubber Gasket, 8 Connectors	32%
	W3	Sliding Window	Two or more sashes slide horizontally along tracks.		Apartments, offices	Sliding Profile (8-Internal & 4-External), 2 Sliding cups	2 Rollers, 2 Lock, 8 Brush, 12 Connector, Guide Track	32%
	W4	Combination 1	Combination of two W1 and one W2	 	Residential homes,	4 L-Profile, 4 Z-Profiles, 1 T-Profile, 8 Ferma	2 (Side, Top or bottom) Hinges, 1 Handle, 1 Lock, 8 Rubber Gasket, 10 Connector	17 %

	W5	Combination 2	Combination of three w1 and two W2	 	Residential homes,	4 L-Profile, 8 Z-Profiles, 2 T-Profile, 12 Ferma	4 Side, Top or bottom Hinges, 2 Handle, 2 Locks, 8 Rubber Gasket, 16 Connector	11%
	W6	Combination 3	Combination of six W1 and two W2	 	Malls, Offices, homes	4 L-Profile, 8 Z-Profiles, 5 T-Profile, 24 Ferma	8 Side, Top or bottom Hinges, 2 Handle, 2 Lock, 16 Rubber Gasket, 20 Connector	8 %
Doors	D1	Swing Door without frame	Opens inwards or outwards, single or double leaf.		Offices, homes	3Z-Profile, 1T-Profile (Fasha), 1L-Profile (Zocalo), 8 Ferma	2 Hinges, 1 Lock, 1 Handle, 6 Connectors	15 %
	D2	Swing Door with frame	Opens inwards or outwards, single or double leaf.		Offices, homes	3L-Profile, 2T-Profile (1T, 1 Fasha), 3Z-Profiles	2 Hinges, 1 Lock, 2 Handle, 10 Connector, 6 Gasket	20 %
	D3	French Door	Two doors that swing open from the middle.		Homes, cafes, offices	4 L-Profile, 2T-Profile, 8Z-Profiles, 12 Ferma	2 Handle, 1 Lock, 4 Hinges, 16 Gasket, 16 Connectors,	17 %

	D4	Sliding Door	Large glass door that slides horizontally.		Balconies, patios, offices	Sliding Profile (Internal & External), 4L-Profiles, 2 Sliding cup	2 Rollers, 2 Lock, 8 Brush, Connector, Handle	13 %
	D5	Combination	Combination of six W1 and one D1		Homes, cafes, offices	6 L-Profile (1 Zocalo), 6T-Profile (1 Fasha), 3Z-Profiles, 28 Ferma	1 Handle, 1 Lock, 2 Hinges, 6 Gasket, 18 Connectors,	25 %
	Other Doors	Folding/Bi-Fold Door	Multiple panels fold to one side.		Large openings, patios	T-Profile, Z-Profile, Sliding Cup Profile	2 Pivot Hinges, 1 Lock, 4 Roller, 10 Connector, 1 Handle	
		Automatic Sliding Door	Sensor-based automatic door, often glass.		Malls, hospitals, offices	Sliding Cup Profile, Vertical Track Profile	Motorized Track, Sensor, 1 Lock, 8 Brush, 4 Roller	10%
		Revolving Door	Circular entrance doors that rotate around a central axis.		Hotels, commercial buildings	Oval Profile, Reinforced L-Profile	Centre Pivot, Rotating Mechanism, Sensor, Lock	

4.1.2 Current Window and Door Manufacturing Operations

Currently the production process at vision aluminum manufacturing plc do not follows a lean manufacturing approach to minimize waste and maximize efficiency. The typical workflow includes:

- Material procurement: The Company purchase good quality aluminum profiles, glass and accessories from international suppliers (from Turkey and Germany) and local suppliers (Sador aluminum).
- Work order: The Company get work through open bid or direct work order from former customers and by recommendation from new customers.
- Design and Customization: Depending on the costumer's requirement the work order can be designed and customized accordingly and the profiles can be cut to various shapes and size, allowing the customized window/door designs.
    - Analyzing the detail drawing
    - Measuring actual size from the construction site
    - Preparing of shop drawing
    - Estimating material quantity
    - Request aluminum profile, accessories & glass sheet from stock
    - Preparing manufacturing & installation drawing
- Production and Machining: Aluminum profiles are cut, shaped, and finished as per the project design and costumer requirement using CNC cutting machines available in the production workshop.
    - Cutting Profile: Cutting the aluminum profiles to precise lengths and required angle using CNC controlled machines.
    - Routering, Punching, Milling, and Drilling: After the profiles cut with the required dimension Routering, punching, milling, and drilling shale be done accordingly to create necessary holes and slots for assembly fitting hardware's like lock, handles, and fasteners.
        - ✓ Routering: Routering of frame is done for windows/doors lock system.
        - ✓ Punching: Punching of profile is done for sliding and casement windows/doors using punching machine.

- ✓ Milling: Milling machine used for T-profile for end milling (chamfering) before fixing on L-profiles.
- ✓ Drilling: Drilling holes for connection, drainage, and ventilation.

▪ Assembling of the Aluminum profile: After the aluminum profile have been cut, routered, punched, milled, and drilled accordingly the next step is frame assembly.
  - Assembly using screw: Joining aluminum sections using mechanical fasteners (connectors), typically stainless-steel screws and connectors.
  - Crimping: In some cases, assembling is done using corner crimping machine for heavy duty doors and large windows, frames sometimes crimped using corner crimping machine that can create strong, seamless joints.
  - Glass stop (Ferma) cutting and installation: Once the main frame assembled, direct manual measurement is taken from the assembled frame and ferma cutting is done as per the measured size one by one and assembled on the main frame.
  - Hardware installation: After assembling of main profile accomplished, the windows/doors are fitted with hardware such as locks, handles, and hinges as required.

▪ Glass cutting: After assembly prosses is accomplished glass dimension is measured and cut as per the frame opening size.
  - Cutting the glass by size
  - Preparing the respective accessories for site installation

▪ Packaging finished aluminum frames and prepared glass: After the aluminum profiles assembled, and glass cut as per the required size, carefully packaged to prevent damage during transportation to the construction site.

▪ Hauling and transportation of the assembled windows /doors. Glass, and accessories to the construction site.

▪ Installation on site: Finished components (window/door) products are installed on the site window/door system (openings) by skilled team of technicians:

▪ Installation of glass with gasket on the installed window/door: Glass panels are installed into the assembled frames in the site. Glazing options, including single or double glazing, using tempered, or laminated glass. Glazing is installed with a rubber gasket to ensure airtight sealing and weather resistance.

- Adjustment and other finishing work.
- Quality control: All finished products undergo quality control process.
- Site Handover: After the hole work is accomplished and ensuring that all products are correctly installed the site is handed over to the client.

4.2 Current state Mapping

4.2.1 Current operations and resource used

Table 4. The main processes, sub process, material and human resources involved in each operation of the aluminum window/door manufacturing processes.

Main Process	Sub-Process	Description	Material Resources	Human resource
1. Material sourcing	- Material Procurement	Sourcing aluminum profiles, glass, and accessary specifications	Supplier contract, quality standards	Procurement specialists
	- Quality inspection	Check raw materials quality	Inspection tools, testing equipment	Quality control equipment
	- Storage	Proper storage of aluminum profiles, glass, and accessories to prevent damage or deterioration t	Storage facilities, racks, pallets	Warehouse staff, inventory manager
2. Design and Customization	-Analyzing the detail drawing	Review and interpret the architectural drawings to understand the window/ door requirements, including dimensions, shapes, and specifications	Architectural drawings, CAD software, design templates	Design engineer, drafter

	-Measuring actual size from the construction site	Take accurate measurement of the window & door opening on site to ensure precise fit and installation.	Measuring tapes, levels, laser distance meter, site plan	Site supervisor, measuring technicians
	-Preparation of shop drawing	Create detailed shop drawings based on the architectural drawings and site measurements, outline the specific dimensions, materials, and fabrication details for each window/door component.	CAD software, drafting templates	Design engineers, drafter
	-Estimating material quantity	Calculate the required quantities of aluminum profile, glass, accessories, and other materials based on the shop drawings and project specifications	Take-off, material cost database	Estimators, project manager
	-Request material	Order the necessary materials from the stockroom or suppliers based on material quantity estimates.	Purchase orders, material requisition, supplier catalogs	Purchasing agents, material planner
	-Prepare manufacturing & installation drawings	Create a detailed manufacturing and installation drawings for the production team,	CAD manufacturing templates,	Design engineers, drafters,

		providing specific instruction for each step of the process.	Installation guides	production supervisor
3. Machining	- Cutting frame	Cutting aluminum profile to precise lengths for window and door frames	Saw(blade), CNC cutting machines	Cutting machine operators
	- Cutting glazing stop profiles (Ferma)	Cut horizontal & vertical glazing stop profiles by respective size of windows/doors frames	Small movable cutting machines	Cutting machine operators
	- Punching	Punching holes for connection and installation	Punching machine	Punching machine operator
	- Drilling	Drilling holes for connection, drainage and ventilation	Drilling machine, drill bits	Assembly workers
	- Millig	Machining edges and surfaces of T-profiles for better fitting during assembly	Milling (Chamfering) machine	Milling machine operator
	- Routering	Creating a hole for lock, handle and other hardware Installation	Routering machine	Routering machine operator
4. Assembly and Glass cutting	- Frame assembly	Joining cut and machined profiles to form the main structure of windows/doors	Fasteners, joint connectors, and assembly jigs	Assembly technicians

	-Crimping	Joining window/door components using specialized tool (Crimping machine) to fold or crimp the aluminum frame, creating a tight connection	Crimping machine	Assembly technicians
	Glass stop (Ferma installation)	Assemble vertical and horizontal glass stop components on the assembled main frame	Sized glass stop components	Assembly technicians
	-Hardware installation	Installation of window and door hardware such as hinges, handles, locks, and other accessories.	Hardware component installation tools	Assembly technicians
	-Cutting glass by size	Cutting glass panels to the specific dimensions required for each window and door panel.	Glass cutting tools, measuring tools	Glass cutters
	- Preparing respective accessories	Preparing the necessary accessories for window and door assembly and installation such as gazing tape, spacers, and wind strippers.	Accessories	Store kipper, material handlers
	-Quality Inspection	Inspecting the assembled window/door unit for any defects, errors, or inconsistencies.	Inspection checklists	Quality inspector, production supervisor

5. Packaging and delivery	-Final packaging	Preparing finished products for delivery, ensuring protection during transit.	Packaging materials, boxes, protective wraps	Packaging staff, logistics coordinator
	-Transportation & delivery	Transportation & delivery of finished products to the construction site	Delivery vehicle	Delivery driver, logistics coordinator
6. Installation on site	-Installation of the assembled window doors frames	Installation of the assembled window doors frames on the construction site	Installation hardware (screws, anchors, fasteners), levelers	Assembly workers, installation crews
	-Installation of glass	Inserting glass panels into the frames.	Glass panels, sealing materials	Glaziers, assembly workers
	- Installation of gasket or silicon	Installation of gasket or silicon on the assembled window/doors	Gasket or silicon	Glaziers, assembly workers
	-Adjustment and other finishing work	Making any necessary adjustments or corrections to the installed windows and doors, such as leveling, caulking.	Levelers, caulking materials	Assembly workers, quality inspectors
	- Quality Control	Final inspection of the installed windows and doors to ensure they are	Checklists, measuring tapes	Quality inspectors

		properly installed, functioning correctly, and meet all quality standards.		
7. Site Handover	- Site Handover	Completing the installation process and handing over the finished windows and doors to the client.	Project documentation, handover checklist	Project manager, site supervisor

4.2.2 Current State value stream mapping

The business planning department of the MIDROC Investment Group's (Vision Aluminum manufacturing department) receives orders from various clients (the government, private businesses, and individual builders) by telephone and Electronic Data Interchange (EDI): The repeat schedule, in which important clients call via EDI, is received approximately twice a month. The open market customers check their warehouse level for inventory every week; if it falls below a predetermined threshold, they call or send in their requirements via EDI.

Making ensuring there is adequate capacity on each unit and that there are enough raw materials available are further aspects of business planning. These are then used to push orders through the production workshop. Truck transportation is used by Vision Aluminum. Shipments are sent to various clients based on their needs. All year round, with the exception of some shutdowns, the workshop operates in a single shift for eight hours six days per week.

The current state map of the production process was shown in Figure 14 below, based on the collected data. The value stream map described two key flows: material and information flows. The operation and data boxes included the number of workers, and uptime. Data on the cycle time for each operation on the production workshop were recorded. This included both value-added and non-value-added activities. Multiple time measurements were collected for each operation, and the average of these measurements was used as the operation's duration for value stream mapping.

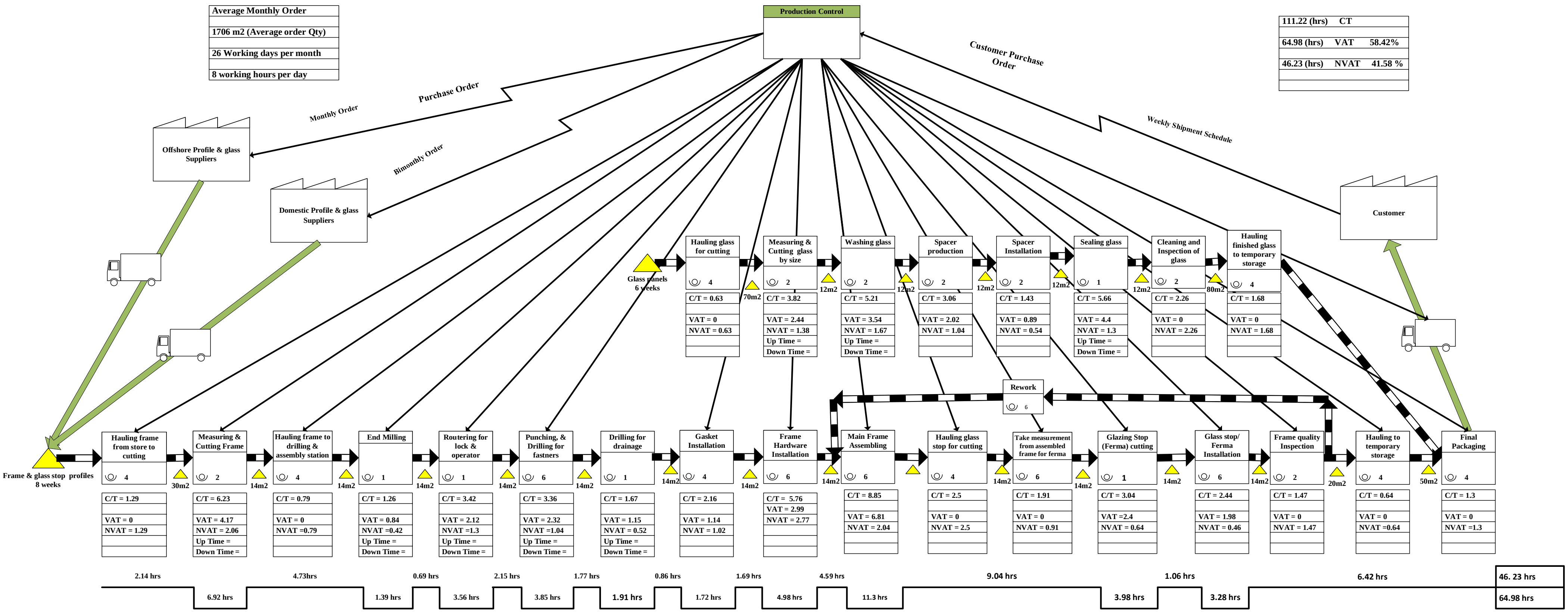


Figure 14. Current State value stream mapping

4.2.3 Current State map analysis

The current VSM was developed using the collected data and summarized in the figure above. The map highlights material and information flows from order receipt up to final product. The main performance indicators derived from the map includes:

- Total cycle time (TCT): 6,670 minutes (13.8 days) per order
- Lead time (LT): 30 days per order
- Value adding time (VAT): 2,801 minutes (5.8 days) per order
- None value adding time (NVAT): 7.96 days (approximately 62% of the total lead time)

When examining Vision Aluminum Manufacturing Plc's current state map, it is observed that the significant difference between the value-added time, and the production lead time. Lean manufacturing aims to improve customer satisfaction by addressing all aspects of the value chain. The research looks for lean manufacturing tools and techniques to reduce them and produce the ideal state map.

Before analyzing the current state map first, it is critical to determine the takt time. “Takt time” refers to the rate at which customers are buying products from the production line; i.e., the unit production rate that must be met to match customer requirements. Takt time is calculated as follows:

$$\text{Takt time} = \frac{\text{Available work time per day}}{\text{Customer demand per day}}$$

From the historical data of vision aluminum manufacturing plc, the average monthly demand of window and door is 1,706m^2. An average of 1,706m^2 windows/doors each month is the throughput needed for the annealed goods. The average daily need, assuming that Vision Aluminum operates 26 days a month, is 65.6m2 windows/doors per day. Vision Aluminum operates continuously for eight hours per day, or 480 working minutes. As a result, the takt time each window is roughly 18.5 minutes:

$$\text{Takt time} = \frac{\text{8hrs x 60min}}{\text{65.6m2}} = 7.3 \text{ min/m}^2 \text{ of window or door}$$

This takt time means that a 1m2 window/door must be produced on average every 7.3 minutes in addition to other types of products. Although the process time depends on the total of the process timings at each workstation, the customer's demand is satisfied in 7.3 minutes for $1m^2$ window and door orders specifically.

Current problems, challenges, and inefficiencies

Inventory: Because the aluminum profiles and accessories are not properly separated or tagged during storage, it is difficult to find particular profiles when needed. Motion waste results from workers spending significant time looking for the necessary items. According to the inventory manager at Vision Aluminum Manufacturing Plc, a frequent stockout caused by poor inventory management disrupts the production schedule. For glass storage, the absence of standardized racks and insufficient protective measures were observed. Additionally, transportation waste is common in glass storage, as glass panels are frequently moved between storage and production areas without optimized workflows. The researcher observed that, there were too much waiting time during material receiving and hauling the profile from the store to the cutting station. This is due to lengthen Bureaucracy of the inventory department and disorganization b/n the store keeper, production supervisor and the laborers those are hauling the profile.

Figure 15. Raw material store

Frame cutting: Aluminum frames are often cut inaccurately due to errors during manual measurement by the machine operator. The available CNC cutting machine can receive saw files. However, the file receiver is not working due to breakdown and not repaired properly yet. Due to this the cutting machine operator measures the cutting dimension and adjust the blade for every varying dimension manually and this is time consuming and errors are common. Delays in cutting process ware observed, particularly during machine setup and cutting operations. Frequent adjustment to accommodate varying frame dimensions were identified the primary cause of these delays. There are three CNC cutting machines on the workshop. However, two of them are not functional currently due to one is total system damaged and not repaired properly, the other is due to only the blade is damaged and new blade is not purchased yet. Therefore, only one CNC cutting machine is working properly. This make the cutting machine station busy and bottleneck for other processes. Another major inefficiency in the cutting process is transportation waste. Due to the storage distance from the cutting stations, materials are transported to and from the cutting area several times. The cause of this problem is an ineffective facility plan that does not give priority to the best possible material flow. During the data collection period, over processing was seen in the form of reworking frame cuttings that had been cut incorrectly.

Figure 16. Profile cutting

In order to reduce the above problems and inefficiencies, the appropriate lean techniques can be implemented. The use of digital measurement can significantly reduce time wastage and defect occurrence probability. The frame cutting machine on the vision aluminum manufacturing plc had the ability to read saw files and cut required lengths accordingly; however, the machinist was not using the saw files to cut, and instead, the worker responsible for set up the cutting machine as per the dimension of a frame manually because the file receiver of the machine is mal-functioned due to breakdown. A strategic plan has to be developed to repair the machine properly and generate saw files automatically to eliminate manual input. The company have automated cutting optimization software for aluminum profiles and glass panels. However, they did not use the output of this software always. Sometimes, they use the window/door drawing for cutting operation and this is time consuming and results material wastage (so many scrubs of profile observed when the cutting is done using drawing only). Excessive delays in repetitive machine setup can be minimized applying set up time reduction technique, such as single-Minute- Exchange of Die (SMED). In addition to the optimization software output, grouping job orders through Kanban system can reduce delays in machine set up. It is critical to redesign the production workshop layout to reduce transportation waste by relocating storage area closer to the cutting work station. The company should establish the preventive maintenance program for the machineries and tools to ensure the available machines properly functional. Finally, implementation of 5S lean principles will improve work place organization, reduce unnecessary motions, and enhance the overall productivity of the workshop.

Routering for lock, Drilling, Punching, Milling processes

Drilling starts simultaneously after some profiles cut. The assembly technicians perform drilling of frame by small movable drilling machines using drill bits one by one and this is time consuming and repetitive errors are common. In the workshop there is big automatic CNC drilling machine. However, this machine is not functioning due to breakdown and not repaired and remains idle for long period. Previously this machine works properly the drilling of profiles, it can drill up to twelve holes once accurately by feeding the file (required dimension and number of holes). If the company properly repair and use this drilling machine it will significantly reduce the drilling time of the profiles and improve the accuracy and reduce the rework probability.

Setup and tool exchanges during routering for lock of window/door frame contributes significant waiting wastage. This delay is due to manual adjustment of dies for different frame and lock type. Punching is done for stronger frame profiles and sliding windows/doors using punching machine. Errors are observed due to misalignment and inaccurate positioning of holes. This leads to time wastage and extra processing. End milling is done for T-profiles of multi frame windows and doors. It was observed that rough and uneven milling surfaces due to dull & broken cutting edges, leading to inaccurate cuts and material damage.

Figure 17. Routering, Drilling, and Milling

Frame Assembly

Frame assembly work is more time consuming than other work processes in the production line. The technicians in the production workshop perform multiple activities in addition to their primary assigned workstation. For instance, the assembly technicians also perform the drilling of profiles manually using drill bits, hauling of sized profiles from the cutting station to the assembly work station, and hauling of finished units from the assembly station to the temporary storage area. The CNC cutting machine operators also perform the routering for lock and end milling of T-frames. This significantly reduce the concentration, influence productivity, and increase fatigue of assembly workers. Therefore, it is better to assign dedicated workers for different activities.

The research observed that, the assembly technicians and their assistant are not doing their job by their full capacity, stand and side talks each other, and this have significant effect on the cycle time of different processes and increase wastage (NAA time). This can be reduced by regular training and careful control by the production supervisor. There is assigned supervisor on the workshop, However, they did not control and supervise all workers as required and the workers are doing their job slowly.

There are some problems and inefficiencies observed during frame assembly process such that: excessive motion, and inconsistency in assembly time. Assembly workers repeatedly search for tools and components due improper organization of workstation, resulting significant excessive motion waste. Components such as profiles, gaskets, and fasteners are often delivered to the assembly line in an unorganized manner, leading to delays as workers sort and retrieve the required parts. Additionally, the absence of standardized organization of work structure results wastage and rework. Inadequate workstation layout and lack of regular training for workers on organized work practice contributes these inefficiencies.

Figure 18. Frame Assembly

To reduce the above challenges, lean tools and techniques should be implemented to enhance the frame assembly process. Redesign and organize the whole workstation based on 5S lean methodology to reduce motion waste and improve components for assembly. Quality controllers also should collaborate with the assembly workers to identify and address issues and defects in early time. Just in time (JIT) lean tool should also be implemented in order to ensure required components are provided to the assembly line. This needs strong coordination between store and assembly teams, in addition visual management tools such as Kanban boards to signal to signal replacement requirements (Shah & Ward, 2007).

Hardware Installation

The assembly workers install the required hardware such as locks, hinges, handles, and arms on the main assembled frame of window/door. Time wastage observed because of respective components are not readily available the assembly workstation when needed, this forcing the assembly technician search for respective parts or wait idle for delivery. This is due to poor inventory management and coordination between the store and assembly teams.

Figure 19. Hardware Installation

The primary issue observed in hardware installation was defects, such as misalignment of components, inadequate fittings, and damage during installation. These defects occur due to unskilled new trainee technicians in the installation process. The root cause of this problem is that, experienced and well-trained technicians leave the company frequently. The human resource department should handle this issue on how to sustain the company workers.

Glass stop (Ferma) cutting & installation

Glass stop cutting is conducted near to the assembly workstation. The assembly technician takes measurement from installed frame. This is because currently they don't do use optimization for glass stop cutting. The assembler takes one ferma measurement, tell the dimension to the cutter, the cutting operator cut that dimension, give the assembler, then the assembler installs the ferma on the assembled frame. This way of work is time consuming. Therefore, glass stop cutting shall to be done by the optimization software and they can improve the time wasted during ferma cutting and installation. There were repetitive reworks observed on ferma cutting & assembly process.

Approximately 8% of ferma work needs rework due to unfitting length due to measurement error and/or cutting error.

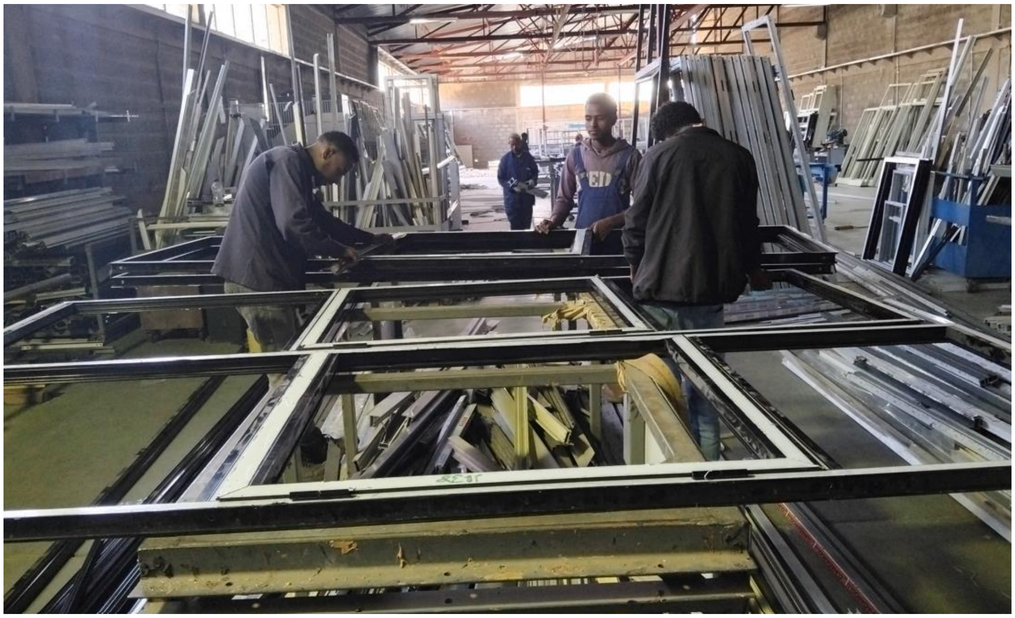


Figure 20. Glass stop (Ferma) cutting & installation

Glass Cutting

Cutting glass panels to the require size is a critical process in production of aluminum windows/doors, which requires precision and efficiency to ensure the glass fits seamlessly into the assembled frames. However, it is subjected to defects and errors that increase the cost and lead time. Lean thinking tools and principles can address these challenges and inefficiencies to optimize the glass cutting operation, minimize observed wastes, and enhance overall productivity (Womack & Jones, 1996). Common challenges observed during glass cutting was material wasting. That was because of inaccurate measurement, improper handling, and cutting errors. Another issue during glass cutting is occurrence of defects, such as cracks, chips, or unfitting edge finishing, which affects the quality of the final product. These defects are caused due to applying excessive force during cutting and handling.

Figure 21. Glass Cutting

To minimize the above problems, some lean principles can be implemented to improve the efficiency of glass cutting process. It is critical to develop and implement standardized work procedures. These should include detail instruction for measuring, marking, cutting, and handling glass to ensure precision and consistency. Regular training program should be scheduled to enhance technicians' skills and ensure the adherence of these procedures.

Quality inspection

In aluminum window and door manufacturing process quality inspection and assurance is a critical step to ensure that the final products meet the required standards for functionality, durability, and aesthetics. Lean thinking can provide a structured approach to streamline the inspection process by eliminating inefficiencies, reducing defects, and improving overall productivity (Liker, 2004).

The occurrence of repetitive defects or errors on the finished products is one of the common challenges in quality inspection process. These defects occur due to unskilled trainee technicians, use of under standard raw materials. Lack of quality control during earlier stages of production, and limited feedback loops between quality inspection team and production teams as primary factor. It was observed that the quality inspectors did not carry out their responsibilities in a consistent manner. Some finished products pass without quality inspection as sent to the construction site and the installation workers found defective products and they are forced to dismantle assembled frames and re assemble after correction work. This extra processing leads wastage of time and increases NVAA.

Lean thinking addresses these challenges by implementing appropriate tools to enhance the inspection process. Applying standard operation procedures (SOPs) will provide clear guideline on the quality criteria to be checked. Poka-yoke, or error-proofing technique, can be integrated into the production process to reduce defects before they reach the inspection stage (Shingo, 1986). Visual management tools, such as checklists and inspection dashboards, can improve communication and organization during inspection process. Checklists ensure that inspectors systematically evaluate all critical aspects of the product, while dashboard provide real time update on inspection results, enables immediate corrective actions.

4.2.4 Root Cause Analysis and Changes Proposal

It is possible to identify the waste on the line from various angles. In this study, the 5 Whys technique is employed to identify the underlying cause of waste. The most often utilized method for determining the root causes is the 5 Whys technique. When used as a tool in lean manufacturing, asking "Why?" five times about a problem helps us better understand it and its nature; hence, "five whys" can lead to "one how" (Ohno, 1988).

For instance, the major problem identified in the production workshop during observation was delay in machine setup for profile cutting operation. The root cause analysis was done by using 5 why root cause analysis technique as follows.

Observed problem: Delay in setup and cutting

- Why 1- Why is the cutting machine operator delayed during machine setup?
  - ⇨ Because there are frequent machine adjustments for different frame type & dimensions
- Why 2 – Why frequent adjustments occur?
  - ⇨ Orders are currently not grouped by similar dimensions.
- Why 3 –Why job orders are not grouped as per their dimension
  - ⇨ Lack of modern efficient production scheduling
- Why 4 – Why is the production scheduling of the workshop inefficient?
  - ⇨ The poor coordination between different departments and absence of scheduling software

Root cause: Poor job scheduling and inefficient production planning

Table 5. Root Cause Analysis and Changes Proposal

Operations	**Issues**	**Root Causes**	**Solutions**
Inventory	Shortage of raw material even through there are many work orders available	Poor inventory management practice by procurement department	Apply good inventory plan (Just in time)
Hauling	A significant amount of time is wasted during material receiving and hauling to cutting station	The raw materials are stored on the workshop randomly	Apply Kanban and 5S lean principle
Cut Frame Profiles	Profiles are too far away in inbound area	No enough space for material, no Kanban system	create proper Kanban system (visual aids, tracking
Cut Frame Profiles	Currently the operator enters the frame, cutting location and set up the machine manually, it is time consuming and mistakes are common	The machine has the ability to cut automatically; however, the file receiver is malfunctioned due to breakdown and not repaired yet	Repair the cutting machine file receiver, create saw files that carry the cutting information, eliminate the manual input & machine setup time
Cut Frame Profiles	Profile cutting is delayed, with excessive material wastage	Sometimes the machine operator used drawing for profile cutting. it is time consuming and mistakes are common	Use always the profile & glass cutting optimization software. This will reduce time and material wastage
Cut Frame Profiles	Rough cutting of profile edge	The machine blade edges are dull and broken	Change the cutting machine blade
Cut Frame Profiles	Extended waiting time for cutting machine recovery during electric power off. Waits up to 15min until the	Electric power fluctuation	Make the power generator stand by when the electric power off, the generator automatically replaces and supply the whole workshop power

	machine gets enough compression air.		
Frame Assembly	Currently frame assemblers wait until the cutting of required frame	Two cutting machines are not working currently due the absence of scheduled repair program. This makes frame cutting a bottleneck in production	use saw files to eliminate manual input time, repair the malfunctioned cutting machines in order to cut by two or three machines
Cut Frame Profiles	the machine requires cleaning, too much scrub dust inside	They do not use the vacuum system (air compressor)	Use the vacuum system for cleaning machines
Machines	Machine and tools deteriorate breakdown	There is no periodic machines and tool repair program	There should be periodic machines and tools repair and replacement program
Drilling	Currently the assemblers drill each frame one by one each hole manually which is time-consuming and mistakes are common.	There is CNC drilling machine and has the ability to drill many holes at a time automatically by receiving drill files, however this machine is malfunctioned due to breakdown and not repaired yet.	Repair the CNC drilling machine, create drill files that carry the drilling information, eliminate the manual drilling by small movable drilling machine
Drilling	Movable drilling machines are too old/slow, need to push down in drilling, pin change too often	Movable tools are too old and need replacement	Tool exchange program, improve feedback system from the line in the workshop from workers
Glass Cutting	Glass is too far away in inbound area	No space for material, no Kanban system	Create proper Kanban system (visual aids, tracking)
Cutting frame	Cutting machine downtime	Cutting machine runs nonstop the whole shift, no time for preventive maintenance schedule.	Create preventive maintenance schedule, improve machine utilization to create machine downtime

Assembly frame	Hauling profiles from cutting station to assembly station is done by the assemblers themselves and this decrease the productivity of assembles	The production human resource management problem	Assign dedicated laborer for hauling of frame from store to cutting station and after cutting to assembly station and after assembly to temporary storage area
Glass cutting	From historical data, 5% of the glasses are damaged during handling and have to be handled carefully	damage through transportation from inbound	work with inbound on transportation standards and training
Install Gasket	excessive gasket wasted during installation	Do not follow standards	Follow standards and training for workers about wastage and productivity
WIP	Random placement of WIP and finished products	No Kanban and 5S system	Apply Kanban and 5S system
Glass stop (Ferma) Cutting	The assembler and glass stop cutter spent a lot of time and waste ferma	The assembler take measurement manually after the main frame assembled and the ferma cutter cut as per this dimension and this is time consuming and dimension errors & reworks are common	Perform ferma cutting as per the optimization software output using small movable cutting machine rather than using CNC cutting machine. This will decrease the rework probability significantly.
Glass stop (Ferma) Cutting	No enough tools in the workshop	Small movable cutting machines are not available in the workshop b/c the installation workers on the site take these machines to use them in the case rework.	Purchase additional small cutting machine for the workshop and for the site
Install Frame Hardware	Waiting for material delivery from inbound	No Kanban ordering system, no automated system to pre-emptively	Make automatic part ordering system from hardware picklist

		stock the line with needed materials	
Glaze Sealed Unit	Missing glass for combination windows	No proper sequencing and labeling for glass	Sequence production on glass line to optimize for production (start with high sequence # and end with low sequence # on the outside of a frame)
Glass cutting	It is difficult for moving full panel glass windows to the cutting area	There is no a designated cart to move heavy glass	Purchase and get a designated cart
Quality Check and Scan	Miss scanning window, mixed up label	Operator training, look at labelling sequences differently for different series	Training of operators, and follow standards

4.3 Simulation Analysis

4.3.1 Developing simulation models

The System Modeling of SIMPHONY CYCLONE template was used to create the simulation models for the current state as well as the suggested future state. The input analyzer of Simphony was used to determine all of the statistical distributions utilized in the simulation, including those for processing times, transfer times, delay times, and others. While real processes are dynamic and more complex, with changes occurring in real time, VSM provides a static and visualization of the process. Simulation is the right tool because it can improve VSM's capabilities by changing the flow's dynamic picture. Both the present and future conditions can be analyzed and assessed using the simulation.

This study models the window/door manufacturing processes using discrete event simulation (DES), because it most closely mimics real production, where materials only change after passing a workstation. The modeling tool is Simphony CYCLONE (CYClic Operations Networks) modelling language (Halpin, 1977), a simulation software created at the University of Alberta.

According to Abourizk et al., (2016) a simulation model should be able to replicate the dynamic responses and behavior of the real system since it is built using the functional relationships and data of the real system. Since Simphony Cyclone is a simulation software program with sophisticated capability, including integrity checks and the ability to track various data points, including cycle time, it was utilized to do the needed simulations.

One of the first simulation languages created for building was CYCLONE. Instead of focusing on a complete construction system, it was primarily designed to mimic construction processes. With this emphasis, the modeling language for assessing construction processes would be simple to learn and rapid to implement. The construction process in CYCLONE is abstracted and represented as operations and processes made up of queues and tasks. Ther collection of directed arrows and graphical modeling elements are used to model the abstracted process. The dynamic element of the building process is then described using virtual entities that represent resources and track their movements within the model. (Abourizk et al., n.d, 2016).

The production of aluminum windows and doors is a repetitive, labor-intensive process that involves a number of interconnected sub processes from preparation to finished product. Based on the operation's current state map, the basic model is built. Each sub process is modeled using the CYCLONE template's corresponding, suitable modeling element (see Table 3). In the model, the labor resources allocated to each sub-process are recognized and included. As previously mentioned, it was challenging to find two identical windows made in the same working day because of the widespread customization. Each operation had numerous variances, which caused the operation time to fluctuate. The "Generate Orders" element formed entities, and each entity's characteristics carried over the order data for each window/door. The event element's coding managed how long each operation lasted when an entity goes through it. The Time Study's collection of both value-added and non-value-added activities was employed in this mode

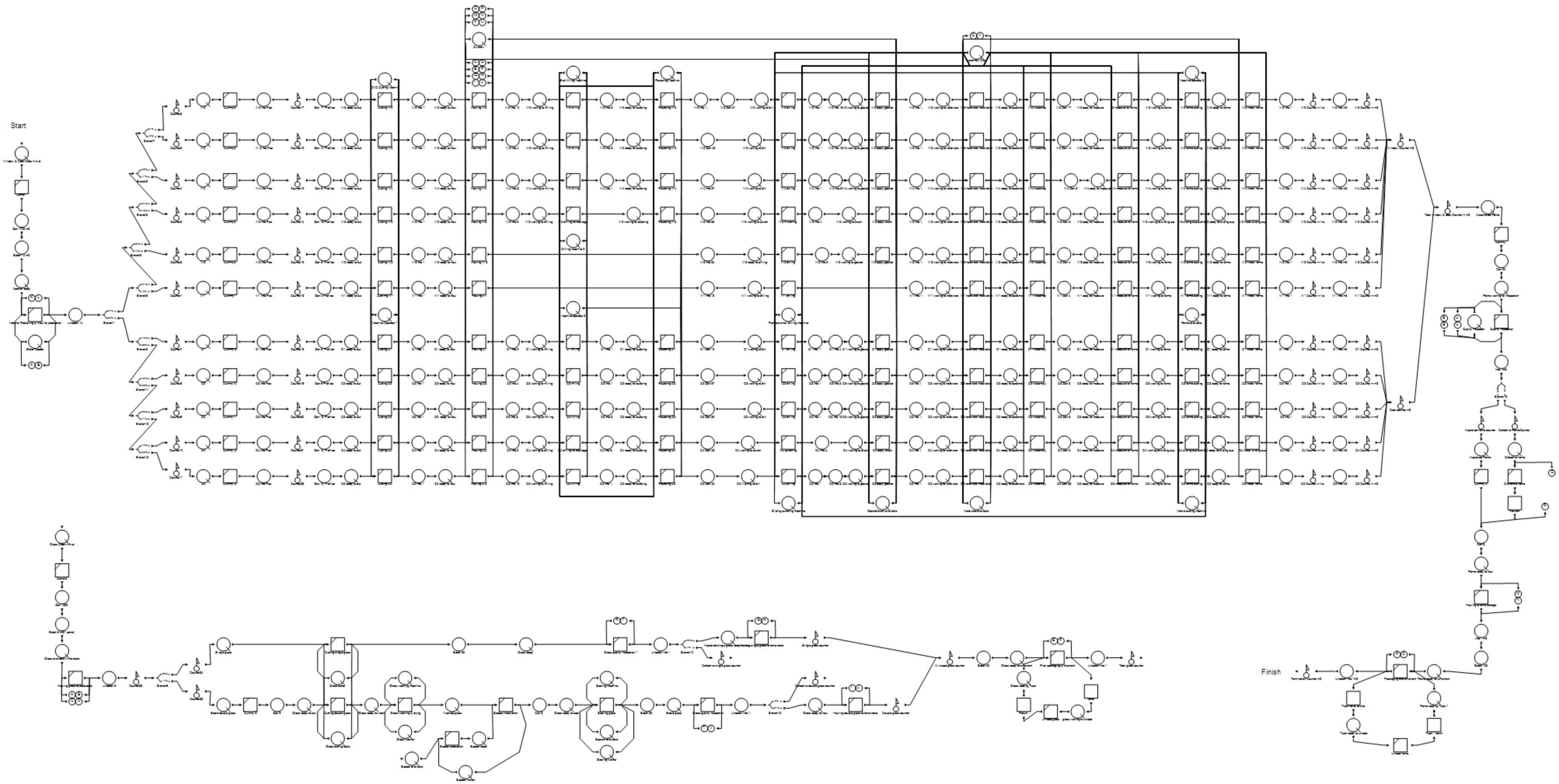


Figure 22. Overall Aluminum window/door production process model developed by Simphony-CYCLO

4.3.2 Data Preparation and Input Modeling

The data used for the simulation of this study was collected from direct observation and previous production records at Vision Aluminum Manufacturing PLC. Creating a simulation model involves more than just using graphics and symbols to describe and depict the complete operation process. It entails accurately gathering and simulating input data from the real-world process for each cycle time, with precisely set parameters. Uncertainty is defined as the generation of model input data and associated parameters, which describe those significant aspects influencing the aluminum window/door manufacturing process.

The analyzer frequently faces the difficulty of gathering and modeling data when assessing any real-world issues. The uncertainty, dynamics, and temporary nature of the majority of construction projects are some of the major elements that can impact the effectiveness of the process in the real world. According to AbouRizk et al. (2016), the real world is neither static nor deterministic; rather, a lot of things happen in an unpredictable way and seem to happen at random. In order to create useful model input data for any type of simulation software, (Banks et al. (2010) proposed four steps: gather input data from the actual operation, choose a suitable data distribution, estimate distribution parameters, and test for goodness of fit data.

4.3.2.1 Input data collecting process

At Vision Aluminum Manufacturing Plc, a time study was conducted in order to achieve the research goals. Raw data is gathered over a number of times for each sub-process. Additionally, a process analysis is conducted at this stage, wherein the resource arrangement and operational sequence are examined. Additionally, documented are the order details and actual productivity. Time study is the process of keeping note of how long each operation takes from start to finish. Current analysis, future planning, and improvement can be carried out using the quantitative data gathered. The time that passed for each sub process was recorded for a period of one month (January 13, 2025 – February 17, 2025) while employees were working, unaffected by their regular work schedule. Additionally, time-lapse images and a video recording of the primary sub process were captured for in-depth examination. Observation by itself rarely provides enough insight into the functioning of the system. As a result, system experts were questioned (Banks et al., 2010).

4.3.2.2 Determine a suitable data distribution

(AbouRizk et al., 2016) and (Banks et al., 2014)B state that the availability of sample data is the first step in determining a probability distribution. One method for determining the form of the underlying distributions is to utilize a frequency distribution or histogram.

A known PDF (probability density function) is gathered in order to create a histogram, according to Banks et al., (2014). The form of the histogram and potential outcomes in the situation under investigation are taken into consideration while choosing a family of distributions. According to (AbouRizk et al., 2016), linking the sample to the theoretical distribution's shape or shape for the distribution family is the simplest method of choosing a statistical distribution as a model for a set of data. Since both show the weight that each sample interval (or sample point) should receive in terms of likelihood occurrence, a histogram created from the sample is comparable to the PDF (probability density function) of the theoretical distribution. This is done in order to correlate the sample's histogram's shape with the known distribution's shape.

4.3.2.3 Determining Distribution Parameters

The distribution parameters that best fit the data must be identified after the distribution type to be used as an input model has been selected. Selecting a suitable approach to estimate the parameters of statistical distributions that fit the data is a crucial matter.

To estimate the parameters of the underlying distribution, one can employ the following methods: least square, maximum likelihood, percentile matching, and moment matching techniques. Various methods frequently provide varying estimations of parameters. Accordingly, the simulator is urged to choose the parameters that yield the best fit and employ all fitting techniques the software offers (AbouRizk et al., 2016). To narrow down the family of distributions to a single distribution and test the resulting hypothesis, numerical estimates of the distribution parameters are required (Banks et al., 2010).

4.3.2.4 Testing for Goodness of Fit

After estimating a distribution's parameters, one should compare the fitted distribution to the empirical distribution and evaluate the quality of fit produced in order to determine whether the distribution is good. The goodness-of-fit test is usually conducted by visual evaluation of the fit or by statistical tests such as the chi-square or Kolmogorov-Smirnov tests (AbouRizk et al., 2016).

Comparing the fitted distribution to the empirical distribution and evaluating the quality of the fit produced are two ways to determine the goodness of fit (AbouRizk et al., 2016; Banks et al., 2010). Based on the null hypothesis that there is no discernible difference between the sample distribution and the theoretical distribution, both tests assess how well the distribution of a sample of generated random numbers matches the theoretical uniform distribution(Banks et al., 2010) (Banks et al., 2010). One crucial challenge is choosing a goodness of fit test to help determine which of the fitted solutions has the best statistical distribution. Two common goodness-of-fit tests used in construction modeling are the chi-square and the Kolmogorov-Smirnov tests. However, visual evaluation of the fit quality is typically used in conjunction with statistical testing and frequently proves to be just as effective as any other test(AbouRizk et al., 2016).

i. Chi-square test

The measurement of the difference between the sample histogram and the fitted probability density function (PDF) forms the basis of the chi-square test. According to (AbouRizk et al., 2016), tests reject the fitted model when the disparity is sufficiently big; if it is minimal, the fit is good. Furthermore, the chi-square test formalizes the intuitive concept of comparing the data's histogram to the candidate density or mass function's shape, according to (Banks et al., 2014). When parameters are calculated using maximum likelihood, the test works with both discrete and continuous distributional assumptions and large sample sizes. The strength of chi-square, according to (Maio et al., 2000), is that it can be used to any kind of distribution function (continuous or discrete) and any kind of input data (sample, density, or cumulative).

ii. The Kolmogorov-Smirnov (K-S) test

The Kolmogorov-Smirnov (K-S) test is especially helpful when the sample size is small and no parameters have been calculated from the data (nonparametric test), according to (AbouRizk et al., 2016) and (Banks et al., 2010). With the estimated parameters, the K-S test determines whether the empirical data might have come from a theoretical distribution (AbouRizk et al., 2016; Maio et al., 2000). Its foundation is the measurement of the greatest difference between the fitted cumulative distribution function and the empirical distribution function determined by the samples. According to AbouRizk et al., (2016) and Maio et al., (2000), the Kolmogorov-Smirnov test is more effective than the Chi-square test since it is independent of the number of intervals and more potent against alternative distributions.

iii. Visually assess the quality of the fit

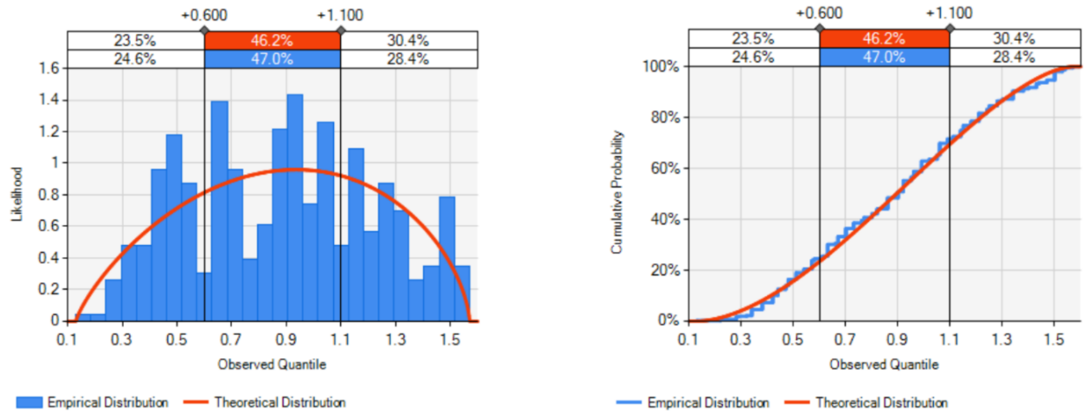
AbouRizk et al., (2016) state that one of the most popular methods for assessing how well a theoretical distribution fits an empirical one is to visualize the quality of the fit. In order to ensure the test findings, the visual evaluation of the quality of fit is typically carried out in tandem with the statistical tests. Plotting the empirical and fitted CDFs together and comparing how well the fitted CDF tracks the empirical one is the straightforward way. As an alternative, we might assess how well the sample histogram's shape matches the theoretical PDF's. Since histograms can be readily twisted to get any desired shape, it is always preferable to use CDF when it is available for comparison.

The four phases must be followed while developing model input data, as stated in the discussion above (4.3.2.1-4.3.2.4). Several academics advise using input data analyzer software for the goodness of-fit test, the process's final stage. Accordingly, AbouRizk et al. (2016) claimed that integrating statistical tests within the fitting program facilitates testing for goodness-of-test utilizing the statistical test. It is both an art and a science to fit a distribution to the data sample. Additionally, Banks et al. (2014)suggested that the researcher employ simulation software when assessing for goodness-of-fit.

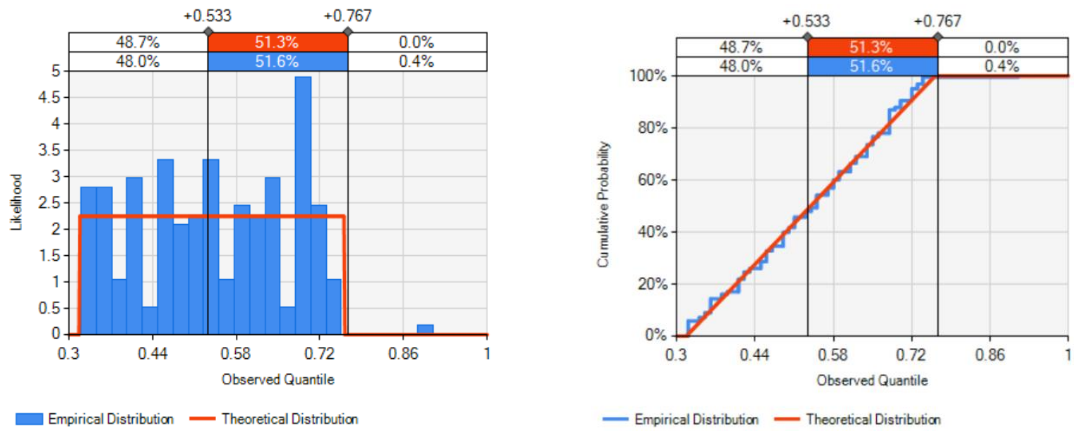
4.3.3 Results of the best-fitting SIMPHONY input data analyzer

The proper statistical distributions are fitted using Simphony's input modeling services. The issues of choosing statistical distributions that are supported by the simulation environment in which the final model is to be constructed arise because the input modeling process is carried out in the same setting as the simulation model development and execution (AbouRizk et al., 2016).

According to AbouRizk et al. (2016), Simphony DES modeling software supports two file formats for importing data to be used in input modeling. These include text files such as notepad and comma-separated values (CSV) files. In both cases, all the data needs to be assembled within one column. Two important issues need to be looked into when performing input modeling. The first relates to the selection of an appropriate method for estimating the parameters of statistical distributions to be fit to the data. The other relates to the selection of a goodness-of-fit test that will guide in the choice of the best statistical distribution from the fitted options.



Theoretical vs. Empirical PDF & CDF for Profile Cutting (Beta Distribution)



Theoretical vs. Empirical PDF & CDF for End Milling(Uniform Distribution)

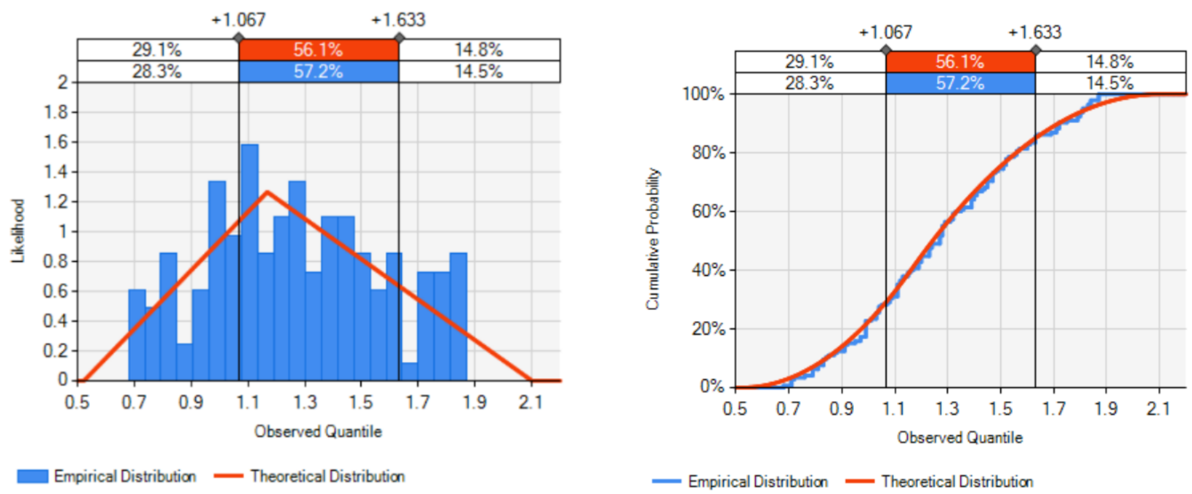


Figure 23. Theoretical vs. Empirical PDF & CDF for Profile Cutting, Punching, and End Milling

The time (duration) of the aluminum profile cutting operation process is represented by the statistical distribution that was automatically fitted and chosen in the above figure. In a similar manner, the Simphony input data analyzer was used to enter the total gathered sample data (cycle times), and the automatically fitted result was chosen as shown in the table below. The results of the works' aluminum manufacturing operation process are displayed in below

Table 6. Fitted Distribution Parameters of Window/Door Production Operation Cycle Time

Window/door production sub operation	Estimation Method	Distribution Fittings		Input data result					Goodness-of fit test		Fitting criteria
		Distribution type	Distribution parameter	Min	Max	Mean	StD	Count	K-S Value	X2 Value	
Hauling profile for Production from Storage Area	Least squares	Uniform (low, high)	Uniform (5.5, 9.4)						0.114	12.61	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (0.959, 2.072, 5.79, 12)	5.79	12	7.75	1.44	62	0.097	12.9	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta (0.959, 2.072, 5.79, 12)						0.097	12.9	
Cutting Profile	Least squares	Beta (Alpha, beta, low, high)	Beta (1.734, .672,0.13, 1.57)						0.053	54.16	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (1.801, .632, 0.13, 1.57)	0.13	1.57	0.88	0.34	415	0.043	77.1	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta (1.801, 1.632, 0.13, 1.57)						0.043	77.1	
Hauling frame to assembly station after cutting	Least squares	Triangular (low high, mode)	Triangular (0.521, 2.10,1.167)						0.043	1.59	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (1.313, 1.318, 0.68, 1.87)	0.68	1.87	1.27	0.31	145	0.053	8.94	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta (0.971, 1.431, 0.9, 1.5)						0.053	8.94	
End Milling	Least squares	Uniform (low, high)	Uniform (0.319, 0.924)						0.049	65.66	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (2.419, 2.063, 0.17,1.02)	0.17	1.02	0.62	0.18	317	0.049	55.32	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta (2.419, 2.063, 0.17, 1.02)						0.049	55.32	
Routering for lock & operator	Least squares	Beta (Alpha, beta, low, high)	Beta (0.960, 0.826, 2.56, 6.77)						0.042	10.37	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (0.961, 0.915,2.56, 6.77)	2.56	6.77	4.83	1.25	254	0.078	16.28	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta (0.962, 0.821, 2.56, 6.77)						0.039	8.5	
Punching	Least squares	Weibull (shape, scale, location)	Weibull (3.951, 0.167, 0)						0.142	787.41	
	Maximum likelihood	Weibull (shape, scale, location)	Weibull (4.178, 0.177,0)	0.05	0.38	0.16	0.04	427	0.113	671.54	Best fit
	Moment matching	Uniform (low, high)	Uniform (0.09, 0.38)						0.105	669.38	
Drilling by small movable drilling machine	Least squares	Uniform (low, high)	Uniform (0.139, 0.362)						0.184	749.22	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (1.981, 1.376, 0.1, 0.38)	0.1	0.38	0.26	0.06	422	0.131	676.07	Best fit
	Moment matching	Uniform (low, high)	Uniform (0.150, 0.379)						0.074		
Drilling external sliding frame for drainage	Least squares	Beta (Alpha, beta, low, high)	Beta (0.841, 1.580, 0.41, 1.16)						0.084	28.55	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (1.033, 1.926, 0.41, 1.16)	0.41	1.16	0.67	0.17	154	0.067	37.64	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta (0.971, 1.431, 0.9, 1.5)						0.067	37.64	
	Least squares	Uniform (low, high)	Uniform (0.309, 0.748)						0.064	27.33	

Apply gasket/ brush	Maximum likelihood	Weibull (shape, scale, location)	Weibull (4.790, 0.589,0)	0.32	0.91	0.53	0.12	223	0.082	26.76	Best fit
	Moment matching	Uniform (low, high)	Uniform (0.316, 0.761)						0.053	51.73	
Install Hardware	Least squares	Triangular (low high, mode)	Triangular (2.784, 12.143,7.551)						0.056	17.17	
	Maximum likelihood	Triangular (low high, mode)	Triangular (3.603, 11.583, 7.27)	4.39	10.76	7.52	1.8	163	0.083	21.23	Best fit
	Moment matching	Uniform (low, high)	Uniform (4.392, 10.652)						0.051	14.36	
Frame Assembly	Least squares	Normal (mean, St Dev)	Normal (20.902, 2.715)						0.096	22.12	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (0.783, 0.767, 7.28, 24.55)	7.28	24.55	15.95	2.27	245	0.097	8.54	Best fit
	Moment matching	Uniform (low, high)	Uniform (14.009, 24.89)						0.091	8.51	
Take measurement for Ferma	Least squares	Triangular (low high, mode)	Triangular (0.07, 0.186,0.154)						0.166	558.75	
	Maximum likelihood	Uniform (low, high)	Uniform (0.07, 0.19)	0.07	0.19	0.12	0.03	418	0.133	558.75	Best fit
	Moment matching	Uniform (low, high)	Uniform (0.065, 0.185)						0.123	558.75	
Cutting Glass stop/ Ferma	Least squares	Beta (Alpha, beta, low, high)	Beta (1.036, 1.133, 0.23, 0.44)						0.113	136.36	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (1.106, 1.063, 0.23, 0.44)	0.23	0.44	0.337	0.058	274	0.071	162.66	Best fit
	Moment matching	Uniform (low, high)	Uniform (0.234, 0.439)						0.077	118.99	
Installing Glass stop/ Ferma	Least squares	Pearson5 (Shape, scale)	Pearson5(39.771, 9.004)						0.153	644.34	
	Maximum likelihood	Cauchy (Location, scale)	Beta (0.236, 0.022)	0.19	0.29	0.23	0.03	410	0.143	644.34	Best fit
	Moment matching	Uniform (low, high)	Uniform (0.234, 0.439)						0.135	644.34	
Frame Quality Inspection	Least squares	Uniform (low, high)	Uniform (7.510, 18.82)						0.057	978	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (1.180, 1.109, 7.08, 19.08)	7.08	19.08	13.26	3.3	100	0.071	9.56	Best fit
	Moment matching	Uniform (low, high)	Uniform (0.234, 0.439)						0.065	7.8	
Hauling Glass panel from store to glass cutting station	Least squares	Gamma (Shape, scale)	Gamma (10.182, 0.242)						0.106	32.5	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (0.742, 0.849, 1.55, 3.65)	1.55	3.65	2.529	0.65	95	0.09	21.93	Best fit
	Moment matching	Uniform (low, high)	Uniform (1.401, 3.656)						0.074	23.22	
Measuring & cutting glass	Least squares	Uniform (low, high)	Uniform (0.520, 1.278)						0.048	31.48	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (0.983, 0.976, 0.53, 1.28)	0.53	1.28	0.9	0.21	245	0.041	34.97	Best fit
	Moment matching	Uniform (low, high)	Uniform (0.530, 1.287)						0.043	30.27	
Washing glass	Least squares	Gamma (Shape, scale)	Gamma (39.93, 0.086)						0.065	1.09	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (0.803, 0.827, 2.72, 4.25)	2.72	4.25	3.47	0.47	44	0.07	3.27	Best fit
	Moment matching	Uniform (low, high)	Uniform (2.656, 4.290)						0.065	2.18	
Sealing	Least squares	Triangular (low high, mode)	Triangular (6.993, 13.401,13.294)						0.077	7.41	

	Maximum likelihood	Logistic (Shape, scale)	Logistic (11.402, 0.839)	8.71	13.27	11.32	1.4	51	0.097	12.71	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta (0.908, 0.677, 8.71, 13.27)						0.085	10.94	
spacer production	Least squares	Weibull (shape, scale, location)	Weibull (7.196, 6.466,0)						0.097	2.51	
	Maximum likelihood	Weibull (shape, scale, location)	Weibull (8.710, 6.471,0)	4.71	7.31	6.1	0.83	41	0.116	10.71	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta (0.759, 0.652, 4.71, 7.31)						0.082	3.29	
Spacer installation	Least squares	Triangular (low high, mode)	Triangular (0.329, 1.329,1.1423)						0.066	2.7	
	Maximum likelihood	Triangular (low high, mode)	Triangular (0.416, 1.333,1.140)	0.51	1.3	0.95	0.2	46	0.064	3.39	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta (1.444, 1.144, 0.51, 1.3)						0.064	3.39	
Glass Cleaning & quality check	Least squares	Triangular (low high, mode)	Triangular (2.19, 2.19,2.19)						0.072	49.89	
	Maximum likelihood	Weibull (shape, scale, location)	Weibull (3.027, 15.245,0)	6.07	23.14	13.56	4.977	146	0.077	40.27	Best fit
	Moment matching	Beta (Alpha, beta, low, high)	Beta (0.83, 1.06, 6.07, 23.14)						0.046	10.01	
Hauling sized glass to temporary storage	Least squares	Triangular (low high, mode)	Triangular (0.521, 2.10,1.167)						0.043	1.59	
	Maximum likelihood	Beta (Alpha, beta, low, high)	Beta (1.313, 1.318, 0.68, 1.87)	0.68	1.87	1.27	0.31	145	0.053	8.94	Best fit
	Moment matching	Normal (Mean, St Dev)	Normal (1.273, 0.312)						0.056	9.48	

4.3.4 Run the SIMPHONY-CYCLONE simulation model

The next crucial step is to run a simulation model after accurate input data analysis has been completed and the best goodness-of-fit statistic distribution has been chosen for the sample data. However, both before and during simulation running, the simulation modeling approach must be examined, including simulation model accreditation, verification, and validation. One of the most challenging issues facing a simulation analyst, according to Banks et al. (2014), is attempting to ascertain whether a simulation model accurately depicts the real system under study, or whether the model is legitimate. The simulation model validation and verification techniques that can be applied at various phases of the simulation model development process are conceptual validation, input data validation, computerized verification, and operational validation. (Banks et al., 2014; Sargent, 2011).

4.3.5 Model Verification and Validation

Simulation models should be able to replicate the behaviors of the real system since they are created using data and observations from the real system. Simulation models will be employed in this study to examine the what-if scenarios and assist in decision-making. It is crucial to evaluate and verify the models to ensure they accurately reflect the real system they mirror because it is expensive for window manufacturing companies to reallocate resources, buy new equipment, and alter the manufacturing process. Figure 4.5 illustrates the connection between simulation and reality. The conceptual model, which has its roots in reality, serves as the foundation for simulation models.

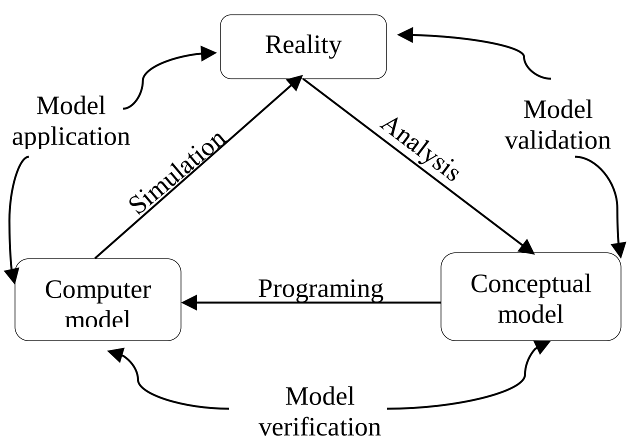


Figure 24. Relationship between Simulation and Reality (Bako & Božek, 2016)

4.3.5.1 Model Verification

According to Sargent, (2010), two verifications must be carried out at the verification stage: 1) Implementation verification to confirm that the simulation model is a valid implementation of simulation model specifications; and 2) Specification verification to guarantee that the attributes and design on the particular computer system can reflect those in the conceptual models. As recommended by AbouRizk et al. (2016), the following errors are examined in order to finish the verification:

- Data errors
- Experimental errors
- Logical errors
- Syntax errors
- Bugs within the models

Keep in mind that verifying whether the model is completely correct and valid might be costly and time-consuming. Rather, a simulation model needs to be deemed valid if sufficient assurance over its attended application is achieved. The figure below illustrates the connection between a simulation model's dependability, model creation effort, and associated value to a user. A fair confidence goal is crucial because, as the figure below illustrates, achieving high model confidence comes at a very high cost while also increasing value in a negligible way. The model will be verified in this study using real production inputs, and the correctness of the model will be assessed by comparing the simulated and real productivity.

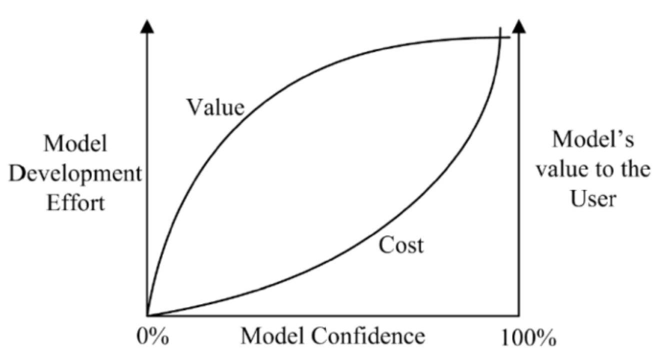


Figure 25. Figure 27. Model Confidence (Sargent, 2010)

4.3.5.2 Model Validation

Historical data validation is the validation approach employed during the validation stage. The number of employees on the production line, the quantity of windows and doors produced daily, and the order information for windows and doors are all tracked by the production system of Vision Aluminum Manufacturing Plc. The model's entities are chosen based on the order information of the windows for the two production days. Eight hours, or one working day, was chosen as the simulation time. The counter element was used to keep track of the total number of sealed units generated at the conclusion of the simulation period. The model uses the following equation to compute productivity, a key performance indicator (KPI). To determine whether the simulation model is accurate, the actual productivity is contrasted with the simulated productivity.

$$\text{Productivity (finished unit/hr.)} = \frac{\text{Total number of finished units produced}}{\text{Total labour hours required (hr)}}$$

A comparison between real productivity and simulated productivity was carried out to verify the model's accuracy after all logical, syntactic, data, experimental, and bug errors had been checked and fixed. Validation for this case study was carried out using the production on May 21st and May 22nd, 2025. As the input for model validation, the scanned completed order data was converted into characteristics and entered into a database. The staff attendance record on the test days served as the basis for setting up the resource arrangement. The table below shows the test results.

Table 7. Simulation Validation Test Results

Date	Employee Number	Produced window/ door Amount (m2)		Productivity m2/labor hour)		Difference (%)
		Actual	Simulated	Actual	Simulated	
May 21st	23	129.8	122.9	0.705	0.668	-5.6%
May 22nd	21	103.4	112.21	0.562	0.609	7.85%

It was observed that the difference between the simulated and actual production on May 21st and May 22nd was less than 5%, and the difference in each day was less than 10%. It was a slight change. The quantity of windows/doors produced on May 21st and May 22nd, 2025, was displayed in Figure below. The validation of the simulation model was deemed successful.

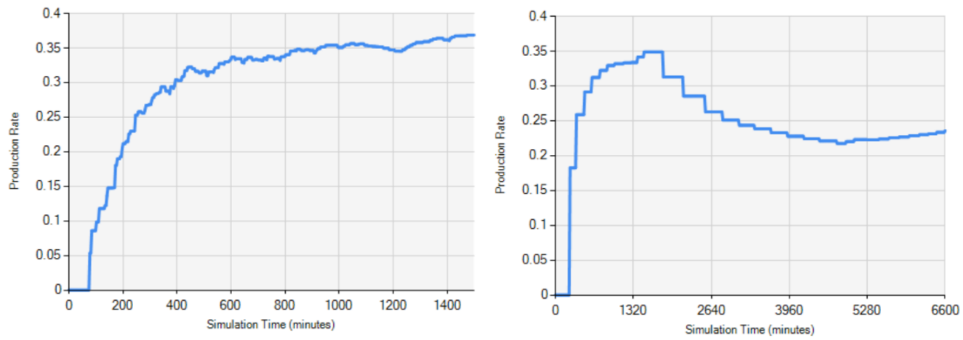


Figure 26. Simulation Production Rate

4.3.6. Simulation Model Output Analysis

The analysis of data produced by a simulation is known as output analysis. Its goal is to either compare the performance of two or more alternative system designs or forecast the performance of a system (Banks et al., 2014). According to AbouRizk et al. (2016), a standard output analysis typically includes figuring out whether the simulation is stochastic or deterministic and whether it represents a steady-state, transient, or static state. For carrying out the extremely thorough analysis, the majority of simulation software providers have included output analysis features in their packages (Banks et al., 2010).

Stochastic simulation, in contrast to deterministic simulation, will yield different results when performed with independent random seeds. To guarantee that an accurate picture of the system under study is given, AbouRizk et al., (2016) state that "this requires one to make a number of runs with independent seeds for the random-number-generating streams" (p. 35). Making decisions based on a stochastic simulation of a system with one replication can be expensive, and according to Law and McComas (1986, as mentioned in AbouRizk et al., 2016), running a stochastic simulation only once is one of the most common risky simulation techniques. According to his discussion, more runs produce more accurate results because:

- The system's characteristics might not be fully disclosed in a limited number of runs (experimental error); and

- As the number of runs increases, the confidence intervals for the mean and variance of the results get smaller. It is a measure of error, and by performing an increasing number of replications, we can simulate away error (Banks et al., 2010).

Accordingly, the researcher calculated the number of necessary runs, conducted analysis using multiple runs, and created confidence intervals for each estimate that was being studied (AbouRizk et al., 2016).

An initial sample size of 20 replications was created after the model was validated and verified; that is, 20 separate replications were created initially, with 10 or more being the preferred initial replication (Banks et al., 2010). In order to seed a pseudo-random number generator using the system time, a seed value was set to zero. This produced a distinct series of pseudorandom numbers each time the scenario was run (AbouRizk et al., 2016). At the significance level, α is taken to be 5%. Therefore, in order to increase the decision maker's confidence in the interval to bound the error between the mean of the normal distribution and the average production time, a confidence interval of $100(1 - \alpha)$ %= 95% was selected. The sample variance of the population was first estimated using the initial replications.

Table 8. Simphony Cyclone Statistics Report for an Initial Run of 100 for Aluminum Window/Door Manufacturing Operation Model

Statistics Report

Non-Intrinsic Statistic

Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Window/Door production (Termination Time)	6,661.49	66.230	100.000	6,477.377	6,818.278

Intrinsic Statistic

Element Name	Mean Value	Standard Deviation	Min Value	Max Value	Current Value
Assembly Crew (Percent Nonempty)	0.802	0.009	0.779	0.823	0.795
CNC Cutting Machine (Percent Nonempty)	0.004	0.000	0.003	0.006	0.004
Defective frame (Percent Nonempty)	0.014	0.009	0.001	0.038	0.033
DL crew (Percent Nonempty)	0.878	0.003	0.872	0.886	0.879
Drilling machine 2 (Percent Nonempty)	0.957	0.002	0.954	0.961	0.959
End Milling Machine (Percent Nonempty)	0.886	0.004	0.877	0.896	0.886

Gasket/brush available (Percent Nonempty)	1.000	0.000	1.000	1.000	1.000
Glass available in the store (Percent Nonempty)	0.207	0.003	0.198	0.215	0.207
Glass cutter (Percent Nonempty)	0.894	0.002	0.890	0.898	0.896
Glass cutting table (Percent Nonempty)	0.894	0.002	0.890	0.898	0.896
Glass loading Truck (Percent Nonempty)	0.919	0.004	0.907	0.927	0.918
Glass Order Arrival (Percent Nonempty)	0.000	0.000	0.000	0.000	0.000
Glass washer (Percent Nonempty)	0.804	0.014	0.770	0.834	0.808
Glass washing machine (Percent Nonempty)	0.804	0.014	0.770	0.834	0.808
Hardware available (Percent Nonempty)	1.000	0.000	1.000	1.000	1.000
Machine Operator 1 (Percent Nonempty)	0.004	0.000	0.003	0.006	0.004
Machine operator 2 (Percent Nonempty)	0.250	0.013	0.213	0.276	0.256
Machine operator 3 (Percent Nonempty)	0.592	0.004	0.579	0.601	0.599
Mobile cutting machine (Percent Nonempty)	0.761	0.004	0.750	0.771	0.761
Portable small drilling machine (Percent Nonempty)	0.977	0.004	0.974	1.000	0.976
Quality inspector (Percent Nonempty)	0.956	0.005	0.944	0.967	0.954
Routering Machine (Percent Nonempty)	0.407	0.011	0.376	0.430	0.412
Sealant available (Percent Nonempty)	1.000	0.000	1.000	1.000	1.000
Sealing machine (Percent Nonempty)	0.823	0.003	0.815	0.829	0.823
Sealing worker (Percent Nonempty)	0.823	0.003	0.815	0.829	0.823
Single glass (Percent Nonempty)	0.106	0.002	0.102	0.110	0.104
Sliding punching machine (Percent Nonempty)	0.831	0.006	0.816	0.848	0.838
Spacer available (Percent Nonempty)	0.248	0.003	0.241	0.257	0.248
Spacer worker (Percent Nonempty)	0.752	0.003	0.743	0.759	0.751
Store Keeper (Percent Nonempty)	0.799	0.003	0.793	0.807	0.800
Washed glass (Percent Nonempty)	0.848	0.011	0.805	0.862	0.805
Window & Door Order Arrival (Percent Nonempty)	0.000	0.000	0.000	0.000	0.000

Counters

Element Name	Final Count	Production Rate	Avg Inter arrival	First Arrival	Last Arrival
D1 Counter in m2	68.000	0.053	13.146	142.202	945.868
D2 Counter in m2	165.000	0.140	5.814	81.494	957.664
D3 Counter in m2	90.000	0.063	10.005	170.345	1,017.423
D4 Counter in m2	88.000	0.052	9.728	75.033	1,183.360
D5 Counter in m2	138.000	0.050	2.646	1,206.777	1,488.510
Defective double glass counter	14.000	0.004	119.574	1,166.566	2,055.268
Defective Frame Counter	96.000	0.014	77.824	235.720	6,588.985
Defective single glass counter	85.000	0.030	8.601	967.666	1,625.528
Door counter m2	549.000	0.315	2.629	75.033	1,488.510

Double glass counter	86.000	0.025	9.952	1,167.544	2,057.129
Single glass counter	1,075.00	0.379	0.640	933.868	1,626.874
Termination Counter m2	1,560.00	0.224	3.854	525.885	6,495.728
Total glass counter	1,140.00	0.381	0.865	999.786	1,867.439
Total window & door Counter in m2	1,683.00	0.275	3.937	43.012	6,684.734
W1 Counter in m2	104.000	0.008	2.431	6,405.735	6,684.734
W2 Counter in m2	157.000	0.037	13.499	43.012	2,552.531
W3 Counter in m2	394.000	0.050	5.677	2,587.514	4,751.157
W4 Counter in m2	214.000	0.020	3.547	4,765.857	5,509.824
W5 Counter in m2	120.000	0.010	3.078	5,549.011	5,901.712
W6 Counter in m2	145.000	0.012	4.146	5,919.140	6,476.211
Window Counter m2	1,134.00	0.112	5.511	43.012	6,684.734

Waiting Files

Element Name	Average Length	Standard Deviation	Max Length	Current Length	Average Wait Time
Assembled Frame	0.000	0.000	0.000	0.000	0.000
Assembly Crew	2.641	0.030	2.708	2.596	0.586
CNC Cutting Machine	0.004	0.000	0.006	0.004	0.001
D1	0.000	0.000	0.000	0.000	0.000
D2	0.000	0.000	0.000	0.000	0.000
D3	0.000	0.000	0.000	0.000	0.000
D4	0.000	0.000	0.000	0.000	0.000
D5	0.000	0.000	0.000	0.000	0.000
Defective frame	0.026	0.025	0.150	0.124	2.060
DL crew	2.869	0.011	2.898	2.871	3.016
Drilling machine 2	0.957	0.002	0.961	0.959	9.666
End Milling Machine	0.886	0.004	0.896	0.886	4.590
Ferma available	99.761	0.004	99.771	99.761	330.943
Frame loading Truck 1	1.947	0.001	1.950	1.947	1,015.822
Gasket/brush available	99.607	0.006	99.621	99.602	193.771
Glass available in the store	29.096	0.433	30.115	29.139	1,140.015
Glass cutter	1.788	0.003	1.796	1.791	1.176
Glass cutting table	1.788	0.003	1.796	1.791	1.176
Glass loading Truck	1.800	0.005	1.810	1.802	62.615
Glass Order Arrival	0.000	0.000	0.000	0.000	0.000
Glass washer	0.804	0.014	0.834	0.808	2.419
Glass washing machine	0.804	0.014	0.834	0.808	2.419
Hardware available	99.131	0.011	99.163	99.121	463.926
Machine Operator 1	0.004	0.000	0.006	0.004	0.001
Machine operator 2	0.250	0.013	0.276	0.256	0.541
Machine operator 3	0.592	0.004	0.601	0.599	0.299
Material ready	8.191	0.139	8.493	8.322	450.914
Mobile cutting machine	0.761	0.004	0.771	0.761	1.073

Portable small drilling machine	0.592	0.004	0.601	0.599	0.299
Quality inspector	1.801	0.007	1.820	1.800	122.317
Routering Machine	0.407	0.011	0.430	0.412	2.917
Sealant available	99.823	0.003	99.829	99.823	1,505.873
Sealing machine	0.823	0.003	0.829	0.823	8.777
Sealing worker	0.823	0.003	0.829	0.823	8.777
Single glass	27.935	1.967	32.321	27.003	159.093
Sliding punching machine	0.831	0.006	0.848	0.838	0.428
Spacer available	40.134	0.510	41.400	40.233	1,272.991
Spacer worker	1.503	0.006	1.517	1.502	0.000
Store Keeper	0.799	0.003	0.807	0.800	0.157
W1	0.000	0.000	0.000	0.000	0.000
W2	0.000	0.000	0.000	0.000	0.000
W3	0.000	0.000	0.000	0.000	0.000
W4	0.000	0.000	0.000	0.000	0.000
W5	0.000	0.000	0.000	0.000	0.000
W6	0.000	0.000	0.000	0.000	0.000
Window & Door Order Arrival	0.000	0.000	0.000	0.000	0.000

*** FURTHER STATISTICS CAN BE OBTAINED FROM INDIVIDUAL ELEMENTS ***

In order to satisfy the half-length requirement, the number of simulations runs required to achieve the required degree of accuracy, R, must be selected so that R > Ro. Therefore, $t_{0.025,14}$ = 2.14 for the 95% CI. The population standard deviation is the standard deviation reported by Simphony, which is displayed in the above table. Consequently, changing to the sample standard deviation:

$$S_0 = \sqrt{\frac{R_0}{R_0 - 1}\delta^2} =$$

In order to estimate the long-term mean to be within $\pm\epsilon$, with a high probability of $1 - \alpha$, an error criterion, ϵ, is assumed to be 1%. Determining the smallest integer R that satisfies R >= R;

$$R \geq \left(\frac{t_{\alpha/2,\mathrm{Ro}-1} s_0}{\epsilon}\right)^2 \ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

$$\mathrm{R} \geq x = \frac{t_\alpha/2}{2a}$$

Since R ≥ 50 is considered a large number of replications, replication of R = 100 ≥ 50 was chosen (Banks et al., 2010).

Assuming Yi are normally distributed, the confidence interval is

Where:

S is the sample variance; R is the number of replications;

H is the half-length of 100(1-α) % (confidence interval width), $t\alpha/2,-1 \sqrt{SR}$, which has to be small to facilitate the decision that the simulation is supposed to support (Banks et al., 2010);

$t_{\alpha/2,-1}$ is the quantile of t-distribution with R-1 degrees of freedom that cuts off $\alpha/2$ of the area of each tail of the normal distribution curve

$$\bar{Y} \pm H \text{……………………...……….... (2)}$$

$$\bar{Y} \pm t_{\alpha/2,R-1}\frac{S}{\sqrt{R}}$$

Where:

S is the sample variance; R is the number of replications;

H is the half length of 100(1-α) % (confidence interval width), $t\alpha/2, -1 \sqrt{SR}$, which has to be small to facilitate the decision that the simulation is supposed to support (Banks et al., 2010);

$t_{\alpha/2,-1}$ is the quantile of t-distribution with R-1 degrees of freedom that cuts off $\alpha/2$ of the area of each tail of the normal distribution curve.

Simphony's multiple-run functionality was used to replicate the simulation experiment 100 times. To obtain a random independent sample of the output parameters, each run was individually seeded. Each of the output parameters in the experiment yielded 100 observations, with the primary parameter of interest being the overall production time needed to finish the job.

Table 7. Simphony Cyclone Statistics Report for an Initial Run of 100 for Aluminum Window/Door Manufacturing Operation Model

Non-Intrinsic Statistic

Element Name	Mean Value	Standard Deviation	Count	Minimum Value	Maximum Value
Window/Door production (Termination Time)	6,661.49	66.230	100.00	6,477.377	6,818.278

Counters

Element Name	Final Count	Production Rate	Avg Interar rival	First Arrival	Last Arrival
Window/Door Counter m2	1,560.00	0.224	3.854	525.885	6,495.728
Total glass counter	1,140.00	0.381	0.865	999.786	1,867.439

6,661.493 ± 1.987 (66.23/ 100) = 6,661.493 ± 1.32

H = 1.32 $\leq \epsilon$ Y = 0.01 $*$ 6,661.493 =66.61, which satisfy the requirement, $P\ (|\overline{Y} - \theta| \leq \epsilon) \geq 1 - \alpha$ = 0.95, where, θ is the population mean. This is in conformity with the actual data observed, 6,661 minutes, or close to fourteen working days. And the production rate is 0.222 m2/min, or 122.91 m2/day.

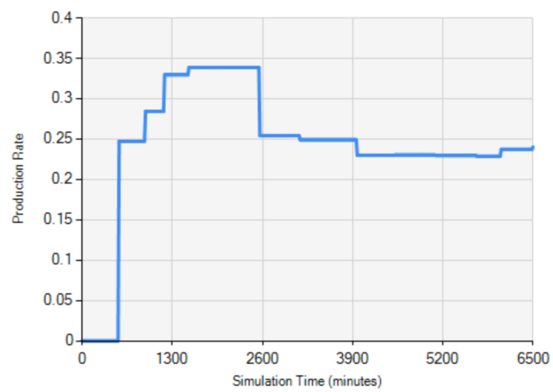


Figure 27. Production Rate vs. Simulation Time of Aluminum Window/Door production Operation Model

4.3.7 Bottleneck identification

All of the resources' utilization rates are computed following the simulation. The figure below displays the resource's utilization report. This allows us to monitor the pace at which all employees and equipment are used on a given working day.

Table 9. Current state DES model resource utilization rate

Statistics Report

Non-Intrinsic Statistic

Element Name	Mean Value	St Dev	Count	Min Value	Max Value
Window/Door production (Termination Time)	6,661.5	66.23	100.00	6,477.37	6,818.3

Intrinsic Statistic

Element Name	Mean Value	St Dev	Min Value	Max Value	Current Value
Assembly Crew (Percent Nonempty)	0.802	0.009	0.779	0.823	0.795
CNC Cutting Machine (Percent Nonempty)	0.004	0.000	0.003	0.006	0.004
DL crew (Percent Nonempty)	0.878	0.003	0.872	0.886	0.879
Drilling machine 2 (Percent Nonempty)	0.957	0.002	0.954	0.961	0.959
End Milling Machine (Percent Nonempty)	0.886	0.004	0.877	0.896	0.886
Frame loading Truck 1 (Percent Nonempty)	1.000	0.000	1.000	1.000	1.000
Glass cutter (Percent Nonempty)	0.894	0.002	0.890	0.898	0.896
Glass cutting table (Percent Nonempty)	0.894	0.002	0.890	0.898	0.896
Glass loading Truck (Percent Nonempty)	0.919	0.004	0.907	0.927	0.918
Glass washer (Percent Nonempty)	0.804	0.014	0.770	0.834	0.808
Glass washing machine (Percent Nonempty)	0.804	0.014	0.770	0.834	0.808
Machine Operator 1 (Percent Nonempty)	0.004	0.000	0.003	0.006	0.004
Machine operator 2 (Percent Nonempty)	0.250	0.013	0.213	0.276	0.256
Machine operator 3 (Percent Nonempty)	0.592	0.004	0.579	0.601	0.599
Mobile cutting machine (Percent Nonempty)	0.761	0.004	0.750	0.771	0.761
Portable small drilling machine (Percent Nonempty)	0.977	0.004	0.974	1.000	0.976
Quality inspector (Percent Nonempty)	0.956	0.005	0.944	0.967	0.954
Routering Machine (Percent Nonempty)	0.407	0.011	0.376	0.430	0.412
Sealing machine (Percent Nonempty)	0.823	0.003	0.815	0.829	0.823
Sealing worker (Percent Nonempty)	0.823	0.003	0.815	0.829	0.823
Single glass (Percent Nonempty)	0.106	0.002	0.102	0.110	0.104
Sliding punching machine (Percent Nonempty)	0.831	0.006	0.816	0.848	0.838
Store Keeper (Percent Nonempty)	0.799	0.003	0.793	0.807	0.800

High productivity requires harmonious collaboration between workstations and a smooth workflow. The utilization rate of resources was determined as: (1-Percent Nonempty) x 100%. When a workstation's workload is higher than usual, it may turn into a bottleneck. A workstation is deemed to be a possible bottleneck in this study if its utilization rate exceeds 90%. The test that follows will be used to ascertain whether a workstation is a bottleneck:

1) To assess the complete capabilities of a single workstation, run a simulation model that only targets that one workstation. Should it be almost equal to the quantity of windows/doors generated each day, then:
2) Increase the bottleneck's resources in the original model to see if overall productivity rises noticeably. The workstation is regarded as a production bottleneck if that is the case.

As can be seen from the above table, the frame cutting station, and routering station had the highest resource utilization rates. Resource utilization rates in the drilling, glass production, and end milling station were low, and the utilization rate of machine operator 3, assembly crew, glass production crew and DL crew is low. This indicates that there are unutilized or underutilized resources in the workshop that should be eliminated after resource optimization. Consequently, the frame cutting station and lock preparation were shown to be the production bottlenecks.

4.4. Lean Concepts and Principles Application

Following the development of the current state models, their validation, verification, and output analysis, the previously suggested lean concepts and principles were implemented in order to observe the improvement in labor productivity. Various scenarios were used to apply the concepts and principles.

I. Scenario 1: - Implementation of Lean Tools which require Low Investment and High Impact

a. Pull-Based Production Control (Kanban System)

It was observed in the case study assessment that the company starts manufacturing activities when customer orders are received. This is in line with the pull system principle in Lean, which says produce to respond to actual demand and not to forecast demand (Womack & Jones, 1996). This keeps overproduction low and also keeps finished goods inventories low. The company’s current "make-to-order" strategy reflects a basic pull mechanism; however, there is no evidence of a formal pull system infrastructure Kanban cards, workload balancing, synchronized flow of materials based on takt time.

The lack of standard production plans, inventory control systems, and visual scheduling boards shows that the idea of pull is not understood at the company and its systematic application is missing. Therefore, this organization does not currently realize the benefits of shorter lead times, smoother flow, and waste elimination that come from an integrated lean-pull system. Especially their inventory is not managed properly. The researcher observed that a lot of profiles, glass, and accessories in the material store which is not necessary in the main time. On the other hand, it was observed that shortage of critical profiles or accessories which was urgently required in the main time was missed after receiving orders and started work. Due to this workshop workers are waiting for the required material which significantly increase the lead time of the order and cause customers unsatisfaction. The above observed problems can be reduced by applying good inventory management practice and pull based Kanban system.

Using supermarkets or a Kanban system, Vision Aluminum will be able to decrease inventory and, consequently, lead time. The Kanban system operates under simple but efficient conditions. Additionally, shorter lead times results quicker deliveries and happier clients. In addition to reducing the quantity of defects on the workshop, the supermarket will expedite the process of defect identification, increasing the likelihood of identifying the problem's underlying cause early.

Early defect detection is crucial, especially in the manufacturing of aluminum windows and doors, since frames gain value as they proceed downstream in the process, and late fault discovery can be highly expensive. Another advantage of the supermarket is that it gives those working on the floor a visual way to manage inventory and respond quickly in the event of an emergency. It is evident that a Kanban-controlled supermarket system can identify a variety of wastes on the shop floor, allowing for corrective action to be taken to lessen or completely eliminate these wastes.

b. Workplace Organization/Standardization using 5S methodology and Production Scheduling

From the beginning of production process in the material storage area profiles are not places and sorted properly. Daily laborers spent extended time on searching the required materials due to the random arrangement and mix-up of profiles and accessories. After receiving the required amount and type of profiles and accessories daily laborers haul to cutting station through their hand which is time consuming and inefficient. Purchasing small cart to transport one batch profiles from store to cutting station is recommended. Inside workshop's cutting and machining stations a lot of unnecessary junk of materials (profiles, unfunctional machineries, scraps, etc.) make the workshop congested and not suitable for workers to perform their activity freely, cause significant delay and decrease overall productivity of aluminum window/door production. Workers especially assembly workers and daily laborers spent a lot of time on stopping and talking each other due to lack of strict control and supervision. The existing cutting and machining tools are completely disorganized at the entire workshop. The production workshop is characterized by a disordered work floor, old machinery taking up space, and tools scattered around. In this case, a lean tool is suggested: first, a 5S program to provide a space for the tools used in the machining and cutting operations.

The 5S methodology will first be investigated in the area used for machining and raw material storage. Sort is the first 5S element. Sorting crucial items from non-essential ones for the workspace is the first step in good housekeeping. Only the tools required for the production process should remain in the workshop; this includes both raw materials and instruments employed in the process. The same is true for the machining area, where defective fixtures, damaged machinery, and unnecessary tools are to be eliminated. Eliminating everything that won't be used in the next days is a smart place to start. Items that are not needed are marked with a red tag. the date and the purpose of the tag. A red tag has to be put on any item where there is uncertainty. Following the red-tagging process, the workshop staff must decide if the objects should be sent to a discharge area, the repair shop, or another location. The things that need to be taken out must have their own discharge space. For instance, broken tools ought to be sent to the repair shop or the discharge area.

Straighten is the second element of the 5S. Straightening entails maintaining order and reducing congestion so that all tasks may be completed quickly and easily. Following the removal of all unnecessary items, the necessary tools must be arranged as efficiently as feasible. First and foremost, there should be a clearly defined and assigned space for the arrangement of all tools, machinery, and raw materials. This space should be clearly marked by painting a rectangle around it, and it should be accessible to the employees. The size must be marked on any item that has a specific storage location. This is also for the machining workstation. To enable speedy transfer whenever a changeover is required, the cutting machine must be positioned relatively close to the machining station. Every machine and tool need to have a label. To reduce transportation and speed up work, the tools, fittings, and accessories required for the frame should be positioned near the actual workstation.

The third component of 5S is sustain. Cleaning the workspace is the next step once the machinery, tools, and raw materials have been positioned correctly. It has to do with maintaining the improvement by keeping the workplace neat. Machines, tools, supplies, equipment, fixtures, floors, and walls are all part of cleaning. Machines should be cleaned of dirt, oil, and stains. Cleaning is required in the areas where red-tagged items were removed. Upon inspecting the machining area, everything appeared to be dirty and disorganized. The machining area is situated close to the assembly station, so it is no accident that it is dusty. Dust is expected on the aluminum production workshop. The floor, walls, equipment, and machines are all major cleaning targets. Cleaning ought to be done every day. Cleaning equipment and tools helps identify malfunctioning parts, including loose nuts or cracked covers, so that these issues can be fixed right away. To make cleaning a team effort, various employees should be given varied cleaning tasks. Simple measures like covering cords, fixture legs, and table legs can help keep dirt out of tools, materials, machinery, and fixtures and make cleaning them easier.

Systematize is the fourth component of the 5S. Systematize refers to ongoing efforts to improve the first three 5S elements. After being used once or twice, kaizen efforts in the workplace continue. Instead, it is an ongoing endeavor to improve. To ensure that workers are sorting, straightening, and shining, procedures should be established. It is simple to carry out kaizen initiatives once at work and see the results. However, it must be done consistently to keep the improvement going; otherwise, things will revert to their previous state. How can Vision Aluminum accomplish this? To check if all 5S initiatives are being followed, a team of two persons (for this case study quality inspectors) can be deployed to the cutting and machining areas to perform weekly audits. It is often difficult to get results in the beginning of a new project, thus it is crucial to create a checklist or assessment form to monitor these efforts. The table below displays a 5S assessment document that can be implemented in Vision Aluminum. Weekly assessments of 5S program's present state can be conducted using this checklist sheet, and improvements and remedial measures can be implemented as necessary.

The final 5S component is standardize. Standardization is a way to maintain and follow 5S guidelines. Supervisors must to establish guidelines and enforce adherence to them. At the cutting and machining areas, workers should be held responsible for implementing 5S practices.

Moreover, excessive waiting also observed especially on punching and assembly workstation due to poor workflow, poor production Scheduling and prioritization management. These, problems can be minimized by applying Production Scheduling. After cutting of profiles, it was observed that the assemblers spend a lot of time on searching the correct profile to assemble. It was also observed that sometimes when the assembler tries to pick up the sized profile from cutting station to move it to assembly station, they find out that it is not the right profile, a profile without a label, or a profile with the wrong label information. Most of the mistakes happen at the beginning of the line when the profile is cut and labeled.

c. Cellular Manufacturing

The layout of overall workstation is inefficient due to parallel and far apart arrangement of workstations and machineries. Unnecessary motions and transportation from one workstation to another workstation is observed and common. These problems can be reduced significant by applying cellular manufacturing lean tool. Therefore, it is better to redesign the workshop layout (U-shaped layout) is recommended. If the workstation is redesigned as u-shape, the activity such as "hauling sized frame from cutting to machining work station" will be eliminated and other unnecessary excessive motions and transportations will be decreased significantly.

d. Setup Time Reduction (SMED Principles)

In vision aluminum delay due to machine set up and changeover is critical issue during observation. Especially CNC cutting machine and punching machine needs frequent set up and adjustment while changing profiles. During power fluctuation period (when the electric power off) CNC cutting machine needs 10-15minute to restart because most machines in the workshop run by both electric and air compression power. During the electric power off suddenly the machine losses the compressed air quickly and needs time up to re fill the required amount of air compression and therefore this cause overall delay and reduce window/door productivity. This problem can be eliminated by using standby power supplement generator during power fluctuation.

The proposed setup reduction procedure explained in the future state map will enable vision aluminum to drive their changeover times down. Again, the changeover reduction times were selected based on a reasonable and optimistic approach, with values that are realistic for vision aluminum to drive their changeover time down according to the procedures explained in the future state map.

e. Total Productive Maintenance (TPM)

TPM environment can significantly reduce random machine breakdowns and in turn, inventory and lead-time. First, if production workers at each machine learn how to carry out the job of simple monitoring maintenance at each machine this would directly improve the availability of the machine. By doing so, the production workers who would be the best judges of the condition of the equipment would address the issue immediately. This in turn would minimize the risk of having a machine break down if things were postponed.

It is supposed that implementing TPM at vision aluminum would significantly reduce machine breakdowns and minor stoppages. The question is by how much? the data provided to during data collection by vision aluminum are based on operators' judgment. Therefore, the researcher makes an estimation from literatures and his own judgment that with TPM the unplanned breakdown would go down 25 to 50%. As one study revealed, equipment monitored using TPM experienced a failure rate of 25% of that for unmonitored equipment (Moore, 1997).

f. Error-Proofing (Poka-Yoke)

Poka-Yoke, meaning "error-proofing", is a Japanese method of preventing errors right at their source by ensuring that it is either very difficult or altogether impossible to perform a task incorrectly (Shingo, 1986). This enables the lean goal; quality at every stage without final inspection.

In the case study company, common errors in incorrect profile cut, misalignment, and wrong part assembly occur quite frequently. This is largely attributed to manual operations and no built-in error-prevention systems. Currently the company does not have formal Poka-Yoke implementations. Mostly reactive quality checks that become identified after the defects have occurred. Increased rework, waste, and lead times result.

Proposed Poka-Yoke solutions:

- ✓ Length stoppers for accurate profile cutting or digitalization of CNC cutting machine
- ✓ Orientation jigs to avoid mis assembly
- ✓ Color-coded parts to prevent mix-ups
- ✓ Drill templates for precise hole placement

Based on the studies and observational findings for implementing lean manufacturing principles, the application of Poka-Yoke tools can reduce the defect rate in manual and semi-automated processes to around 50–70% (Shingo, 1986). Considering the current dependence on visual inspections and rework in the case study company, this level of simple manual inspection error proofing can be accomplished using basic low-cost tools at profile cutting, drilling, and assembly workstation. Based on the above reference for this case study 60% of defect reduction was assumed and the decreased amount of defect percentage was applied on the improvement scenario of DES model. This decreases the rework time and increase the overall productivity and efficiency of aluminum window/door production.

The productivity improvement was done by implementing the above discussed lean tools that needs low effort to implement practically but have great gains or benefits such that Kanban pull system, work place organization & standardization, production scheduling, 5S methodology, Cellular manufacturing (workshop layout redesign), setup time reduction, TPM, Poka-Yoke. These principles applied simultaneously because the application of one prompts the other and so on. The implementation of these lean tools helps to eliminate & reduce different none value adding activities, unnecessary extra processing and wastes like unwanted transportation, motion, defects, inventory, and overproduction. For this case study each sub processes cycle time are sub decided into VA, NVAR, and NVA time. Then after the implementation of the above lean tools automatically eliminate or significantly reduce those none value adding activities. Doing do, a reduced amount of cycle time was obtained by eliminating unnecessary activities. Finally, the reduced cycle time was used on DES model and the improvement was calculated. As per the result of DES model implementation of the above tools improved the vision aluminum manufacturing plc's productivity by 22.4%. This is a very good improvement without a strategic and cost consuming changes.

Table 10. Simphony CYCLONE Statistics Report after implementation of Lean Tools which require Low Investment but results high impact on productivity improvement for 100 Run Count

Non-Intrinsic Statistic

Element Name	Mean Value	Standard Deviation	Count	Minimum Value	Maximum Value
Window/Door production (Termination Time)	5,195.04	55.36	100.00	5,058.28	5,311.94

As discussed above the cycle time of current state Simphony CYCLONE model was 6,670.02 min, and the production rate was 0.222 min/m2. A notable improvement in the overall cycle time was obtained after the implementation of the aforementioned lean concepts. The cycle time decreased to 5,195.04 minutes, and the production rate increased to 0.287 m2/min, or 137.76 m2/day, as shown in the above table.

Improvement (%) = $\left(\frac{6{,}670.02\text{ min} - 5{,}195.04\text{ min}}{6{,}670.02\text{ min}}\right) x100\%$ = 22.11%

The result shows the implementation of the above lean tools which require low investment to apply improve the overall productivity by 22.11% compared to the current state production output.

Figure 35

Production Rate vs. Simulation Time after implementation of Lean Tools which require Low Investment but results high impact

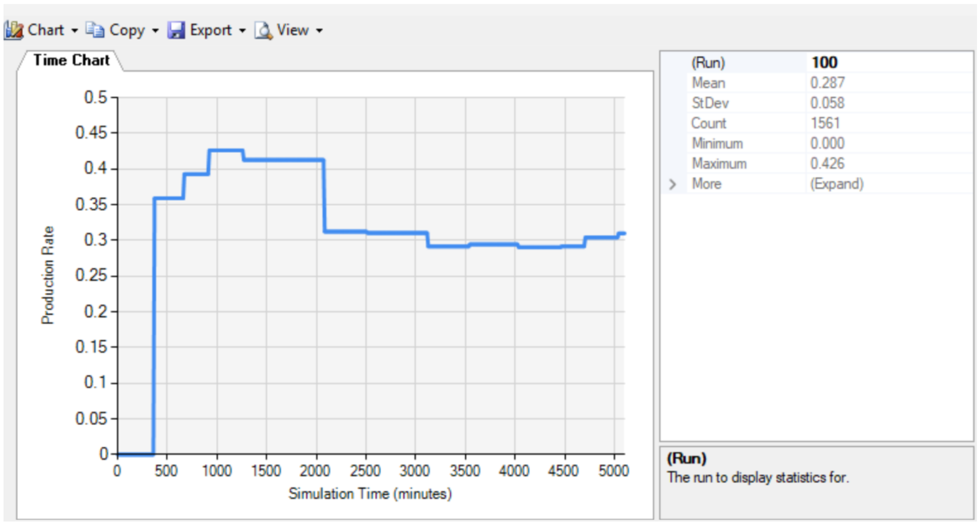


Figure 28. Production Rate vs. Simulation Time after implementation of Lean Tools which require Low Investment but results high impact

II. Scenario 2: Implementation of Strategic Changes through Machine Repair and Digitization to Eliminate Bottleneck

This Scenario targets major bottlenecks by implementing high-impact but cost-intensive interventions.

a. Repairing Unfunctional Machines (CNC cutting, and Drilling machines)

There are two unfunctional CNC frame cutting machines and one CNC drilling machine in vision aluminum window/door production workshop. As clearly observed on the current state DES model frame cutting operation is identified a bottleneck operation which cause waiting of downstream activities until the required frame cutting operation performed. By restoring the functionality of these machines, it is proposed to increase the productivity of frame cutting operation as well as overall production of the workshop. From the two unfunctional CNC cutting machines the researcher proposed to use one for main profile cutting and the other for Ferma (glass stop) cutting instead of cutting Ferma (glass stop) using small mobile cutting machine. The use of this automated CNC cutting machine could reduce the cycle time of Ferma cutting operation significantly. In the DES mode the addition of one CNC cutting machine doubled the productivity of frame cutting operation.

As observed on the current state operation of vision aluminum window/door production drilling for fastener operation was performed by assembly technicians using small mobile drilling machines manually which cause repetitive errors and reworks. Repairing this unfunctional drilling machine and use it for drilling operation improved the cycle time and reduce defect & rework rate which was common during current state manual drilling operation. The drilling machine can drill/punch multiple holes at a time. Dedicated CNC cutting and drilling machine operators should be assigned after unfunctional machine repaired.

b. CNC Cutting Saw and Drilling files

Vision aluminum manufacturing plc owns three CNC aluminum cutting machines and one drilling machine on which one cutting machine and the drilling machine are capable of receiving digital files (saw files & drilling files) from software. However, the file receiver (communication port) is not currently working due to machine breakdown. Due to this, the machine operators forced to manual setup & adjustment of machine, set angle & dimensions results extended and repetitive machine set up, excessive material waste (profile scraps), defects & reworks (dimension errors) are common. This strategic change and improvement scenario by repairing unfunctional machines file receiver and restore their automation design to production workflow via software by importing saw and drilling files. The implementation of this scenario could reduce the cutting and drilling operations significantly, minimize defect error, improve accuracy and consistency. Therefore, the researcher strongly recommends to repair the CNC cutting machines and drilling machine file receiver as it will improve overall workshop productivity and pay off the repair investment within few months due to labor and material saving.

c. Glass stop cutting using CNC cutting machine using Optimization Software

From the two non-operational CNC cutting machines the researcher proposed to use one for main profile cutting and the other for Ferma (glass stop) cutting instead of cutting Ferma (glass stop) using small mobile cutting machine. The use of this automated CNC cutting machine could reduce the cycle time of ferma cutting operation significantly. Currently class stop (Ferma) cutting operation done by small mobile cutting machine manually. Before, actual cutting operation, none value adding and unnecessary work around observed that delays the operation time significantly. The strategic plan is to use the repaired CNC machine for glass stop (Ferma) cutting operation instead of manual mobile cutting machine. Additionally, ferma cutting operation shall be done by using cutting optimization software output as frame cutting. Using the optimization software to cut the activity specified (measuring dimension for ferma from assembled main frame) will be automatically emanated.

d. Automated glass cutting

Vision aluminum manufacturing plc currently uses manual glass cutting method for the production of customizes window/door products. The researcher observed this manual method is high labor intensive, safety concerns and it results delay of class production and caused for repetitive errors and defects. The proposed automation for glass cutting will improve the above problems on which increase productivity of glass, consistent quality and precision, reduction waste and rework and improve safety for operators. Based on DES model analysis result, automated CNC glass cutting machine improved glass cutting operation by 1.9% improvement on overall glass production operation. However, since the initial cost of this machine is very high and glass production process is not bottlenecking this scenario is not recommended due to high initial capital investment.

After implementing the above strategic change scenario, the total cycle time becomes 3,534.48 min and production rate equals to 0.322 m2/min or 154.56 m2/day.

Table 11. Simphony CYCLONE Statistics Report After implementing the above strategic change scenario

Non-Intrinsic Statistic

Element Name	Mean Value	Standard Deviation	Count	Minimum Value	Maximum Value
Window/Door production (Termination Time)	3,534.48	52.35	100.00	3,395.56	3,650.18

The cycle time of Simphony CYCLONE model after implementation of first scenario (Lean tools which require low investment) was 5,195.04 min, and the production rate was 0.222 min/m2. Further significant improvement in the overall cycle time obtained after the implementation of second scenario (Strategic changes). The cycle time decreased to 3,534.48 minutes, and the production rate increased to 0.322 m2/min, or 154.56 m2/day, as shown in the above table.

Improvement (%) = $\left(\frac{5{,}195.04 \text{ min} - 3{,}534.48 \text{ min}}{5{,}195.04 \text{ min}}\right)$ x 100% = 31.96 %

The result shows the implementation of the above strategic changes which require higher investment to apply compared to first scenario. These strategic changes improve the overall productivity by 31.96 % further compared to the first scenario production output.

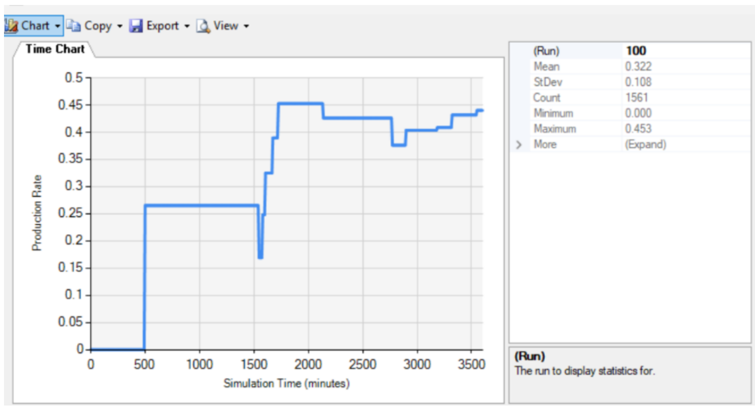


Figure 29. Production Rate vs. Simulation Time graph after implementation of strategic Changes through machine repair and digitization

III. I. Scenario 3: - Line balancing (Labor Optimization)

This scenario tries to improve the workshop labor productivity by labeling the available human resources. Doing so, there are some laborers that are idle for long period of time (Lower utilization rate). Laborers that have very low utilization rate was eliminated and production/man hours was improved. There are extra workers that are not fully utilized in the workshop while they are paid monthly salary without utilizing them efficiently.

Bottleneck identification after lean tools application

The potential bottleneck should be checked after implementation of lean tools and strategic changes. After the simulation run of the second scenario, the utilization rates of all the resources are calculated. The resource's utilization report is shown in Figure below. This enables to track the utilization rate of all workers and machines on a certain production day. This part of the analysis was used to identify any existing bottlenecks in the production flow. Currently 23 labor resources (machine operators, daily laborers, and different technicians) are directly involved on aluminum window/door production process. The utilization rates of all resources on the workshop are shown on the figure below in Figure. The productivity of the production line was 0.84 m2/labor hour.

Table 12. Resource utilization rate after implementation of strategic changes

Counters

Element Name	Final Count	Production Rate	Average Interarrival	First Arrival	Last Arrival
D1 Counter in m2	58.000	0.085	10.890	42.364	556.790
D2 Counter in m2	183.000	0.164	9.494	38.536	1,489.411
D3 Counter in m2	85.000	0.030	8.825	109.617	1,496.407
D4 Counter in m2	92.000	0.031	3.517	1,496.661	1,503.326
D5 Counter in m2	144.000	0.049	1.092	79.702	1,532.883
Total Door counter m2	562.000	0.271	2.771	38.536	1,532.883
W1 Counter in m2	99.000	0.018	1.818	2,707.776	2,775.370
W2 Counter in m2	144.000	0.048	10.227	23.735	1,641.720
W3 Counter in m2	414.000	0.090	4.059	1,642.242	2,882.697
W4 Counter in m2	190.000	0.031	1.420	2,885.624	3,187.623
W5 Counter in m2	116.000	0.017	1.392	3,199.106	3,393.615
W6 Counter in m2	160.000	0.023	1.246	3,402.599	3,612.193
Total Window Counter m2	1,123.000	0.197	3.068	23.735	3,612.193
Defective Frame Counter in m2	26.000	0.006	104.630	150.584	3,574.667
Total window & door Counter	1,560.000	0.322	1.918	490.250	3,544.451
Single glass counter in m2	1,162.000	0.660	0.416	561.874	1,021.374
Double glass counter in m2	137.000	0.055	6.573	708.755	1,563.694
Defective single glass counter	38.000	0.022	13.466	561.117	1,020.042
Defective double glass counter	4.110	0.001	1.037	796.245	1,185.520
Total glass counter in m2	1,290.000	0.424	1.166	607.403	2,120.013

Non-Intrinsic Statistic

Element Name	Mean Value	Standard Deviation	Observation Count	Minimum Value	Maximum Value
Window/Door production (Termination Time)	3,534.48	52.35	100.000	3,395.55	3,650.18

Intrinsic Statistic

Element Name	Mean Value	Standard Deviation	Minimum Value	Maximum Value	Current Value
Assembly Crew (Percent Nonempty)	0.470	0.023	0.411	0.531	0.510
CNC cutting Machine 1 (Percent Nonempty)	0.267	0.009	0.245	0.290	0.286
CNC cutting machine 2 (Percent Nonempty)	0.679	0.008	0.660	0.696	0.688
CNC drilling machine (Percent Nonempty)	0.948	0.032	0.919	1.000	0.931
DL crew (Percent Nonempty)	0.859	0.007	0.840	0.873	0.868
Drilling machine 2 (Percent Nonempty)	0.934	0.002	0.927	0.941	0.935
End Milling Machine (Percent Nonempty)	0.823	0.006	0.807	0.838	0.821
Glass cutter (Percent Nonempty)	0.864	0.003	0.858	0.872	0.871

Glass cutting table (Percent Nonempty)	0.864	0.003	0.858	0.872	0.871
Glass loading Truck (Percent Nonempty)	0.567	0.010	0.539	0.589	0.573
Glass washer (Percent Nonempty)	0.706	0.022	0.651	0.767	0.767
Glass washing machine (Percent Nonempty)	0.706	0.022	0.651	0.767	0.767
Machine Operator 1 (Percent Nonempty)	0.267	0.009	0.245	0.290	0.286
Machine operator 2 (Percent Nonempty)	0.021	0.009	0.010	0.048	0.014
Machine operator 3 (Percent Nonempty)	0.425	0.006	0.411	0.441	0.433
Quality inspectors (Percent Nonempty)	0.940	0.007	0.920	0.955	0.941
Routering Machine (Percent Nonempty)	0.264	0.008	0.248	0.286	0.259
Sealing machine (Percent Nonempty)	0.619	0.029	0.545	0.697	0.697
Sealing worker (Percent Nonempty)	0.619	0.029	0.545	0.697	0.697
Punching machine (Percent Nonempty)	0.746	0.008	0.726	0.772	0.746
Spacer worker (Percent Nonempty)	0.684	0.005	0.673	0.695	0.675
Store Keeper (Percent Nonempty)	0.767	0.004	0.758	0.775	0.772

The resource utilization rate can be calculated as: - (1- Percent Nonempty) x 100%

Resources

Element Name	Average Utilization	Standard Deviation	Minimum Value	Maximum Value	Current Value
Human Resources					
Assembly Crew	53.00%	97.66%	58.91%	46.90%	6.00
DL crew	14.12%	99.30%	15.97%	12.72%	4.00
Machine Operator 1	73.28%	99.10%	75.47%	70.98%	2.00
Machine operator 2	97.88%	99.14%	99.00%	95.15%	1.00
Machine operator 3	57.47%	99.38%	58.92%	55.88%	1.00
Quality inspector	5.97%	99.27%	8.04%	4.51%	2.00
Glass cutter	13.56%	99.73%	14.20%	12.85%	2.00
Glass washer	29.45%	97.76%	34.88%	23.26%	1.00
Sealing worker	38.14%	97.08%	45.50%	30.26%	1.00
Spacer worker	31.60%	99.50%	32.70%	30.50%	2.00
Store Keeper	23.30%	99.61%	24.23%	22.52%	1.00
				Total	23.00
Machinery					
CNC cutting Machine 1	73.28%	99.10%	75.47%	70.98%	2.00
CNC cutting machine 2	32.08%	99.24%	33.98%	30.44%	1.00
CNC drilling machine	5.22%	96.84%	8.14%	0.00%	1.00
Drilling machine 2	6.61%	99.78%	7.27%	5.94%	1.00
End Milling Machine	17.69%	99.42%	19.27%	16.24%	1.00
Routering Machine	73.58%	99.21%	75.23%	71.41%	1.00
Punching machine	25.39%	99.20%	27.41%	22.82%	1.00
Glass washing machine	29.45%	97.76%	34.88%	23.26%	1.00
Sealing machine	38.14%	97.08%	45.50%	30.26%	1.00

High productivity requires a seamless workflow and collaboration among workstations. When a workstation has a higher load than average, it may create a bottleneck. In this study, a workstation is deemed to be a possible bottleneck if its utilization rate exceeds 90%. From the symphony CYCLONE model statistical report, it was found that the workstations with higher utilization rates were the end milling, and routering workstations. Both processes are performed by one machine operator (machine operator 2) whose utilization rate is 97.88%.

On the other hand, the statistical report shows very low utilization rate of human resources and machinery. The utilization rate of DL crew, Quality inspector, Glass cutter, Glass washer, Spacer worker, and Store Keeper is very low as shown on the above table.

Line balancing

End milling and routering activities were identified as the bottlenecks, and there was only one operator for both activities. This bottleneck problem can be avoided by adding one operator for milling and routering tasks. Since the company was more focused on improving productivity and was less concerned about the number of units produced per day, the best strategy to balance the production line was to remove workers from the workstations where the worker utilization rates were low. Production line balancing (labor optimization), was carried out by removing one worker from the workstation with the lowest worker utilization rate and by having one worker perform two or more activities which have a short cycle time. The new productivity was then compared to the previous scenario; if productivity increased, the utilization rates of all resources were recalculated, and another worker was dropped in the workstation with the lowest utilization rate. This cycle was repeated until removing a worker didn't affect productivity. A comparison of outputs for various combinations of labor resources was conducted in order to investigate the potential for more improvements. One worker added to routering & milling operations, Two workers daily laborer crew were removed, one worker removed form assembly crew, glass cutter assigned on glass washing activity in addition to glass cutting operation and the glass washer was removed. As a result, a total of 5 workers were eliminated from the workshop and the production rate increased to 0.386 m2/minute, or 185.28 m2 per day, and the total cycle time further reduced to 3,333.513 minutes. The labor resource (input) decreased significantly in this case, which indicates a greater increase in labor productivity. After line balancing the total labor resource reduced from 23 to 18 laborers. The labor productivity improved to 1.287m2/labor hour.

Table 13. Simphony CYCLONE Statistics Report of Future State Model for 100 Run Count

Non-Intrinsic Statistic

Element Name	Mean Value	Standard Deviation	Count	Minimum Value	Maximum Value
Window/Door production (Termination Time)	3,333.51	33.75	100.00	3,244.54	3,422.54

Further improvement in the overall cycle time obtained after the implementation of third scenario (line balancing). The cycle time reduced to 3,333.513 minutes, and the production rate increased to 0.386 m2/min, or 185.28 m2/day.

Improvement (%) = $\left(\frac{3{,}534.48 \text{ min} - 3{,}333.51 \text{ min}}{3{,}534.48 \text{ min}}\right)$ x 100% = 5.68 %

The result shows the implementation of line balancing which did not require any investment to apply improve the overall productivity by 5.68 % further from scenario production output.

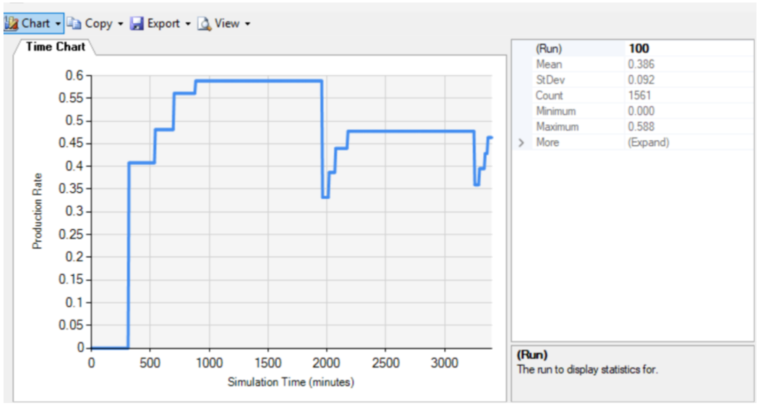


Figure 30. Production Rate vs. Simulation Time graph after implementation of line balancing (labor optimization)

4.5 Research Findings Summary

A case study in a window and door manufacturing company was carried out to investigate and validate the suggested methodology. The case study began by investigating the manufacturing process's resources, operating time, and procedure. The study's collected data used as the raw data for the simulation analysis and value stream mapping.

The production line's current value stream was first mapped. The case study identified the wastes on the line and suggested solutions by using value stream mapping, and lean manufacturing tools. Based on the advantages and amount of work needed, the suggested solutions were divided into three groups. The proposed improvement solutions were categorized into three scenarios based on the benefits and efforts required.

1) In the first improvement scenario is implementation of lean tools which require low effort but gives significant improvement such as pull based production control (Kanban), workplace organization/standardization using 5S methodology, production scheduling, cellular manufacturing (layout redesign), scheduling machine preventive maintenance (TPM), error-proofing (poka-yoke) were implemented first as they required low effort but are associated with a great benefit in return.
2) The second scenario is implementation of strategic changes. Four strategic improvements were proposed, such that: - repairing two CNC cutting and one drilling machines, developing saw & drilling files to eliminate manual inputs for cutting and drilling operations, and use of optimization software for ferma cutting using CNC cutting machine.
3) Finally, the third scenario is production line balancing (labor utilization optimization). Simulation analysis was performed proposed scenarios to statistically analyze the payback of changes before actual implementation.

The data and information gathered from the time study and production process study were used to develop a simulation model of the vision aluminum production line, which was then verified and validated using actual production data. The simulated productivity was compared to the actual productivity, and the difference was minor, therefore the model was deemed to have passed verification and validation. The simulation was used to mimic having scenario 1 in the production, and it proved that the implementation of suggested lean tools could increase the production productivity by 22.11%. The simulation analysis also showed scenario 2: repairing CNC cutting and drilling machines was able to increase overall productivity by 31.96%. Finally, the simulation was used to identify the bottlenecks in production and perform line balancing. End milling and routering operations were identified as the bottlenecks in production. The simulation model was used to determine the productivity under various labor allocation scenarios through trial and error. A best resource allocation scenario was found, which was able to increase the overall productivity by 5.8%. By combining all improvement scenarios, the overall productivity of vision aluminum manufacturing plc enhanced by 49.87%. The production rate improved from 0.222m2/min to 0.386m2/min. The overall labor productivity improved from 0.579m2/mhr to 1.287m2/mhr compared to current state model.

Table 14. Comparison of Productivity Output for aluminum window/door production Current State and Lean Models

	Scenario	Cycle time (min)	Production rate (m2/min)	Average no of man power	Total man hour	Labor Productivity (m2/mhr)	Productivity Improvement (%)
1	Current State	6,670.02	0.222	23	2,556.84	0.61	22.11
2	Lean tools that require low effort	5,195.04	0.287	23	1,991.43	0.78	31.9
3	Strategic changes	3,534.48	0.322	23	1,354.88	1.15	31.96
4	Line balancing	3,333.51	0.386	18	1,000.05	1.56	5.68
					Overall Improvement		49.87

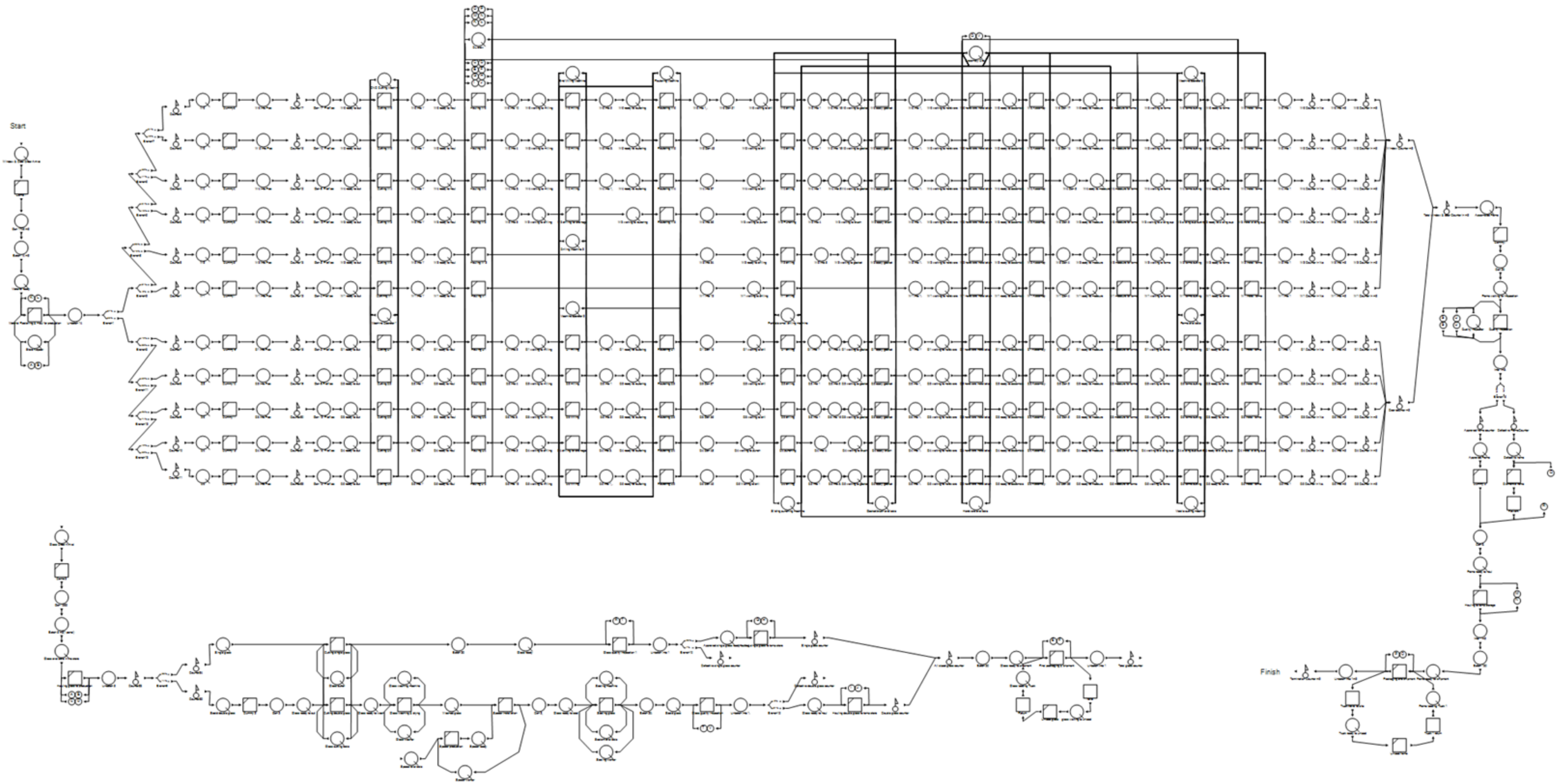


Figure 39. Aluminum window/door production Future State CYCLONE Model

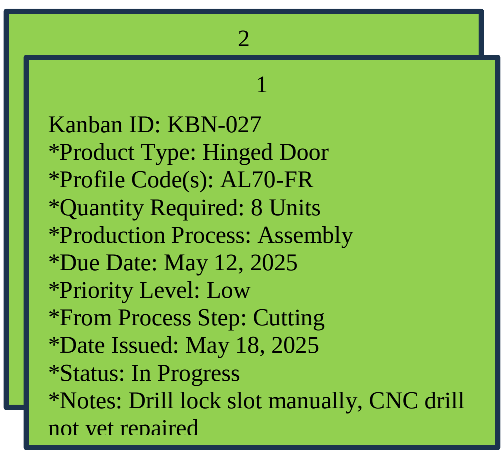
4. 5. Future State VSM Mapping

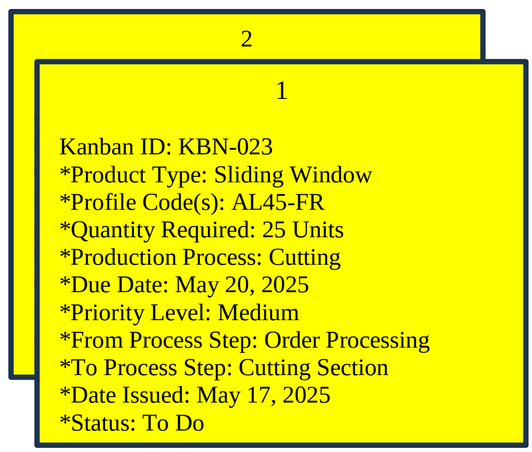
Simphony Cyclone is used to model the scenarios and test the suggested lean concepts and principles. Then, the suitable and appropriate lean concepts and principles are incorporated into the final future state map of the operations. The redesign of the workshop layout could incorporate the small-batch flow, and FIFO could be implemented such that each work sub-station is built to store no more than 30 m2. The new redesigned workshop layout and the Kanban are displayed in the figure below.

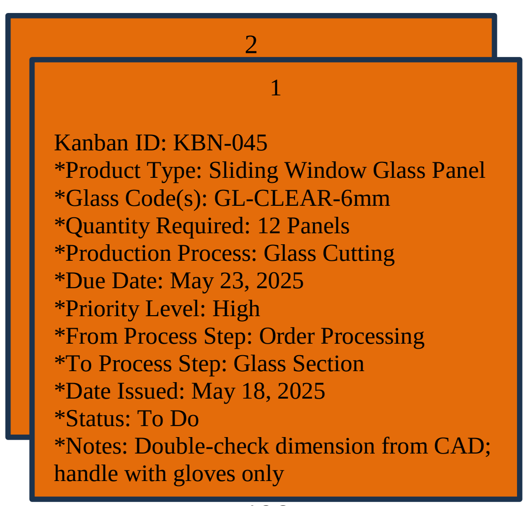
1. Pull-Based Production Control (Kanban)

Action:

g. Design simple Kanban cards or boards specifying job type, quantity, and due date.
h. Assign a visual signal (e.g., colored bins, cards) for every production station.
i. Release new work orders only when downstream processes pull parts







In the case company, which operates through incoming orders, the use of Kanban cards formalizes and streamlines work process between workstations (e.g., from cutting to assembly, and from glass preparation to final inspection). The cards contain vital information such as product type, profile/glass codes, quantity required, due dates, production stage, source and destination processes, and special remarks. This promotes smooth communication between workstations and prevents misinterpretation of production specifications.

For instance, when a customer orders 12 sliding windows, the Order Processing department initiates sending a Kanban card to the cutting department specifying the profiles and amounts required. Once the cutting is complete, a new Kanban card accompanies the batch to the assembly point, and so on. This ensures a streamlined material flow and adheres to lean practices by fostering Just-In-Time (JIT) production. The application of Kanban cards is a low-investment, high-impact lean tool that raises visibility of workflow, accountability, and responsiveness. With efficient production scheduling and cellular manufacturing, Kanban-based control is a key factor in improving total productivity in aluminum window and door manufacturing process.

2. Workplace organization using 5S methodology

One individual (quality Inspector) in a group in charge of completing the checklist, while two others charge of cleaning and sorting, and two more in charge of sorting. Although 5S does not support for hiring more workers, it does mandate that current employees in each area do these duties and develop a habit of using the 5S tools. Additionally, employees at Vision Aluminum workshop should to be urged to take before and after photos so that they can see the progress and feel more inspired.

Table 15. 5S Audit Checklist Based on (Sweeney, 2003)

Date:	Target Area:		Performed by:
5S element	Initiative	Score	Notes for next Level improvement
(Sort)	1) Necessary items are sorted from those that are unnecessary		
	2) Discharge area is defined.		
	3) Unwanted items are moved to discharge area.		
(Straighten)	5) An access system is in place with labels and color code to identify		
	6) Proper position of tools, materials, and objects.		
	7) Materials or objects are always in their designated position.		
Scrub	8) Machineries, tools, and fixtures are well maintained and clean.		
	9) Walls, floors, conveyance equipment and hallways are shiny and stainless.		
	10) Actions have been developed to remove sources of wastes.		
Systematize	11) Procedures are set to work on sort, straighten, and scrub.		
	12) 5S is run on a daily basis.		
	13) Working environment is healthy and pleasant.		
	14) Standards are set and followed.		
	15) Goals of 5S have been achieved.		
	Total Score:		Divided by 15 = Avg. Score:

1. Little or No 5S Apparent (<20%) 3. Meets Several 5S Requirements (60%) 5. 5S Compliant (100%) 2. Meets Minimal 5S Requirements (40%) 4. Meets Most 5S Requirements (80%)

3. Cellular manufacturing (layout redesign)

The current workshop layout is process-based (functional), that is, machines are grouped in clusters (all cutting machines in one pace, all drilling, etc.). This resulted the following consequences:

- ✓ Transport distances between stations are too long
- ✓ Too much WIP accumulation (work-in-progress)
- ✓ Increased waiting time
- ✓ Poor line of sight and communication for operators

Proposed Changes:

- ▪ Re-Organize machinery/tools into Product-Based Cells: Set up separate production cells by product families:
  - ✓ Sliding Window/Door Cell: CNC cutting saw, punch, frame assembly, final inspection
  - ✓ Casement Window/Door Cell: Profiling cutting, end milling, frame assembly, final inspection
  - ✓ Glass Cutting/Washing Cell: Glass cutting table, buffer racks, glazing station
- ▪ Reduce travel distance between workstations: Regroup machines and workstations so that parts flow in a U-shape layout
- ▪ Placing CNC cutting machine near the aluminum storage, placing glass cutting near the glass store, relocating frame assembly tables closer to machining zone to minimize travel distance in between workstations.
- ▪ Store rubber gaskets, screws, and fasteners, and other tools inside each cell. Rather than storing all tools and accessories in centralized store.

Table 16.Proposed changes to implement cellular manufacturing

Current Layout Problem	Proposed Change
Unnecessary long movement within workstations	Create product-based cells
Machines far from raw materials	Move raw materials storage close to cutting station
Central tool storage	Tool storage within each cell
Idle workers during workload imbalance	Train employees to perform multiple operations
Batching with long lines	Use small batch flow
Communication and control not good	Visual boards and ownership by each cell

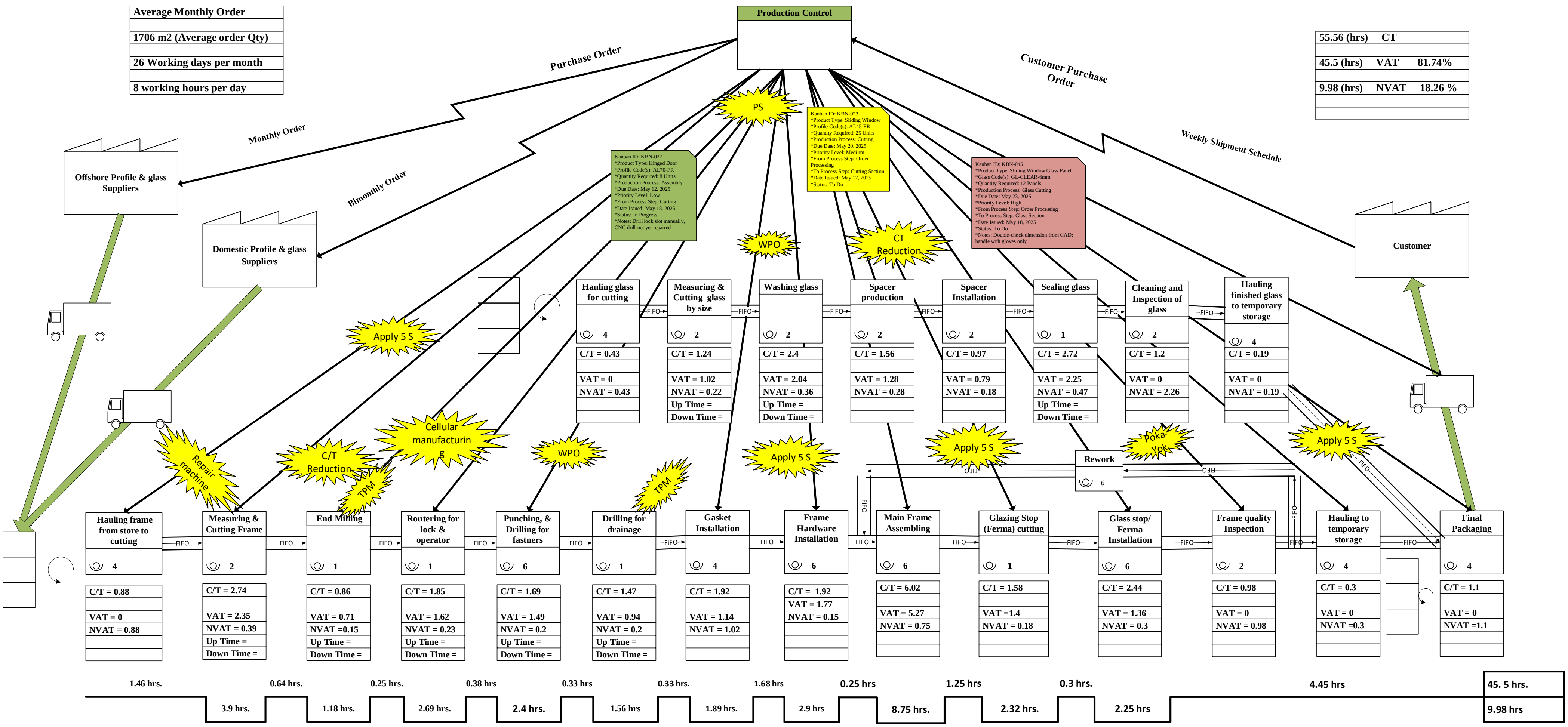


Figure 31. Future State Map of Aluminum Window/Door Production

Performance indicators derived from future state VSM:

- ✓ Total cycle time (TCT): 6.94 days
- ✓ Lead time (LT): 14 da
- ✓ VAT: 2,730 minutes (5.68 days)
- ✓ NVAT: 588.8 minutes 1.25 days (18.26% of the total cycle time)

Table 14. Comparison of Productivity for Current State and Future Model

Metric	Cycle time (min)	Production rate (m2/min)	Avg man power	Total man hour	Labor Productivity (m2/mhr)
Current State	6,670.02	0.222	23	2,556.84	0.61
Future State	3,333.51	0.386	18	1,000.05	1.56
Improvement (%)	49.8 %	42.5 %	21.7 %	60.9 %	60.9 %

Combined improvement raised productivity by 49.87%, improving production rate from 0.222 m^2/min to 0.386 m^2/min, and labor productivity from 0.579 m^2/man-hour to 1.287 m^2/man-hour.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusion

This research was conducted with the aim of investigating and improving the productivity of aluminum window and door manufacturing processes by integrating lean manufacturing principles/tools and Discrete Event Simulation (DES). A comprehensive case study was conducted in Vision Aluminum Manufacturing PLC, where the current manufacturing processes were studied in terms of layout, resources, cycle times, and production process. The study presented a framework to combine lean manufacturing and discrete event simulation analysis in productivity improvement for aluminum window/door manufactures.

Through value stream mapping, the various wastes such as waiting time, unnecessary motion, transportation, excess inventory, unbalanced workloads, and equipment downtime were mapped. These inefficiencies were addressed with a line of targeted lean involvements to improve the flow of production, eradicate wastes, and optimize the utilization of resources. Different lean manufacturing tools and techniques were employed to identify the waste that is exist on the production lines, identify the root causes, and propose solutions to improve. Most companies have been hesitant to adopt the strategic changes suggested by lean analysis since it needs higher effort and the payback cannot be calculated by lean analysis. In order to address this issue, discrete event simulation models were developed to simulate the changes that require great amount of effort but have the potential to yield significant benefits. These models statistically analyze the modifications' payback in terms of increased productivity. With the combination of lean manufacturing tools and discrete event simulation, not only could identify the waste and find ways to eliminate the waste, but could also statistically forecast the resulting benefits before actual implementation of the suggested changes.

In order to discover the underlying root causes of these NVAA, and inefficiencies, the Five-Why root cause analysis technique was employed systematically with the help of unstructured interviews during data collection. This method assisted the researcher to find out through symptoms and discovering the root causes behind NVAA and performance deficiencies. By asking "Why?" five times about a problem helps us better understand it and its nature; hence, "five whys" can lead to "one how" (Ohno, 1988).

Lean concepts and principles that would increase productivity were implemented in different scenarios on the validated and verified CYCLONE models following the determination of the NVAA share and the identification of the root causes. The improvement process started with the application of the fundamental lean tools that require minimal efforts yet brought significant benefits to the production improvement. A Kanban system was employed for the production control in a pull-based approach as against overproduction and increased response to customer demand. The 5S methodology was used to present the workplace with organization, eliminate unnecessary motion waste, and have a cleaner and more standardized workplace. Production scheduling techniques were brought in to enhance workflow control and utilization of resources, and cellular manufacturing layout redesign enabled productive flow of manufacturing and eliminated unnecessary movement. Preventive maintenance (TPM) was brought in to reduce equipment downtime and error-proofing (poka-yoke) employed to eliminate defects caused by human errors. In addition to these lean tools, other strategic improvements were implemented to address equipment-based constraints. By repairing and digitalizing two previously non-functional CNC cutting machines and one CNC drilling machine, enabling faster and more accurate processing. Manual input procedures were replaced by file-based automation for cutting and drilling operations, significantly reducing setup time and input errors. Cutting optimization software that assisted in improving material utilization and reducing cutting waste, especially in glass stop (Ferma) cutting operation was implemented.

To support the above improvements, a discrete event simulation model for the production workshop was developed using Simphony Cyclone and compared against actual real-time production data. The simulation confirmed that the use of lean tools dramatically improved productivity by increasing throughput and reducing cycle time. The impact of strategic equipment modernization was also profound with monumental speed-up in production and process disruption avoidance. Line balancing efforts, led by simulation analysis, tested out the overall productivity under various resource allocation scenarios, supported the redistribution of labor resources so that bottlenecks observed in the routering and end milling stations could be minimized. Improved utilization of workers with optimized human resource utilization enabled better production flow and following productivity enhancements.

With these collective improvements, the total production time significantly improved from 6,670.02 minutes to 3,333.51 minutes, overall production rate improved from 0.222 m^2/min to 0.386 m^2/min, and the labor productivity improved from 0.579 m^2/man-hour to 1.287 m^2/man-hour. From these findings, it is demonstrated that the collective application of lean manufacturing tools, strategic machine optimization, and simulation-based study can lead to substantial productivity enhancements.

5.2 Recommendations

Based on the results of this research and the significant productivity improvements achieved through the implementation of lean manufacturing tools and Discrete Event Simulation (DES), the following recommendations are made:

1. Institutionalize Lean Thinking: Aluminum manufacturing companies must formally adopt lean manufacturing as a continuous improvement philosophy. Lean concepts like workplace organization (5S), pull-based production (Kanban), cellular layout, and Total Productive Maintenance (TPM) need to be embedded in day-to-day operations with regular reviews and employee participation to ensure that it maintains itself.
2. Continue and Enhance Simulation-Based Decision Making: Simulation modeling experience with Simphony Cyclone has been found helpful in experimenting with different alternative improvements before physical implementation. The aluminum window/door production companies recommended to continue investigating their productivity with the help of simulation modeling and enhance its utilization for capacity planning, layout planning, and labor optimization in future projects.
3. Emphasize equipment digitalization and functionality: Based on the findings of the research, repair and digitalization of drilling and cutting machines improved productivity significantly. The company should emphasize regular maintenance schedules (TPM), and digitalize critical machines to file-based mode to reduce extended delays and manual errors.
4. Implement and Practice Line Balancing Procedures: Production bottlenecks were avoided through labor reassignment. The researcher recommended to regularly review labor allocation and conduct line balancing studies especially on new product introduction or changed order volumes.

5. Standardize Work and Visual Management: Standardization of operating procedures (SOPs), visual work instructions, and Kanban cards should be codified for all workstations. This improves understanding, lessens training time for new employees, and reduces product quality variation.
6. Train Workers and Enthusiasm: Since lean success depends on individuals, the company has to provide constant lean tool training, simulation, and quality improvement to operators and management staff. Team-based problem-solving and integration of shop floor staff in lean activities should be encouraged.
7. Monitor and Verify Performance: The impact of the changes being implemented has to be monitored regularly through KPIs such as production capacity, labor efficiency, equipment availability, and defect rate to establish that benefits are sustained and a point to further improve is identified at the earliest.

5.3 Recommendations for Future Study

This study demonstrated how to use simulation analysis and lean manufacturing principles to improve the productivity of the aluminum window and door production process. Several recommendations are made for future study. Based on the findings of this case study of producing aluminum windows and doors, the same lean and simulation-based methodology is recommended to be applied to other production lines or factories owned by the company.

1. Integration of Cost Analysis with Lean and Simulation: Future studies should incorporate a comprehensive cost-benefit analysis to evaluate the financial impact of lean tool implementation and machine digitization. This would help quantify the return on investment (ROI) and support management decision-making with economic justification.
2. Application of Lean-Simulation Framework to Other Manufacturing Sectors: Similar research methodologies could be extended to other types of construction manufacturing industries, such as steel structures, HCB production, and prefabricated components.
3. Investigating how implementing VSM combined with DES can enhance other performance metrics for aluminum window and door manufacturing operations.
4. Improving the overall productivity of the aluminum window/door production process through the implementation of other lean manufacturing tools

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APPENDIX

Secondary Data

Yearly manufactured products quantity

1.5 የሽያጭ አፈፃፀም (በመጠን/በዋጋ) ፤

የአራት አመት ዝርዝር የሽያጭ ክንውን በመጠንና በገንዘብ እንደሚከተለው ቀርቧል።

ተ.ቁ.	የምርት/አገልግሎት አይነት	2013		2014		2015		2016	
		በብር	በካ.ሜ	በብር	በካ.ሜ	በብር	በካ.ሜ	በብር	በካ.ሜ
1	በርና መስኮት	31,109,000	11,116	28,022,000	6,157	33,872,161	6,704	83,522,602.11	11,125
2	ፓርቲሽን	28,515,000	11,011	23,271,000	2,865	16,870,870	1,408	20,669,937.53	2,183
3	ከርተን ወል	6,000,000	1,881	3,557,000	5,978	15,643,034	5,139	30,514,461.04	5,223
4	ክላዲንግ	3,271,000	1,160	4,195,000	3,063	8,082,031	1,462	5,958,761.01	1,298
5	የደረጃመደገፊያና መወጣጫ	3,877,000	1,379	7,325,000	1,048	3,009,089	384	7,126,920.26	584
6	ስካይ ላይት	1,492,000	281			1,229,904.76	178	1,038,998.25	256
7	ሌሎች					3,290,950.00		1,268,420	3
	ድምር	74,264,000	26,828	66,370,000	19,110	81,998,039	15,274	132,986,175	20,672

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Vision Aluminum Manufacturing P.L.C

13

የያለበተት ሀሂደተት	ብዛት	የኮንትራት መጠን	የተሰራ ስራ (በብር)	ማብራሪያ
ያለቁ	27	64,404,437.20	71,091,569.58	
በሂደት ላይ ያሉ	9	162,853,900.14	66,339,457.04	
የያለልተጀመረሩ	2	33,465,027.72		
ደድመምረር		260,723,365.06	137,431,026.62	

Primary Data

Shift Schedule and Work Allocation Data Collection

Parameter	Details
Date	13/01/25 – 17/02/2025
Shift Number	Only 1 shift with 8hrs working time
Number of Workers	18 - 23
Machines Operated	1 CNC cutting machine, 2 Portable cutting machines, 1 end milling machine, 1 lock routering machine, 2 drilling machines, 1 heavy duty drilling machine, 1 crimping machine, small portable drilling machines, 2 glass cutting saw, 1 glass washing machine, 1 glass sealing machine,
Operator Names	Mideksa Gutema, Tomas Ayana, Sintayehu Werku,
Break Times	1hr lunch break
Overtime Hours (if any)	None, during data collection
Shift Supervisor	Mathias Mesele, Nathnael Demssie
Comments on Work Efficiency	Workers are not performing by their full capacity. There are too much unnecessary motions, delay by waiting and side talk, machine breakdown

Labor Productivity & Defect rate

Addis Ababa Institute of Technology
School of Civil and Environmental Engineering Graduate Program in Construction Technology and Management
Thesis on: Implementation of Value Stream Mapping Integrated with Discrete Event Simulation for Productivity Improvement of Aluminum Window and Door Manufacturing
Observation Data Collection Sheet Format

Data: Labor Productivity & Defect rate
Case Study: Vision Aluminum Manufacturing plc
Location: Sululta

Date	Crew Size	Crew Composition						Total man hours (mhr)	Unit (window/ door)	Completed Amount	Labor Productivity	Defects observed (Pcs)
		Machine operators	Ass. Machine operators	Assembly Technicians	Assembly helpers	Laborers	Glass production technicians				Manufactured Quantity /T. Manhours	
13-Jan-25	21	3	1	5	6	0	6	168	m2	124.5	0.74	0
14-Jan-25	21	3	2	6	4	0	6	168	m2	120.4	0.71	0
15-Jan-25	20	3	2	6	4	0	5	160	m2	119.4	0.74	0
16-Jan-25	20	2	2	6	4	0	6	160	m2	84.2	0.52	1
17-Jan-25	21	2	2	4	4	3	6	168	m2	67.6	0.40	0
21-Jan-25	21	2	0	4	6	3	6	168	m2	102.3	0.60	0
22-Jan-25	21	3	0	4	6	3	5	168	m2	122.7	0.73	3
23-Jan-25	22	3	0	6	6	3	4	176	m2	125.3	0.71	0
27-Jan-25	22	3	0	6	5	3	5	176	m2	123.4	0.72	0
28-Jan-25	22	3	2	6	5	2	5	176	m2	132.5	0.75	3
29-Jan-25	23	3	2	6	6	2	4	184	m2	134.5	0.72	2
30-Jan-25	23	3	2	6	6	2	4	184	m2	122.9	0.66	0
31-Jan-25	23	3	2	4	6	3	5	184	m2	121.3	0.66	1
1-Feb-25	23	3	2	6	5	3	4	184	m2	129.7	0.70	0
3-Feb-25	23	3	2	4	6	3	5	184	m2	123.1	0.66	2
4-Feb-25	21	3	0	6	6	3	4	168	m2	122.5	0.72	0
5-Feb-25	22	2	2	4	6	3	5	176	m2	98.3	0.55	1

6-Feb-25	23	3	1	6	6	3	4	184	m2	81.5	0.46	3
7-Feb-25	23	3	2	6	6	3	3	184	m2	69.5	0.37	1
10-Feb-25	22	1	2	6	6	2	5	176	m2	99.8	0.56	0
11-Feb-25	23	3	2	4	5	3	6	184	m2	124.7	0.67	0
12-Feb-25	22	3	2	6	4	3	4	176	m2	126.3	0.71	0
13-Feb-25	23	3	2	6	4	3	5	184	m2	130.6	0.70	3
14-Feb-25	22	3	1	4	6	2	6	176	m2	129.4	0.73	0
15-Feb-25	20	3	2	6	4	2	3	160	m2	122.9	0.76	2
16-Feb-25	20	3	2	6	6	3	3	160	m2	128.4	0.80	0
17-Feb-25	21	3	2	4	4	3	5	168	m2	122.6	0.72	2
												23

Cycle Time and Process Time Data Collection

Addis Ababa Institute of Technology
School of Civil and Environmental Engineering Graduate Program in Construction Technology and Management
Thesis on: Implementation of Value Stream Mapping Integrated with Discrete Event Simulation for Productivity Improvement of Aluminum Window and Door Manufacturing
Observation Data Collection Sheet Format

Cycle time of Sub-processes
Case Study: Vision Aluminum Manufacturing plc
Location: Sululta

Data No	Hauling Frame & Ferma from store to cutting station CT (Min	Measuring & cutting frame	Hauling frame to assembly station after cutting CT (Min)	End Milling CT (Min)	Routering for 1 lock & operator CT (Min)	Punching CT (Min)	Drilling by small movable drilling machine CT (Min	Drilling external sliding frame for drainage	Apply gasket/ brush CT (Min)	Install Hardware CT (Min)	Type	Assembly CT (Min)	Take measurement for Ferma	Cutting Glass stop/ Ferma CT (Min)	Installing Glass stop/ Ferma CT (Min)	Quality Inspection CT (Min), 20pcs	Hauling assembled frame to temporary storage CT (Min)	Hauling Glass panel from store to glass cutting station CT (Min)	Measuring & cutting glass CT (Min)	Washing glass	Sealing	spacer production	Spacer installation	Cleaning & quality check CT (Min), 20 pcs	Hauling sized glass to temporary storage CT (Min), 1pcs
1	6	0.57	1.51	0.36	2.87	0.09	0.08	0.48	0.91	6.12		3.08	0.07	0.43	0.28	9	2.04	1.95	1.18	4.1	12.64	7.06	1.19	11.01	1.8
2	8.4	0.28	1.18	0.33	6.47	0.15	0.05	0.41	0.56	10.75		2.96	0.09	0.35	0.26	18.72	4.18	3.64	0.94	4.25	12.35	5.11	1.21	20.11	0.82
3	6.2	0.63	2.19	0.42	3.35	0.22	0.07	0.47	0.4	7.38		3.28	0.08	0.25	0.24	8.64	3.78	3.38	0.63	3.52	8.99	4.86	0.88	14.99	1.12
4	7.6	0.34	1.99	0.34	4.06	0.12	0.1	0.58	0.68	6.42		2.52	0.16	0.33	0.25	9	2.38	1.69	0.63	3.58	12.57	6.5	0.82	18.72	1.1
5	6.2	0.13	1.26	0.27	5.07	0.2	0.08	0.51	0.48	10		3.32	0.17	0.33	0.22	18.24	2.04	3.64	1.27	3.39	13.27	4.95	0.64	21.49	1.2
6	6.6	0.34	1.38	0.32	6.14	0.18	0.06	1.16	0.38	4.56		4.2	0.15	0.4	0.23	11.52	3.88	3.51	0.59	3.68	10.97	6.45	0.81	13.17	1.61
7	8.6	0.25	1.78	0.27	4.53	0.22	0.14	0.47	0.43	8.88		4.2	0.16	0.43	0.26	13.68	1.72	2.99	0.91	3.3	10.24	6.53	0.9	18.63	1.23
8	7	0.28	0.95	0.3	5.08	0.12	0.05	0.64	0.58	10.76		3.6	0.16	0.42	0.27	18.12	2.26	2.6	0.88	2.94	8.98	4.97	0.92	11.96	1.42
9	8	0.51	1.76	0.28	3.05	0.23	0.1	0.94	0.54	6.93		4.32	0.18	0.38	0.24	11.52	3.92	2.47	0.98	3.02	12.96	5.54	1.03	11.7	1.1
10	6.4	0.92	1.06	0.34	6.68	0.11	0.07	0.5	0.38	5.23		3.84	0.11	0.3	0.2	8.16	2.6	1.56	0.6	3.9	13.1	6.81	1	11.27	0.97
11	7	0.61	1.61	0.17	3.89	0.13	0.08	0.63	0.55	7.39	W1	4.48	0.1	0.34	0.26	16.44	3.6	1.56	0.72	2.93	12.05	5.61	0.72	12.65	0.83
12	7.4	1.57	1.48	0.26	2.77	0.13	0.16	0.85	0.71	7.33		3.76	0.12	0.38	0.22	11.16	2.54	2.08	0.82	2.78	12.64	7.22	1.15	18.03	1.06
13	8.6	0.73	1.72	0.2	3.66	0.19	0.16	0.63	0.36	8.19		4.08	0.07	0.26	0.22	16.56	3.38	3.64	1.22	3.35	12.62	4.7	1.23	7.19	0.7
14	6.8	0.95	1.35	0.29	4.57	0.13	0.15	0.68	0.57	8.33		3.52	0.17	0.27	0.24	9.96	2.64	1.69	0.59	3.58	11.71	6.06	0.62	11.01	0.91
15	7.4	0.47	1.53	0.21	4.54	0.14	0.13	0.77	0.37	4.78		4	0.14	0.25	0.22	18.24	2.28	2.47	0.82	3.07	9.81	7.11	1.21	8.67	0.98
16	8	0.42	2.03	0.51	3.48	0.13	0.12	0.42	0.74	7.29		3.12	0.1	0.32	0.22	9.84	2.02	1.56	1.17	3.46	9.66	7.31	1.14	16.38	1.24
17	7.6	0.34	1.35	0.67	5.57	0.17	0.08	0.63	0.51	9.32		3.6	0.1	0.24	0.28	18.48	4.08	3.25	1.04	4.21	13.03	4.88	0.87	9.27	0.78
18	6.2	0.42	1.76	0.61	5.5	0.09	0.11	0.69	0.47	9.18		3.72	0.15	0.34	0.23	18.96	2.96	3.38	0.85	4.2	11.79	6.38	1.1	20.71	1.15
19	6.6	0.67	1.42	0.46	4.74	0.14	0.17	0.82	0.32	8.58		2.88	0.1	0.32	0.21	11.28	4.28	1.95	0.87	3.66	10.41	6	0.81	11.01	0.81
20	8.4	0.7	1.54	0.79	2.8	0.12	0.16	0.73	0.7	8.12		3.8	0.09	0.35	0.2	11.4	1.62	2.34	0.95	3.96	11.49	5.06	1.04	21.67	1.6
21	6.4	1.15	1.74	0.93	5.71	0.27	0.17	0.56	0.54	6.48		4	0.13	0.34	0.21	15.6	1.64	3.51	0.68	4.19	12.41	6.55	0.67	14.39	1.15

22	5.8	0.22	1.24	0.51	3.04	0.12	0.08	0.44	0.53	8.59		4	0.07	0.39	0.24	7.08	3.18	2.47	1.05	3.66	8.96	7.14	1.07	17.51	1.27
23	7.8	0.44	2.03	0.4	6.66	0.27	0.12	0.51	0.36	10.47		4.48	0.14	0.43	0.21	17.04	1.98	2.86	0.82	2.9	9.08	6.6	0.99	13.17	1.28
24	6.4	0.47	1.08	0.39	3.69	0.12	0.13	0.52	0.59	8.7			0.09	0.29	0.2	14.52	2.1	1.95	0.88	3.02	8.72	6.65	0.78	7.8	1.29
25	6.4	0.67	1.22	0.7	4.09	0.18	0.14	0.94	0.44	9.33		6.84	0.13	0.27	0.23	16.92	2.64	2.99	1.03	3.85	11.47	5.15	1.13	10.05	1.38
26	8.4	0.44	1.37	0.83	3.91	0.11	0.14	0.85	0.74	5.69		7.82	0.16	0.4	0.28	15.24	1.72	1.56	0.92	4.04	11.4	6.75	0.64	23.14	1.04
27	12	0.63	1.35	0.4	6.55	0.14	0.09	0.42	0.35	7.55		6.52	0.18	0.38	0.27	8.88	1.18	2.6	0.94	2.72	12.7	7.21	0.93	19.85	1.4
28	8.2	1.57	1.28	0.72	3.68	0.21	0.12	0.83	0.7	5.21		8.67	0.18	0.43	0.26	10.08	4.14	3.51	0.77	4.22	9.08	5.07	0.56	8.75	1.16
29	6.8	0.86	1.04	0.85	4.24	0.12	0.15	0.44	0.5	6.38		9.21	0.17	0.41	0.23	14.64	3.56	3.25	0.91	3.89	11.76	5.47	0.75	12.65	0.78
30	8.2	1.18	1.95	0.59	5.15	0.14	0.17	0.88	0.46	7.21		8.43	0.09	0.28	0.19	18.48	3.66	2.47	1.14	2.87	12.6	6.69	1.17	9.62	1.02
31	5.8	0.29	1.06	0.4	5.28	0.15	0.16	0.42	0.52	8.48		6.53	0.14	0.29	0.27	19.08	1.5	3.51	1.17	4.02	9.85	4.78	0.81	10.92	0.94
32	8	0.51	2.20	0.69	4.08	0.18	0.13	0.84	0.56	9.18		7.27	0.13	0.28	0.27	15.84	2.82	1.95	1.24	3.69	10.52	6.31	1.02	10.83	1.17
33	8.2	0.32	2.18	0.37	5.39	0.12	0.11	0.49	0.41	8.55		7.95	0.11	0.38	0.22	15.72	1.72	1.56	1.19	3.1	13.21	6.46	0.97	8.58	1.47
34	6.8	0.82	1.42	0.76	5.67	0.14	0.15	0.64	0.41	8.42		8.66	0.1	0.41	0.26	12.96	1.42	3.12	0.89	2.82	10.92	7.29	0.85	18.46	1.48
35	7.8	1.25	1.49	0.61	4.53	0.11	0.16	0.62	0.34	6.05		8.61	0.09	0.27	0.22	16.92	3.4	2.08	0.59	3.27	13	7.29	1.3	20.71	1.45
36	8.8	1.09	2.01	0.86	5.82	0.2	0.1	0.5	0.32	4.9		8.05	0.14	0.32	0.23	12.48	2.18	1.95	1.24	3.48	13.08	6.95	1.14	15.6	1.19
37	6.8	0.28	1.04	0.41	5.64	0.23	0.18	0.78	0.71	8.22		7.85	0.17	0.25	0.22	18.48	1.5	2.08	0.79	3.6	11.66	5.68	1.04	14.3	1.32
38	8.2	0.28	1.26	0.69	5.47	0.15	0.17	0.97	0.39	10.11	W2	7.6	0.14	0.35	0.28	7.32	3.82	2.08	0.69	3.69	13.27	5.38	1.1	22.71	1.36
39	5.8	1.5	1.10	1.01	3.51	0.18	0.16	0.79	0.35	4.99		9.08	0.18	0.31	0.23	9.84	3.04	3.12	0.83	3.79	11.02	5.72	1.06	16.99	1.46
40	8	0.38	1.03	0.89	3.62	0.17	0.19	0.45	0.61	6.09		7.63	0.12	0.31	0.28	9.12	2.36	1.95	0.62	3.39	9.7	6.35	0.56	21.41	1.23
41	6.6	1.05	1.33	0.63	5.57	0.1	0.1	0.42	0.67	9.88		7.78	0.09	0.33	0.21	13.68	2.1	1.69	0.75	3.04	11.48	5.88	0.51	18.46	1.55
42	9	1.18	1.96	0.6	4	0.13	0.15	0.65	0.72	7.87		8	0.08	0.38	0.27	11.16	1.98	1.82	1.13	2.74	11.6		0.98	7.11	1.13
43	8.8	0.77	1.24	0.87	6.5	0.1	0.1	0.87	0.42	10.06		7.17	0.17	0.25	0.22	13.44	3.06	2.21	0.53	2.72	9.3		1.25	20.8	1.72
44	6.6	0.54	2.23	0.85	5.79	0.11	0.17	0.71	0.62	4.54		9.1	0.09	0.25	0.24	12.6	3.72	1.69	1.16	3.22	13.13		1.22	14.39	1.29
45	6.4	0.63	1.85	0.69	4.82	0.05	0.12	0.82	0.32	7.51		8.71	0.11	0.25	0.25	14.04	2.64	2.47	1.05		11.29		0.85	7.37	1.41
46	8	0.86	0.96	0.56	4.25	0.13	0.17	0.43	0.51	6.16		8.08	0.16	0.32	0.21	16.2	1.7	1.95	1.03		10.38		1.06	20.45	1.24
47	6.2	0.86	0.99	0.44	5.49	0.09	0.11	0.94	0.49	9.96		8.25	0.14	0.39	0.28	9.6	1.34	3.25	0.6		11.5			19.93	1.84
48	9.2	0.9	1.49	0.87	4.34	0.12	0.18	0.62	0.48	6.99		10.03	0.12	0.32	0.28	12.84	2.84	2.86	1.02		11.06			11.09	1.01
49	9.2	0.76	1.79	0.87	5.47	0.09	0.15	0.92	0.33	5.06		7.28	0.17	0.42	0.23	12.96	2.18	1.69	1.15		8.89			15.17	1.28
50	7.2	1.06	1.58	0.78	6.5	0.13	0.14	0.7	0.38	5.92		7.59	0.11	0.25	0.26	10.44	2.64	2.99	0.76		11.27			8.58	1.82
51	8.6	0.92	1.98	0.44	6.21	0.12	0.13	0.8	0.62	9.64		6.74	0.16	0.34	0.22	16.56	3.46	3.12	1.28		11.79			6.67	1.39
52	8	0.82	1.87	0.74	2.93	0.12	0.17	0.97	0.33	6.59		8.02	0.1	0.33	0.26	12	2.46	2.6	0.99					16.03	0.79

53	9.2	0.66	1.68	0.47	4.93	0.09	0.1	0.6	0.71	7.75		6.41	0.08	0.42	0.25	11.76	1.28	2.34	0.86					14.99	0.9
54	11.4	0.77	1.65	0.74	5.92	0.38	0.13	0.49	0.63	4.92		6.03	0.18	0.26	0.19	10.44	2.26	1.95	0.75					15.69	0.97
55	11.2	0.92	1.62	0.64	6.31	0.2	0.12	0.75	0.65	8.96		6.2	0.11	0.27	0.23	14.76	2.82	2.21	0.82					6.93	1.64
56	8.4	0.7	1.84	0.66	2.93	0.11	0.18	0.44	0.36	8.19		6.11	0.07	0.29	0.21	12.36	3.46	1.95	1.14					13.43	1.72
57	6	0.61	1.36	0.63	3.42	0.17	0.11	0.94	0.42	4.39		5.92	0.17	0.36	0.28	16.44	1.36	2.08	0.94					18.89	1.52
58	10.2	1.06	1.81	0.62	6.44	0.21	0.09	0.67	0.56	6.84		8.41	0.08	0.39	0.23	15.96	2.08	3.25	1.2					12.74	0.99
59	10.8	0.63	2.12	0.79	5.86	0.13	0.11	0.84	0.49	10.09		8.78	0.14	0.3	0.28	16.08	3.74	3.64	1.04					21.41	1.04
60	8	0.82	1.72	0.44	6.01	0.18	0.17	0.42	0.45	5.28		9.65	0.07	0.34	0.23	17.28	3.9	2.99	0.84					7.54	1.31
61	10	0.7	1.54	0.64	4.96	0.07	0.11	0.43	0.46	7.02		6.86	0.14	0.26	0.21	13.08	2.88	1.95	0.62					6.76	1.53
62	6.2	0.8	0.91	0.89	5.09	0.12	0.12	0.79	0.61	5.25		8.69	0.17	0.28	0.19	13.2	2.8	1.95	0.6					23.05	1.02
63		0.61	1.68	0.94	4.02	0.12	0.08	0.73	0.73	7.67		6.13	0.09	0.24	0.24	12.48	1.58	1.82	1.19					14.91	1.63
64		0.99	1.54	0.46	5.77	0.19	0.13	0.41	0.58	9.13		6.78	0.16	0.39	0.25	10.8	1.34	2.21	0.62					8.58	1.28
65		0.99	1.39	0.77	6.4	0.1	0.11	0.91	0.37	7.27		6.47	0.12	0.24	0.22	16.08	1.3	2.73	0.82					20.02	1.57
66		0.7	1.25	0.75	6.33	0.15	0.17	0.48	0.54	9.47		6.77	0.11	0.39	0.21	18.48	1.92	3.51	1.14					16.9	0.81
67		1.06	1.45	0.79	6.37	0.11	0.12	0.81	0.47	8.22		8.62	0.09	0.36	0.2	10.68	1.38	2.99	0.74					6.76	1.1
68		1.06	1.52	0.61	3.01	0.16	0.11	0.56	0.69	5.57		8.2	0.18	0.3	0.26	12	4.06	2.47	0.78					7.28	1.23
69		0.67	1.29	0.75	6.64	0.09	0.15	0.53	0.61	7.13		7.09	0.09	0.35	0.27	13.2	2.66	1.56	0.78					7.89	0.98
70		0.99	2.24	0.84	4.42	0.12	0.08	0.96	0.74	6.05		5.77	0.11	0.38	0.28	13.44	1.24	2.47	1.02					22.1	0.84
71		0.73	1.21	1.03	3.37	0.19	0.16	0.49	0.68	7.38		6.83	0.11	0.38	0.24	18.96	4.02	2.21	1.2					8.06	1.74
72		0.96	1.68	0.77	4.67	0.11	0.15	0.91	0.68	10.67		7.95	0.17	0.39	0.28	9.12	2.72	2.73	1.25					13.35	1.72
73		0.57	1.31	0.76	6.56	0.13	0.17	0.51	0.49	9.37		7.14	0.09	0.36	0.28	12.6	1.48	2.73	0.61					17.33	0.99
74		0.86	0.93	0.53	3.25	0.1	0.12	0.42	0.36	7.22		7.09	0.07	0.38	0.25	12.12	4.08	3.25	1.12					17.68	1.08
75		0.99	0.92	0.59	6.24	0.18	0.11	0.47	0.57	8.76		11.91	0.13	0.41	0.19	7.08	2.44	2.6	0.83					17.25	1.19
76		0.8	1.16	0.48	3.07	0.13	0.12	0.56	0.62	6.99		9.58	0.14	0.33	0.2	9.6	2.62	2.21	1.26					20.71	1.11
77		0.99	0.95	0.64	5.58	0.16	0.11	0.6	0.68	6.36		11.81	0.15	0.34	0.2	9.36	1.16	1.95	0.86					20.11	1.23
78		0.86	2.24	0.61	3.08	0.14	0.16	0.57	0.45	7.93		12.2	0.12	0.24	0.25	16.32	2.18	3.64	0.53					20.89	1.56
79		0.76	1.99	0.90	4.12	0.21	0.13	0.49	0.68	7.25	W3	10.62	0.11	0.42	0.27	15.6	1.46	3.12	0.54					21.67	1.03
80		0.57	1.82	0.81	3.5	0.12	0.15	0.93	0.5	6.94		12.54	0.15	0.28	0.28	17.4	3.62	3.64	0.87					11.18	1.28
81		0.99	1.18	0.63	3.9	0.17	0.18	0.41	0.62	6.25		11.74	0.16	0.39	0.26	9.72	1.9	3.25	1.24					20.19	1.08
82		0.99	1.26	0.81	2.69	0.17	0.12	0.51	0.4	5.7		14.19	0.08	0.27	0.27	10.92	3.7	2.73	0.77					10.92	0.98
83		1.06	1.30	0.64	4.67	0.21	0.15	0.68	0.37	8.07		11.33	0.14	0.35	0.23	15.96	3.34	1.56	0.76					11.96	1.56

84		0.67	1.75	0.94	5.27	0.11	0.13	0.93	0.64	4.65		9.23	0.11	0.29	0.27	11.16	1.8	2.6	1.1					7.11	0.9
85		0.7	1.20	0.64	6.59	0.14	0.18	0.72	0.52	8.87		13.48	0.13	0.37	0.27	9.96	2.56	2.73	0.8					11.18	1.19
86		0.92	1.48	0.48	4.46	0.09	0.18	0.66	0.68	10.64		10.72	0.08	0.38	0.19	15.12	3.5	2.47	0.61					15.6	1.45
87		0.7	1.72	0.85	5.32	0.21	0.12	0.93	0.53	8.77		13.35	0.17	0.42	0.21	8.52	1.2	2.08	0.82					18.03	1.26
88		1.05	1.76	0.73	4.78	0.14	0.09	0.91	0.72	10.29		13.31	0.14	0.34	0.26	16.92	1.84	3.64	1.15					16.21	0.98
89		0.99	1.08	0.75	3.14	0.11	0.15	0.69	0.45	4.78		13.5	0.16	0.31	0.2	9.48	3.22	2.86	1.07					20.8	1.05
90		1.06	1.35	0.36	6.55	0.09	0.15	0.72	0.37	9.76		10.76	0.08	0.24	0.23	12.96	2.38	2.6	1.27					20.97	1.7
91		0.96	1.24	0.57	2.85	0.19	0.11	0.84	0.4	5.08		10.08	0.1	0.3	0.28	12	1.46	1.95	0.77					9.01	1.4
92		1.06	1.92	0.42	4.53	0.12	0.18	0.51	0.67	10.5		11.9	0.17	0.34	0.23	11.88		1.69	0.95					10.23	0.98
93		0.7	1.38	0.48	6.54	0.21	0.14	0.49	0.4	9.05		11.66	0.11	0.37	0.26	17.04		1.82	0.98					11.53	1.87
94		1.09	1.32	0.90	3.36	0.09	0.08	0.43	0.63	4.98		10.56	0.1	0.29	0.2	11.28		2.6	0.99					6.33	1.33
95		0.8	1.60	0.92	5.89	0.18	0.1	0.69	0.34	7.9		12.84	0.1	0.42	0.25	10.32		3.25	0.84					14.56	1.45
96		0.63	1.75	0.77	6.06	0.19	0.17	0.56	0.55	4.83		10.94	0.11	0.29	0.19	11.16			0.56					20.11	1.04
97		0.86	1.63	0.77	5.17	0.15	0.18	0.52	0.55	4.58		11.5	0.1	0.25	0.26	12			0.81					11.53	1.39
98		1.06	1.97	0.76	5.92	0.18	0.09	0.63	0.55	10.69		13.32	0.1	0.42	0.19	17.28			0.56					12.65	1.63
99		0.82	1.31	0.56	3.33	0.09	0.09	0.42	0.74	8.37		11.15	0.09	0.33	0.26	17.76			1.27					19.07	0.92
100		0.96	1.80	0.65	5.42	0.13	0.15	0.43	0.55	7.74		11.9	0.09	0.32	0.19	8.04			0.95					11.61	0.87
101		0.51	1.03	0.41	6.14	0.29	0.13	0.89	0.42	9.33		15.08	0.09	0.23	0.25				0.98					10.66	1.86
102		1.47	2.21	0.9	5.32	0.14	0.17	0.41	0.59	8.46		11.61	0.09	0.25	0.21				0.59					11.35	1.52
103		0.42	1.8	0.81	3.2	0.18	0.13	0.61	0.71	10.44		8.9	0.09	0.27	0.23				1.1					15.69	1.32
104		1.38	1.08	0.94	6.69	0.15	0.12	0.76	0.72	6.59		10.5	0.17	0.43	0.27				1.02					14.56	0.7
105		0.54	1.01	0.94	3.59	0.2	0.15	0.87	0.62	4.51		12.78	0.17	0.33	0.24				0.95					11.35	1.51
106		0.73	2.02	0.59	3.43	0.1	0.09	0.94	0.65	4.71		12.75	0.16	0.34	0.21				0.73					12.48	1.12
107		0.92	1.54	0.48	6.48	0.18	0.16	0.78	0.73	8.18		12.89	0.14	0.42	0.19				1.24					11.96	1.51
108		1.4	1.01	0.39	6.64	0.2	0.09	0.94	0.5	5.22		11.2	0.15	0.31	0.24				0.57					6.07	0.76
109		0.86	1.34	0.75	6.3	0.25	0.17	0.82	0.32	6.08		13.37	0.15	0.33	0.2				1.04					6.33	0.68
110		1.09	1.2	0.95	6.49	0.11	0.1	0.93	0.41	9.44		12.69	0.09	0.35	0.29				0.53					6.85	0.82
111		0.9	1.01	0.45	5.46	0.19	0.09	0.75	0.35	9.91		11.26	0.15	0.37	0.25				1.25					15.77	1.09
112		0.48	2.14	0.59	3.67	0.12	0.12	0.89	0.51	8.05		14.77	0.09	0.25	0.28				1.23					13.43	1.6
113		1.28	1.37	0.39	3.05	0.14	0.09	0.81	0.46	10.59		14.06	0.1	0.37	0.28				0.91					21.75	1.79
114		1.21	1.5	0.86	4.38	0.07	0.18	0.73	0.58	8.62		11.92	0.17	0.31	0.28				0.62					7.37	1.39

115		0.96	1.13	0.61	3.95	0.13	0.09	0.73	0.45	6.43		12.73	0.16	0.4	0.27				1.17					12.31	1.35
116		0.76	1.4	0.51	3.68	0.17	0.08	0.87	0.65	10.58		13.63	0.08	0.38	0.2				0.85					15.69	1.52
117		0.73	1.7	0.89	2.79	0.15	0.11	0.81	0.39	5.17		12.51	0.16	0.35	0.26				1.25					18.29	1.8
118		1.21	1.51	0.59	3.18	0.21	0.14	0.52	0.66	6		12.41	0.08	0.37	0.2				1.27					14.21	1.11
119		1.15	1.2	0.49	3.89	0.14	0.1	0.7	0.65	8.83		13.43	0.07	0.43	0.23				0.61					18.63	0.85
120		1.06	1.84	0.62	5.65	0.18	0.18	0.95	0.67	8.98		13.11	0.12	0.35	0.2				0.97					17.94	1.49
121		1.11	1.9	0.54	3.71	0.13	0.14	0.78	0.47	8.67		13.16	0.11	0.36	0.24				0.6					16.03	1.2
122		1.28	1.44	0.54	5.38	0.13	0.15	0.42	0.37	6.62		13.24	0.14	0.28	0.26				1					7.8	0.88
123		1.34	2.09	0.47	4.13	0.18	0.11	0.9	0.58	10.35		8.79	0.11	0.33	0.21				1.18					14.56	1.69
124		0.63	1.55	0.39	2.79	0.16	0.17	0.55	0.43	4.43		9.29	0.08	0.34	0.27				1.08					8.06	1.11
125		0.54	1.31	0.71	5.85	0.18	0.16	0.57	0.4	6.67		16.09	0.08	0.38	0.26				1.19					7.37	1.26
126		1.34	2.05	0.54	4.66	0.17	0.15	0.96	0.5	7.35		9.98	0.08	0.27	0.25				0.67					6.33	1.84
127		0.63	1.85	0.88	5.44	0.22	0.17	0.66	0.68	8.72		13.13	0.13	0.42	0.19				0.94					14.56	0.7
128		0.9	1.06	0.73	3.3	0.12	0.12	0.52	0.38	7.15		13.03	0.1	0.33	0.23				0.67					9.97	0.72
129		0.51	2.11	0.39	4.18	0.14	0.11	0.45	0.64	6.83		13.46	0.15	0.4	0.27				0.74					9.1	1.82
130		0.57	1.26	0.68	2.58	0.18	0.09	0.92	0.58	4.92		14.28	0.1	0.37	0.2				1.21					18.63	1.26
131		1.34	1.22	0.47	4.03	0.15	0.18	0.8	0.74	5.32		10.59	0.1	0.41	0.27				0.84					7.19	1.81
132		0.54	1.72	0.69	4.3	0.13	0.16	0.5	0.51	6.53		14.9	0.12	0.32	0.27				1.11					7.19	1.86
133		1.21	1.4	0.4	6.12	0.19	0.09	0.63	0.73	10.14		12.74	0.17	0.33	0.25				0.6					20.37	1.62
134		0.7	0.9	0.53	6.55	0.18	0.09	0.84	0.58	9.38		11.8	0.08	0.41	0.22				0.73					7.02	1.41
135		1.21	2	0.43	3.39	0.19	0.16	0.45	0.7	7.23		12.75	0.09	0.35	0.24				0.66					6.76	1.44
136		0.92	2.24	0.55	5.85	0.16	0.18	0.54	0.49	4.53		9.97	0.1	0.3	0.26				0.62					10.14	1.2
137		0.48	2.24	0.47	5.86	0.17	0.15	0.64	0.49	6.22		12.58	0.07	0.29	0.23				0.96					7.11	1.47
138		0.44	1.55	0.81	5.94	0.19	0.14	0.66	0.55	7.22		13.63	0.16	0.42	0.28				0.62					17.51	1.13
139		0.51	1.55	0.95	2.66	0.17	0.16	0.57	0.6	8.18		12.63	0.14	0.27	0.25				0.99					11.18	1.79
140		0.48	1.09	0.36	3.1	0.19	0.19	0.74	0.37	10.18		10.56	0.08	0.33	0.24				1.27					11.7	1.46
141		0.82	2.21	0.41	6.47	0.19	0.18	0.48	0.58	9.53		13.11	0.1	0.25	0.22				0.84					6.15	1.28
142		1.14	0.91	0.82	4.48	0.22	0.12	0.49	0.71	6.99		10.46	0.17	0.42	0.23				1.24					7.45	0.98
143		0.9	1.49	0.47	3.13	0.15	0.19	0.77	0.46	4.61		12.9	0.17	0.37	0.2				1.08					15.08	1.32
144		0.57	2.15	0.49	5.74	0.16	0.09	0.49	0.61	4.57		9.47	0.15	0.31	0.26				0.79					7.71	1.7
145		0.48	2.21	0.49	6.23	0.16	0.18	0.55	0.53	7.26		11.44	0.07	0.32	0.21				0.78					9.27	1.81

146		1.02	1.36	0.42	4.62	0.13	0.17	0.76	0.33	6.28		13.17	0.17	0.39	0.27				1.23					7.19	
147		0.99	1.22	0.52	4.63	0.17	0.09	0.85	0.51	6.73		9.77	0.13	0.35	0.28				0.56					22.62	
148		0.92	2.07	0.36	5.46	0.21	0.13	0.45	0.59	7.85		11.49	0.08	0.43	0.25				0.88					18.89	
149		0.67	1.07	0.61	3.15	0.12	0.16	0.76	0.61	7.53		13.41	0.08	0.26	0.26				0.76					15.69	
150		1.3	1.47	0.87	5.44	0.2	0.17	0.81	0.55	7.34		11.12	0.14	0.27	0.25				0.83					14.47	
151		0.57	2.16	0.69	5.62	0.19	0.1	0.47	0.73	8.44		10.89	0.14	0.26	0.27				0.83					10.4	
152		1.5	1.22	0.71	2.84	0.15	0.12	0.69	0.48	6.87		9.82	0.16	0.38	0.25				0.61					12.65	
153		0.51	1.65	0.68	6.01	0.16	0.12	0.95	0.68	7.27		10.44	0.16	0.37	0.21				1.08					19.59	
154		0.77	1.74	0.6	4.11	0.13	0.09	0.65	0.53	10.26		11.35	0.15	0.41	0.25				1.18					19.33	
155		0.67	1.94	0.41	3.86	0.13	0.16		0.57	8.84		9.25	0.14	0.33	0.25				0.71					9.53	
156		1.53	1.6	0.57	5.19	0.12	0.12		0.68	4.84		10.49	0.07	0.4	0.26				0.72					10.05	
157		0.57	1.48	0.84	5.83	0.17	0.14		0.65	6.26		11.03	0.1	0.35	0.26				0.71					7.89	
158		1.06	1.1	0.86	5.24	0.14	0.15		0.35	9.72		10.11	0.16	0.36	0.21				0.55					13	
159		1.25	1.51	0.56	6.08	0.15	0.08		0.63	9.64		13.45	0.12	0.42	0.22				0.86					21.23	
160		1.09	2.23	0.4	6.07	0.2	0.16		0.65	4.66		10.48	0.09	0.37	0.24				1.2					18.81	
161		0.99	1.69	0.45	4.6	0.17	0.09		0.46	6.39		11.42	0.12	0.41	0.26				1.02					14.21	
162		0.42	1.48	0.62	6.46	0.2	0.09		0.6	7.99		15.19	0.17	0.28	0.24				1.07					12.05	
163		0.63	1.93	0.37	3.02	0.17	0.15		0.33	7.53		10.6	0.17	0.29	0.23				0.76					10.75	
164		0.61	2	0.77	6.39	0.16	0.17		0.48			7.76	0.09	0.25	0.23				1.13					6.85	
165		1.05	1.9	0.81	4.85	0.19	0.11		0.48			9.36	0.14	0.29	0.23				1.27					13.17	
166		1.09	1.15	0.5	6.49	0.17	0.16		0.51			7.26	0.17	0.43	0.24				1.01					12.74	
167		1.28	1.15	0.91	2.59	0.18	0.14		0.71			8.25	0.16	0.41	0.27				0.81					23.14	
168		1.54	2.14	0.69	6.23	0.22	0.12		0.64			9.77	0.11	0.27	0.25				0.7					18.63	
169		1.18	1.57	0.47	2.65	0.22	0.08		0.61			10	0.1	0.36	0.27				0.76					8.15	
170		0.34	2.03	0.46	6.26	0.2	0.18		0.41		W4	6.8	0.11	0.27	0.21				1.06					17.59	
171		0.92	1.42	0.8	6	0.16	0.15		0.43			10.51	0.17	0.34	0.23				0.96					18.89	
172		1.14	1.51	0.55	3.15	0.21	0.1		0.37			10.97	0.15	0.4	0.19				0.72					8.41	
173		1.14	0.95	0.68	6.4	0.19	0.12		0.48			12.12	0.09	0.39	0.22				1.19					15.43	
174		1.28	1.55	0.55	5.44	0.11	0.12		0.56			10.24	0.17	0.33	0.26				0.59					10.66	
175		1.53	1.39	0.69	5.34	0.14	0.09		0.53			10.11	0.14	0.42	0.26				0.99					17.42	
176		1.21	2.15	0.74	3.05	0.13	0.19		0.33			9.51	0.15	0.29	0.21				0.56					21.67	

177		1.28	0.93	0.42	5	0.13	0.08		0.4			10.94	0.13	0.32	0.27				0.98					18.98	
178		0.38	1.41	0.55	3.91	0.2	0.11		0.68			12.18	0.14	0.24	0.2				0.69					20.63	
179		0.51	1.79	0.76	4.95	0.2	0.15		0.74			10.06	0.17	0.4	0.22				0.83					16.12	
180		0.86	1.98	0.59	5.35	0.15	0.11		0.32			9.67	0.1	0.31	0.24				0.99					18.55	
181		0.92	2.22	0.9	2.57	0.14	0.09		0.64			11.12	0.12	0.32	0.24				0.93					22.62	
182		1.43	1.23	0.53	6.06	0.16	0.11		0.57			7.74	0.1	0.25	0.21				0.58					17.59	
183		1.5	1.88	0.42	6.45	0.13	0.12		0.67			11.56	0.14	0.36	0.22				1.21					18.72	
184		0.77	1.41	0.63	6.25	0.2	0.08		0.49			8.64	0.12	0.41	0.2				1.09					22.36	
185		1.25	1.9	0.41	5.65	0.14	0.16		0.57			9.18	0.14	0.33	0.24				0.67					8.93	
186		0.42	2.19	0.51	3.96	0.21	0.11		0.46			8.41	0.11	0.42	0.23				0.85					14.47	
187		0.99	1.27	0.73	4.84	0.2	0.09		0.67			8.03	0.1	0.32	0.24				0.68					10.75	
188		1.28	1.56	0.71	6.65	0.12	0.15		0.37			10.16	0.18	0.27	0.28				0.87					22.62	
189		0.51	1.57	0.49	6.75	0.11	0.13		0.34			11.29	0.07	0.35	0.26				0.78					6.15	
190		0.42	2.25	0.52	5.89	0.18	0.12		0.32			7.98	0.17	0.41	0.29				1					21.06	
191		0.63	2.13	0.56	3.62	0.17	0.11		0.66			8.56	0.14	0.39	0.21				0.84					22.19	
192		1.11	1.88	0.62	3.72	0.22	0.16		0.44			11.26	0.15	0.42	0.25				1.22					11.96	
193		0.73	1.06	0.77	5.7	0.13	0.08		0.57			11.76	0.13	0.27	0.22				1.07						
194		1.21	1.65	0.92	2.74	0.16	0.12		0.61			8.32	0.13	0.35	0.26				0.94						
195		0.54	1.91	0.46	4.18	0.17	0.11		0.62			10.67	0.09	0.27	0.21				1.27						
196		0.42	1.38	0.74	3.71	0.17	0.13		0.68			8.64	0.16	0.26	0.27				1.02						
197		1.06	1.47	0.68	5.28	0.15	0.09		0.47			8.45	0.12	0.35	0.27				0.84						
198		0.44	1.86	0.68	5.63	0.18	0.09		0.7			7.1	0.16	0.42	0.26				1.19						
199		0.67	1.71	0.86	4.03	0.15	0.18		0.46			10.81	0.1	0.42	0.22				0.82						
200		0.82	1.94	0.85	6.65	0.22	0.08		0.59			7.82	0.16	0.38	0.23				1.09						
201		0.42	1.61	0.46	6.37	0.15	0.14		0.72			9.49	0.14	0.23	0.28				0.83						
202		0.57	1.32	0.74	2.68	0.14	0.17		0.7			7.42	0.08	0.35	0.27				0.94						
203		0.86	1.42	0.68	3.49	0.14	0.09		0.52			7.77	0.08	0.4	0.28				0.7						
204		0.95	2.1	0.58	3.63	0.11	0.08		0.32			11.45	0.08	0.4	0.27				0.65						
205		0.92	1.96	0.44	5.6	0.15	0.11		0.42			10.78	0.13	0.41	0.22				0.65						
206		1.02		0.94	6.56	0.12	0.1		0.46			8.61	0.12	0.29	0.22				1.23						
207		0.76		0.65	6.54	0.12	0.13		0.64			11.88	0.12	0.31	0.27				1.19						

208		1.34		0.66	2.62	0.2	0.13		0.63			7.51	0.09	0.43	0.24				0.81						
209		1.25		0.39	5.99	0.17	0.18		0.67			8.95	0.13	0.28	0.28				0.87						
210		0.63		0.46	6.6	0.18	0.17		0.66			6.83	0.12	0.37	0.22				1.16						
211		0.7		0.7	2.69	0.13	0.08		0.42			16.86	0.18	0.25	0.24				1.1						
212		0.86		0.57	3.48	0.18	0.09		0.69			13.3	0.13	0.38	0.2				1.12						
213		0.77		0.5	5.28	0.2	0.18		0.67			13.5	0.1	0.26	0.2				0.53						
214		0.34		0.8	6.35	0.2	0.08		0.65			14.02	0.14	0.25	0.24				0.91						
215		0.38		0.61	5.67	0.15	0.14		0.41			14.22	0.12	0.26	0.28				1.03						
216		0.95		0.76	4.86	0.2	0.19		0.68			17.4	0.15	0.28	0.21				1						
217		0.57		0.85	4.78	0.16	0.15		0.67			15.44	0.12	0.26	0.28				1.08						
218		0.42		0.63	4.36	0.13	0.11		0.42			13.54	0.17	0.38	0.23				1.13						
219		0.92		0.7	4.64	0.19	0.19		0.33			18.66	0.13	0.4	0.24				0.98						
220		1.15		0.37	2.7	0.14	0.1		0.59			14.62	0.11	0.43	0.21				0.66						
221		1.24		0.88	4.73	0.12	0.19		0.46			13.38	0.08	0.3	0.26				0.7						
222		1.21		0.82	3.95	0.17	0.11		0.7			18.22	0.14	0.42	0.24				0.83						
223		0.34		0.56	4.18	0.2	0.15		0.63			17.62	0.17	0.33	0.2				1.04						
224		0.66		0.41	4.13	0.11	0.18				W5	18.26	0.14	0.4	0.21				0.56						
225		1.14		0.62	4.11	0.19	0.18					17.7	0.16	0.27	0.19				0.79						
226		1.34		0.75	3.46	0.15	0.13					14.76	0.09	0.32	0.25				1.28						
227		1.15		0.36	4.26	0.2	0.1					16.1	0.18	0.34	0.29				1.26						
228		0.48		0.73	3.07	0.12	0.17					17.08	0.16	0.43	0.29				0.54						
229		0.51		0.5	6.73	0.16	0.12					16.4	0.13	0.36	0.2				0.62						
230		1.15		0.81	5.48	0.14	0.12					17.52	0.07	0.41	0.28				0.62						
231		1.5		0.91	6.58	0.13	0.16					17.52	0.15	0.4	0.25				0.72						
232		0.82		0.93	3.25	0.17	0.16					18.88	0.08	0.3	0.23				1.28						
233		1.34		0.92	3.58	0.17	0.1					17.28	0.09	0.26	0.21				1.05						
234		0.99		0.41	5.5	0.21	0.14					18.24	0.14	0.24	0.22				0.83						
235		0.7		0.85	5.09	0.19	0.11					16.44	0.16	0.42	0.25				0.84						
236		0.92		0.52	4.99	0.21	0.18					16.72	0.09	0.31	0.21				0.87						
237		0.34		0.64	5.85	0.15	0.11					14.7	0.11	0.36	0.24				0.86						
238		1.09		0.76	5.73	0.14	0.17					13.5	0.08	0.29	0.29				1.26						

239		1.14		0.36	5.29	0.17	0.11					16.06	0.16	0.32	0.22				1.05						
240		0.7		0.73	5.02	0.19	0.13					15.52	0.15	0.36	0.22				1.11						
241		0.86		0.92	6.77	0.18	0.16					16.24	0.09	0.31	0.2				1.11						
242		1.06		0.44	6.4	0.21	0.14					16.88	0.13	0.24	0.22				0.89						
243		1.5		0.77	5.4	0.2	0.14					17.64	0.12	0.37	0.26				0.7						
244		1.25		0.64	5.83	0.2	0.11					19.52	0.15	0.34	0.19				0.67						
245		0.44		0.63	6.21	0.16	0.1					15.22	0.14	0.37	0.22				1.08						
246		1.3		0.8	5.67	0.18	0.17					14.8	0.16	0.41	0.23										
247		0.67		0.54	2.56	0.22	0.1					20.7	0.07	0.25	0.2										
248		1.18		0.9	6.45	0.18	0.08					13.34	0.12	0.43	0.28										
249		1.06		0.71	4.03	0.16	0.17					18.2	0.12	0.31	0.25										
250		1.18		0.58	3.08	0.19	0.11					20.68	0.12	0.27	0.2										
251		0.44		0.6	6.27	0.14	0.14					21.74	0.15	0.28	0.19										
252		1.06		0.78	4.04	0.2	0.15				W6	23.16	0.15	0.24	0.27										
253		1.24		0.91	5.96	0.12	0.1					18.62	0.12	0.35	0.2										
254		0.47		0.51	4.91	0.2	0.08					18.36	0.17	0.33	0.27										
255		0.42		0.51		0.19	0.09					21.6	0.14	0.34	0.28										
256		0.38		0.76		0.13	0.16					16.12	0.09	0.37	0.27										
257		0.51		0.5		0.21	0.1					19.52	0.08	0.35	0.22										
258		0.86		0.77		0.15	0.08					16.66	0.17	0.24	0.24										
259		0.95		0.66		0.18	0.16					19.04	0.11	0.25	0.24										
260		0.8		0.66		0.18	0.18					17.96	0.09	0.34	0.22										
261		0.73		0.46		0.14	0.13					19.24	0.14	0.41	0.24										
262		0.51		0.6		0.18	0.18					20.98	0.11	0.36	0.27										
263		1.47		0.84		0.13	0.13					17.52	0.08	0.29	0.25										
264		0.99		0.79		0.21	0.11					15.8	0.1	0.36	0.22										
265		0.54		0.4		0.16	0.11					20.62	0.13	0.33	0.19										
266		0.95		0.87		0.19	0.13				Other Windows	19.4	0.12	0.29	0.2										
267		1.14		0.79		0.19	0.18					22.82	0.15	0.43	0.25										
268		0.63		0.57		0.19	0.12					25.94	0.09	0.3	0.26										
269		0.48		0.61		0.15	0.16					18.1	0.08	0.32	0.28										

270		0.38		0.55		0.13	0.17					20.08	0.08	0.37	0.22										
271		0.86		0.49		0.21	0.12					19.06	0.09	0.24	0.2										
272		1.5		0.77		0.17	0.15					16.14	0.16	0.38	0.27										
273		1.24		0.59		0.15	0.18					16.86	0.15	0.27	0.27										
274		1.44		0.81		0.11	0.17					21.1	0.1	0.39	0.22										
275		1.02		0.6		0.16	0.17					18.46	0.08		0.28										
276		1.34		0.66		0.12	0.12					23.3	0.17		0.2										
277		1.06		0.39		0.19	0.08					19.82	0.15		0.24										
278		0.7		0.92		0.18	0.13					4.74	0.14		0.26										
279		1.06		0.36		0.11	0.12					6.24	0.11		0.23										
280		1.24		0.58		0.2	0.18					5.46	0.09		0.27										
281		1.28		0.71		0.13	0.17					4.32	0.13		0.26										
282		0.63		0.41		0.15	0.12					4.2	0.11		0.27										
283		0.63		0.36		0.12	0.15					4.86	0.18		0.26										
284		0.44		0.59		0.21	0.13					5.34	0.15		0.2										
285		1.21		0.71		0.15	0.11					4.5	0.18		0.26										
286		0.57		0.81		0.22	0.15					5.94	0.09		0.27										
287		0.67		0.8		0.14	0.1					6.06	0.18		0.23										
288		1.14		0.9		0.16	0.18				D1	4.5	0.11		0.26										
289		1.15		0.48		0.21	0.11					6.72	0.1		0.25										
290		0.95		0.69		0.21	0.12					6.84	0.14		0.22										
291		0.92		0.47		0.19	0.19					5.46	0.16		0.28										
292		0.47		0.71		0.17	0.17					4.86	0.17		0.23										
293		0.63		0.46		0.13	0.19					5.88	0.17		0.21										
294		1.24		0.7		0.21	0.12					6.84	0.12		0.27										
295		1.43		0.43		0.12	0.16					4.38	0.14		0.25										
296		1.38		0.6		0.14	0.16					4.5	0.11		0.21										
297		0.44		0.52		0.15	0.1					4.62	0.15		0.25										
298		1.09		0.72		0.16	0.09					6.78	0.12		0.2										
299		1.18		0.76		0.12	0.14				D2	11.57	0.12		0.19										
300		0.38		0.42		0.21	0.15					11.54	0.12		0.25										

301		1.53		0.43		0.2	0.15					8.76	0.17		0.25										
302		0.96		0.59		0.14	0.16					8.98	0.08		0.28										
303		0.42		0.41		0.15	0.12					9.87	0.14		0.29										
304		0.86		0.65		0.14	0.15					9.77	0.07		0.21										
305		1.18		0.49		0.11	0.15					7.97	0.07		0.23										
306		0.67		0.66		0.16	0.09					9.34	0.08		0.25										
307		1.34		0.88		0.13	0.11					9.7	0.11		0.24										
308		1.14		0.79		0.13	0.14					8.37	0.08		0.22										
309		1.43		0.78		0.14	0.11					9.82	0.09		0.27										
310		1.06		0.61		0.17	0.19					8.13	0.11		0.23										
311		1.21		0.4		0.13	0.18					7.8	0.16		0.2										
312		0.9		0.48		0.15	0.12					7.37	0.17		0.22										
313		1.05		0.76		0.21	0.11					8.82	0.11		0.28										
314		0.47		0.77		0.19	0.09					8.47	0.15		0.24										
315		1.34		0.91		0.14	0.13					9.24	0.1		0.22										
316		1.38		0.9		0.14	0.18					8.45	0.18		0.28										
317		1.34		0.53		0.21	0.17					8.65	0.16		0.25										
318		0.9				0.21	0.1					9.45	0.13		0.21										
319		0.96				0.19	0.18					8.63	0.16		0.28										
320		0.58				0.17	0.15					9.26	0.1		0.22										
321		1.21				0.21	0.16					10.67	0.1		0.24										
322		0.9				0.18	0.16					7.49	0.09		0.21										
323		0.96				0.19	0.1					8.15	0.08		0.2										
324		0.73				0.19	0.13					10.7	0.08		0.23										
325		0.47				0.12	0.19					7.48	0.17		0.23										
326		0.82				0.22	0.1					13.78	0.18		0.22										
327		0.86				0.14	0.18					9.94	0.14		0.21										
328		0.9				0.2	0.14				D3	10.64	0.13		0.24										
329		1.05				0.12	0.09					13.44	0.12		0.19										
330		0.48				0.15	0.13					10.7	0.09		0.25										
331		0.63				0.11	0.17					12.42	0.12		0.27										

332		1.5				0.13	0.14					10.64	0.07		0.25										
333		0.92				0.17	0.19					11.42	0.15		0.23										
334		0.92				0.15	0.08					14.38	0.1		0.22										
335		1.15				0.21	0.18					13.86	0.16		0.24										
336		0.99				0.2	0.14					10.92	0.15		0.27										
337		0.44				0.18	0.19					13.02	0.09		0.2										
338		1.05				0.2	0.15					12.78	0.15		0.26										
339		1.14				0.11	0.13					11.76	0.18		0.2										
340		1.54				0.22	0.15					10.96	0.08		0.26										
341		0.92				0.12	0.14					11.2	0.15		0.24										
342		0.9				0.16	0.09					11.04	0.17		0.23										
343		1.15				0.19	0.15					11.84	0.16		0.21										
344		0.99				0.12	0.17					11.22	0.09		0.28										
345		0.63				0.2	0.16					10.44	0.14		0.27										
346		1.5				0.14	0.1					15.92	0.12		0.28										
347		0.38				0.19	0.17					11.8	0.13		0.21										
348		1.44				0.2	0.18					12.12	0.09		0.2										
349		1.3				0.15	0.14					12.76	0.16		0.21										
350		0.57				0.2	0.1					16.01	0.13		0.28										
351		0.92				0.16	0.15					14.52	0.11		0.21										
352		0.34				0.11	0.09					11.12	0.1		0.24										
353		1.5				0.16	0.16					12.61	0.09		0.21										
354		0.58				0.14	0.17					13.38	0.16		0.23										
355		0.57				0.21	0.17				D4	14.35	0.17		0.25										
356		1.21				0.18	0.13					12.31	0.16		0.21										
357		0.58				0.18	0.16					14.31	0.17		0.27										
358		0.38				0.2	0.1					13.14	0.12		0.25										
359		0.42				0.12	0.11					13.23	0.15		0.24										
360		1.14				0.12	0.08					14.78	0.18		0.24										
361		1.21				0.18	0.15					10.37	0.14		0.27										
362		0.63				0.13	0.1					12.05	0.16		0.26										

363		0.57				0.17	0.11					13.54	0.14		0.27										
364		0.48				0.18	0.13					10.71	0.08		0.19										
365		0.73				0.22	0.08					14.34	0.15		0.23										
366		0.96				0.12	0.15					13.11	0.07		0.2										
367		0.67				0.21	0.17					20.86	0.12		0.28										
368		1.05				0.16	0.11					17.29	0.1		0.27										
369		1.24				0.12	0.15					11.77	0.11		0.23										
370		0.86				0.17	0.15					19.23	0.18		0.2										
371		0.86				0.19	0.12					16.02	0.12		0.22										
372		0.92				0.17	0.1					19.45	0.17		0.24										
373		1.21				0.11	0.15					15.65	0.16		0.22										
374		1.43				0.15	0.19					16.34	0.17		0.25										
375		0.63				0.16	0.14					18.46	0.14		0.24										
376		1.34				0.2	0.18					16.27	0.1		0.22										
377		1.54				0.14	0.08					16.92	0.15		0.28										
378		1.43				0.19	0.15					19.12	0.11		0.21										
379		1.06				0.18	0.1					15.45	0.13		0.23										
380		1.34				0.13	0.12				D5	14.77	0.07		0.22										
381		0.63				0.18	0.08					20.23	0.14		0.27										
382		1.25				0.21	0.13					15.65	0.11		0.2										
383		0.73				0.18	0.14					17.44	0.07		0.23										
384		0.38				0.12	0.1					17.78	0.12		0.22										
385		0.96				0.13	0.19					13.23	0.07		0.23										
386		1.5				0.18	0.17					19.92	0.1		0.22										
387		1.5				0.16	0.11					15.75	0.13		0.22										
388		1.5				0.17	0.15					17.34	0.17		0.24										
389		0.38				0.15	0.13					12.31	0.12		0.24										
390		0.48				0.2	0.18					16.57	0.15		0.22										
391		0.7				0.19	0.17					21.4	0.11		0.22										
392		1.06				0.21	0.12					19.27	0.1		0.24										
393		1.5				0.19	0.1					15.73	0.13		0.26										

394		0.8				0.14	0.15					13.77	0.13		0.28										
395		0.99				0.15	0.1					16.48	0.16		0.22										
396		0.38				0.18	0.11					16.63	0.15		0.26										
397		0.34				0.17	0.09					15.73	0.14		0.2										
398		1.38				0.2	0.16					16.95	0.13		0.27										
399		1.34				0.12	0.09					10.99	0.08		0.22										
400		0.86				0.22	0.19					17.04	0.16		0.25										
401		1.4				0.2	0.16					16.3	0.16		0.21										
402		1.47				0.19	0.1				Other Doors	16.84	0.16		0.29										
403		0.9				0.2	0.1					15.28	0.09		0.26										
404		0.99				0.2	0.16					16.48	0.16		0.2										
405		0.44				0.2	0.19					21.36	0.13		0.2										
406		0.48				0.22	0.1					23.84	0.12		0.2										
407		1.47				0.2	0.11					17.74	0.17		0.22										
408		1.11				0.13	0.17					20.08	0.09		0.22										
409		1.5				0.2	0.13					19.9	0.15		0.2										
410		1.11				0.19	0.16					15.72	0.16		0.24										
411		0.34				0.11	0.15						0.14												
412		1.43				0.22	0.14						0.14												
413		1.28				0.21	0.15						0.17												
414		0.8				0.21	0.11						0.09												
415		0.57				0.14	0.17						0.14												
						0.16	0.08						0.07												
						0.12	0.09						0.12												
						0.12	0.15						0.12												
						0.13	0.09																		
						0.13	0.13																		
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						0.15	0.13																		
						0.21																			
						0.17																			

Addis Ababa Institute of Technology School of Civil and Environmental Engineering Graduate Program in Construction Technology and Management Thesis on: Implementation of Value Stream Mapping Integrated with Discrete Event Simulation for Productivity Improvement of Aluminum Window and Door Manufacturing Observation Data Collection Sheet Format										
Summary of Sub-processes Case Study: Vision Aluminum Manufacturing plc Location: Sululta										
No.	Operation	Operation Description	Average man power involved	Machinery/ Tools used	Time calculation unit	Avg Cycle Time (min)	Avg CT (min) /unit	VAA (min)	NVA A (min)	Waste type
1	Hauling Frame & Ferma profiles from store to cutting workstation	Receiving required aluminum frame from store keeper, arrange and transport to the cutting work station	3 Laborers	Cart	20 frames	7.8	0.39	0	0.39	Transportation , Waiting, Motion
2	Measuring & cutting frame	The CNC cutting machine operator get frame profile, measure the dimension, adjust the cutting machine and cut the frame as per the cutting optimization output.	1 Machine operator, & 1 Helper	CNC cutting machine, Marker	each window/ door	5.67	5.67	4.23	1.44	Setup, rework, Minor Adjustments
3	Hauling frame to assembly station after cutting	Once the frame cut as per the required size, the laborers pick up to 10 sized frames and transport to the drilling & assembly workstation	3 Labourers	None	10 sized frames	1.56	1.56	0	1.56	Transport
4	End Milling	The End milling (Chamfering) for T-profiles, mullion & transom end-milling for fitting different frame using CNC chamfering machine	1 Chamfering machine operator	Chamfering machine	each window/door	1.28	1.28	0.99	0.29	Machine Setup, waiting,
5	Routering for lock & operator	Router for one lock and one operator	1 Routering machine operator	Routering machine	each lock and operator	4.79	4.79	2.84	1.95	Extra Motion, Machine

										Adjustment, Rework
6	Punching	Drill holes on aluminum frames using punching machine	1 Punching machine operator	Punching machine	each window/door	1.29	1.29	1.01	0.28	Motion, Machine Adjustment, waiting
7	Drilling by small movable drill	Drill holes on aluminum frames using small mobile drilling machine	1 Assembly technician with 1 helper on one assembly table. There are 6 assembly tables with each of 1 assembler & 1 helper, total of 12 workers	Assembly table, Small mobile drilling machine, drill bits	each window/ door	4.06	4.06	2.63	1.43	Motion, Tool Adjustments, waiting
8	Gasket/Tape Installation on	Apply gasket	1 Assembly technician & 1 helper	Assembly table	each window/ door	3.21	3.21	2.3	0.91	Extra Handling, waiting, over processing
9	Install Hardware	Install track, ramp, operator, snubber, lock handle, tie bar and accessories	1 Assembly technician & 1 helper	Assembly table, Screw tighter	each window/ door	7.52	7.52	4.13	3.39	Motion, Handling Errors, rework
10	Frame Assembly	Joining aluminum frame components using screw, and connecters	1 Assembly technician & 1 helper	Assembly table, Screw tighter	each window/door	10.97	10.97	6.17	4.8	Repositioning, Minor Adjustments
11	Measuring & Cutting Glass stop/ Ferma	Get glazing stop profile, cut profile in a small mobile cutting machine saw,	1 Mobile cutting machine operator, 1 Assembly technician & 1 helper	Mobile cutting machine, Assembly table	each window/ door	6.67	6.67	2.79	3.88	Setup Time, defects, motion, Extra processing
12	Installing Glass stop/ Ferma	Fixing sized glass vertical and horizontal stop on the assembled main frame	1 Assembly technician & 1 helper	Assembly table	each window/ door	3.58	3.58	2.01	1.57	Motion, Extra processing, waiting
13	Quality Inspection	Quality check and scan unit	1 Quality inspection professional		each window/ door	1.11	1.11	0	1.11	Inspection

14	Hauling assembled frame to temporary storage	After quality inspection transport the assembled frame to the temporary storage	3 Labourers		Two window/ door	2.76	1.38	0	1.38	Transportation
15	Hauling Glass from store to glass cutting station	Receive glass panel from store and transport to glass cutting table	4 Labourers	Glass vacuum holder	Each full glass panel	0.2	0.2	0	0.2	Transportation
16	Measuring & cutting glass	Measure and cut the glass panel as per the size of each window/door	1 Glass cutter, 1 helper	Glass cutting table	each window/door	5.42	5.42	3.72	1.7	Setup, Adjustments, waiting
17	Cleaning & quality check	Cleaning, quality check and scan unit	1 Quality inspection professional, 1 Labourers	Glass cutting table	each window/ door	1.64	1.64	0	1.64	Inspection
18	Hauling sized glass to temporary storage	After quality check hauling sized glass to temporary storage	4 Labourers		each window/ door	1.29	1.29	0	1.29	Transportation