Simulation-Based Lean Framework to Improve Window-Manufacturing Production System

By

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ABSTRACT

The construction industry has been long recognized for its low productivity, lack of digitalization, and a reduced appetite for innovation. This has shed light on industrialization as paradigm to ensure the successful implementation of construction projects through offsite construction methods. As such, key industry participants are scaling up their production, which enables them to position themselves in a firmly competitive market in terms of strategic R&D facilities and adoption of technological advancements systems to create a diverse array of innovative products. These companies compete based on manufacturing processes, productivity, efficiency, waste minimization, and quality, all of which cater to cost reduction, faster delivery, higher quality, and a better work environment. Implementing lean simulation, multi-criterion decision making (MCDM), and experiment techniques in an Offsite Construction (OSC) facility are essential decision-making tools in a volatile market. Value stream mapping (VSM) is effective in visualizing the production process and identifying waste. However, this tool has its shortcomings and challenges on a case-by-case basis. Therefore, researchers propose to merge it with simulation-based methods to overcome its deficiencies. Simulation has been proven to be a valuable tool to test potential solutions and showcase their impact. The OSC is rich with case studies that have successfully combined both tools. However, there is limited research on incorporating Choosing by Advantages (CBA) as a mechanism to objectively filter the potential set of solutions prior to testing. This is expected to reduce the effort needed in testing and analyzing the solution and will ensure an objective and collaborative selection process. Additionally, most solutions are tested theoretically through developing simulation models, with limited attention given to conducting hands-on experiments. This research aims to present a framework to assess and improve the state of OSC. This can be achieved through an application of VSM and simulation, with the aid of CBA

and other experiments. The developed framework was successfully tested on a window and door OSC facility. This system can ultimately provide management with a valuable decision support system to improve the state of the production line, enhance the well being of the workers, and make the workplace more inclusive.

PREFACE

This thesis is an original work by Omar Ahmad Azakir. The research of which this thesis is a part received research ethics approval from the University of Alberta Research Ethics Board, project name "Simulation-Based Lean Framework to Improve Window-Manufacturing Production System", No. Pro00132779.

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LIST OF ABBREVATIONS

Abbreviation	Full Expression
AEC	Architectural Engineering and Construction.
AHP	Analytical Hierarchy Process
CBA	Choosing by Advantage
CSM	Concept Selection Method
DES	Discrete-event Simulation
DP	Dynamic Programming system
DSR	Design Science Research
DSS	Decision-Support System
ELECTRE Tri	Elimination and Choice Translating Reality
IDEF0	Icam Definition Zero
IOA	Importance of Advantage
IOA	Importance of Advantage
LP	Lean Production
MARR	Minimum Attractive Rate of Return
MCDM	Multi-Criterion Decision Making
MMH	Manual Material Handling
OSC	Off Site Construction
PLT	Production Lead Time
PW	Present Worth
SAW	Simple Additive Weighting
Smart	Simplified Multi-Attribute Rating Technique
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TPT	Total Processing time
VIKOR	VlseKriterijumska Optimizcija I Kaompromisno Resenje (in Serbian)
VSM	Value Stream Mapping
WIP	Work in Progress
WRC	Weighting, Rating, and Calculating (WRC)

CHAPTER 1: RESEARCH MOTIVATION AND OBJECTIVES

1.1 Research Motivation

The construction industry is among one of Canada's largest industries, with a $151 billion contribution to Canada's gross domestic product (GDP) in 2022 (Statista 2023). In the recent decades, the industry has been witnessing the process of industrialization through the application of different construction methods, one of which is OSC (Kamali and Hewage 2016). In OSC, building elements are manufactured in an offsite facility and transported onto the construction site for installation and assembly (Kamali & Hewage 2016). OSC has been associated with several benefits, including enhanced productivity (Blismas et al. 2006), a shorter schedule (Haas et al. 2000), lower cost (Lawson et al. 2012), higher quality (Ambler 2013), and safer working environments as opposed to other construction methods (Li et al. 2013). In an effort to achieve these benefits, lean tools can be employed in offsite production systems. Through the integration of lean tools, the effective adoption of lean production practices to maximize value and minimize waste can result in a streamlined, high-quality system with improved productivity, reduced costs, shorter lead times, and enhanced volume flexibility (Shah & Ward 2003). Ultimately, this can enhance the state of organizations in terms of overall performance, workers' well-being, and workplace inclusiveness (Hendrick 2003). Among these tools is value stream mapping (VSM), which showcases the "big picture" of a production system rather than myopically focusing on certain parts (Rother 1999). It provides a better visibility into the process of detecting the associated issues (Klotz et al. 2008). More than one solution can be suggested to tackle these issues. This necessitates the use of multi-criterion decision making (MCDM) tools as a selection method. Specifically, the use of a Choosing by Advantage (CBA) MCDM tool overcomes the limitations of traditional methods such as AHP (Analytical Hierarchy Process), as it reduces the subjectivity and improves collaboration (Parrish & Tommelein 2009). When it comes to implementation, organizations often feel reluctant to make changes to their processes, especially if the changes are substantial or if they are not well supported. Thus, there is an urge to have a tool that can reflect the possible outcomes of the solution. Therefore, simulation can be considered crucial to showcase and visualize the benefits of lean concepts or any other solution in the system. Although not very common, conducting hands-on experiments can also be valuable, when applicable, as it can better reflect reality.

Based on the above, the novelty of this study relies on providing a framework to improve the state of production system in OSC. This approach combines state-of-the-art tools and techniques, such as lean thinking, CBA, simulation, and experiments.

1.2 Study Objectives

The framework is tested on a case study of a window and door manufacturing company to achieve the following objectives:

- **Objective 1:** Obtain an overview of the current glass production process and its interdependences.
- **Objective 2:** Map down the current process to identify issues through observations and conduct a value stream map.
- **Objective 3:** Identify potential solution(s) and apply CBA to select the most favourable solution.
- **Objective 4:** Analyze multiple solutions by developing simulation models or experiments to validate their potential effects on the process and work environment.

1.3 Thesis Organization

The thesis consists of five chapters, structured as follows:

Chapter 2 provides a literature review on various topics including Lean Production (LP) and lean tools such as VSM, simulation, MCDM, CBA, and Manual Material Handling Systems (MMH).

Chapter 3 introduces the methodology followed in the thesis, outlining the approach and techniques used in the research.

Chapter 4 focuses on the implementation of the methodology. It begins with an overview of the glass process and data collection. It then presents a detailed analysis of the VSM, identifying existing waste in the system. The chapter then proceeds with CBA that helps determine which solution should be implemented. It further explains the design of the simulation model, including its verification and validation. The chapter presents the results obtained from the model, discussing the implemented solutions in the simulation, and analyzes the simulation results. Lastly, it covers the experimental plan and the results of the implemented solutions.

Chapter 5 concludes the thesis by providing an overall conclusion of the study. It also includes the contributions, discussion of the limitations of the study, and provides recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 Lean Production

Lean production (LP) is a production methodology that aims to eliminate wasteful expenditure of resources for any purpose other than value creation. This section provides a critical review of Lean. It encompasses the historical background of Lean, its application across various domains, and the advantages derived from its implementation. Lean's main objective is creating value and eliminating non-value-added activities. As the Industrial Revolution progressed, LP experienced substantial, noteworthy advancement. Its origins can be traced back to the 1800s with the introduction of interchangeable parts, eventually leading to the emergence of lean manufacturing during the 1900s.

In 1992, LP made a significant breakthrough by being introduced as a new production philosophy in the construction industry by Koskela (1992). Lean construction also marked a massive breakthrough in regard to time and cost improvements (Rick & Best 1999). The main goal of Lean is to satisfy the customer's demand with minimal waste, meaning that the product should be produced with the least number of resources, minimal costs, and delivered in the shortest possible amount of time (Bhamu & Sangwan 2014). Waste can be identified at any time, and it can be seen in operational procedures, design, and policies (Seth & Gupta 2005). Moreover, the term 'waste' refers to anything that exceeds the fewest of resources required create the product (Russell &Taylor 2011). Defects, overproduction, waiting, transportation, inventory, over-processing, and motion are considered the seven types of waste that will lead to non-value-added activities (Melton 2005).

In 2007, a study conducted by Imtiaz & Ibrahim (2007) affirmed the beneficial effects of integrating LP with operational performance. The study emphasized that this integration significantly enhanced the systems' efficiency and effectiveness. This expansion into the construction sector showed that LP is not confined solely to manufacturing. The introduction of LP principles and practices in construction aimed to optimize processes, reduce waste, and improve overall project performance.

The offsite construction industry has witnessed a substantial impact on production systems through the implementation of LP principles. Barkokébas et al. (2021) found that the integration of LP principles and building information modelling (BIM) in the management system for offsite construction proved to be highly beneficial. This adoption led to decreased waste and a yearly time reduction of 9.45%–23.33% for the enhancements implemented during the pre-manufacturing stage. Moreover, a case study conducted by (Spisakova &Kozlovska 2019) provided evidence of the effectiveness of lean techniques within a modular construction company, highlighting a range of benefits. The study revealed that through the proper adoption and execution of LP principles, the company achieved remarkable results, including a 50% reduction in machine usage, labour hours, workspace requirements, and rework, as well as a 90% reduction in the stock of materials. Yu et al. (2013) also analyzed a case study implemented in an offsite modular company and demonstrated significant improvements in operational efficiency and reduced waste through the application of lean techniques.

These studies collectively emphasize the importance of implementing LP principles in the offsite construction industry. The adoption of lean techniques can lead to substantial benefits, including reduced resource utilization, improved productivity, and minimized rework. By restructuring processes and optimizing operations, offsite construction companies can enhance their overall performance and achieve higher levels of efficiency.

2.2 Lean Tools

A range of lean tools can be applied in different manners, including principal techniques such as VSM, takt time, and other tools.

2.2.1 Value Stream Mapping

VSM has been widely used in manufacturing companies for its simplicity and applicability in the manufacturing environment. VSM is a highly valuable tool that effectively illustrates the production process and material flow. It can significantly enhance enterprises by providing a clear and concise visual representation of an entire production cycle. Moreover, it is a tool used for enterprise improvement to help envision the whole production process that showcases information and material flow (Singh et al. 2011). In essence, VSM depicts the transformation of raw materials into a product of value for the end-user (Rother 1999). VSM consists of three steps: (1) study the product from inbound to outbound in order to conduct a current VSM, (2) identify bottlenecks, find root causes, non -value-added activities, and eliminate the waste in an effort to create a future state, and (3) implement modifications in a process in order to improve production. By using VSM, production flow, waiting time, cycle time, lead time, inventory, and flow can be visualized, allowing the bottleneck cycle time to be identified over the takt time (Sundar et al. 2014).

Previous work showcases many tools available for redesigning a productive system. However, only some incorporate a framework similar to VSM in terms of level of detail and objectives. Many existing tools do not provide the merits that VSM offers. For instance, process mapping has become a popular tool to create any business model (Paper et al. 2001; Hines &Rich 1997) for the following reasons: it is founded on the measurement and analysis of quantitative data (Hammer 1990), and contains multiple languages to make the tool helpful and user-friendly (Baudin 2020). However, this tool is broad, and is not frequently adopted in manufacturing systems.

Another tool that can be used to redesign a production system is the Icam Definition Zero (IDEF0), which has been tailored towards modelling manufacturing systems. A hierarchical functional-structured analysis is performed using IDEF0 to describe the activities of a manufacturing system (Roboam 1993). However, this technique is qualitative and not quantitative (Wu 1996). A third tool is the material and information flow modelling and simulation software. Although it is a quantitative tool and focus method, it is time-consuming, limiting its favourability for application (Oyarbide 2003).

VSM is widely used in the health industry (Souza 2009), and has been adopted by the construction industry as an effective lean tool for enhancing process performance, as indicated by research conducted by (Pasqualini &Zawislak 2005). Additionally, VSM has gained recognition as one of the most prevalent lean techniques for promoting sustainability, as highlighted by (Oladapo et al. 2014). VSM has been applied in the product development sector as a functional model to assess and appraise the effectiveness of a product development process. The literature shows many articles related to lean product development that have concentrated on the application and implementation of VSM in the product development process (Shou et al. 2017). The manufacturing industry has witnessed the utilization of VSM in many publications. For instance, both Forno et al. (2014) and Singh et al. (2011) conducted literature reviews that focused on VSM implementation within the manufacturing sector.

VSM has been widely applied in numerous cases within the context of OSC. Goh and Goh (2019) employed VSM as a lean tool in with discrete-event simulation (DES) to evaluate the Prefabricated Prefinished Volumetric Construction (PPVC) process. The study found that using VSM led to a reduction in cycle time, improved process efficiency, and increased productivity among workers.

By leveraging VSM and DES, the study successfully identified areas for improvement, optimized the workflow, and enhanced overall performance in PPVC. Youyi et al. (2020) suggested a framework using production line breakdown with VSM on a construction manufacturing production line. This study resulted in a 15% reduction in total work hours and a 20% reduction in total lead time. Haiyan et al. (2018) proposed a study that implemented a simulation, measurement, and optimization system for determining energy consumption in OSC. The system integrated VSM, discrete optimization, and system dynamics to assess and improve energy efficiency. By developing this system, the study successfully identified and mitigated waste, resulting in reduced energy consumption and increased profitability within the OSC process. Alsakka et al. (2016) applied lean principles in the fabrication phase of OSC by using VSM. The study demonstrated significant improvements, including a 50.6% reduction in Production Lead Time (PLT), reduction in various types of waste, and decreased safety costs. These outcomes were consolidated in the future VSM, providing a comprehensive overview of the achieved enhancements.

All of this work showed undisputable advantages of VSM where it is considered the essence of LP implementation.

2.1.2.2 Takt Time

The term "takt time" originates from the German word "takt", which pertains to the tempo and time signature in a musical composition. "Takt time" is calculated as follows: the total production time available in a selected period divided by the number of completed units needed within the given time frame by the projected customer demand for that period (Deshpande & Prajapati 2015). According to Hopp &Spearman (2008), takt time is a design parameter that can be used in various production settings, such as manufacturing, construction, and other industries. It is a function of customer demand and refers to the allotted time for completing a specific process (Liker 2004b). Takt time is influenced by the monthly production demand, meaning that, when demand rises, takt time decreases, and, when demand falls, takt time increases. This results in a corresponding increase or decrease in the output interval.

$$Takt\ Time = \frac{Time\ available}{Customer\ demand} \tag{1}$$

$$Time\ available = Total\ time\ per\ shift - (Breaks + maintence) \tag{2}$$

2.2 Multi-criterion Decision-Making

2.2.1 Introduction

Multi-criterion decision-making (MCDM) is a field within management science and operations research that finds extensive practical applications across different domains and models, according to Munier et al. (2019). MCDM focuses on the process of organizing and solving decision-making issues that encompass multiple criteria (Majumder and Saha 2016). Organizing a decision-making problem involves defining the problem, identifying potential solutions or alternatives, and establishing criteria based upon which to evaluate those alternatives. Solving the problem requires prioritizing the alternatives or selecting the best or most desirable option from the given set of alternatives.

Most stakeholders believe that employing a new solution can be a risky decision, especially if it will alter the existing process. Selecting one of the multiple solutions for a specific problem is considered a MCDM process. Thus, addressing this matter necessitates the employment of mathematical programming, simulation, statistical procedures, or artificial intelligence, as stated by Gautam Mitra (1988). Abdel-Malak et al. (2017) states that MCDM provides decision-makers with a structured and systematic approach to ranking and/or selecting alternatives that exhibit conflicting criteria.

2.2.2 Types of MCDM

There are several MCDM methods, and each method differs in terms of the computational methodology and prioritization of alternatives. They can be categorized based on the criteria considered, and each MCDM approach leads to different conclusions. There is no guarantee that using various methodologies with identical input data will yield comparable findings. Depending on the type of outcome required, different methods can be chosen (Ishizaka & Nemery 2013).

In 1977 Edwards established the Simplified Multi-Attribute Rating Technique (SMART) as a basic decision support system. Nonetheless, SMART proved inadequate for facilitating decisions involving an extensive list of criteria. After that Saaty created the Analytical Hierarchy Process (AHP) in 1987 to organize hierarchical problems and make pairwise comparisons between various options. AHP has become a prevalent tool in various industries for its efficiency. Nevertheless, it requires additional care in determining decision rules. Suhr then created CBA in 1999 to achieve the ability to make decisions by comparing different options. King &Sivaloganathan (1999), meanwhile, proposed the Concept Selection Method (CSM) to simplify complex selection decisions, although this method is intricate and complex. Finally, Kulak (2005) introduced the Dynamic Programming (DP) system to optimize solutions for complex problems by involving the user in goal setting.

For comparative value analysis, AHP, MULTIMOORA, MAUT, Weighted Sum Method, Weighted Product Method, and other approaches may be employed. To achieve the predefined objective and determine the best option from the given alternatives, COPRAS, STEP, AHP, TOPSIS, VIKOR, and other methods can be used.

2.2.3 Application of MCDM

MCDM has been applied in many sectors, the environmental sector being among the most prominent (Eshlaghy & Homayounfar 2011). Chen et al. (2009) employed a fuzzy MCDM approach in conjunction with fuzzy AHP as the basis for determining the optimal environment-watershed plan in Taiwan. Similarly, Georgopoulou et al. (2003) used the ELECTRE Tri (Elimination and Choice Translating Reality) method to establish national priorities for reducing greenhouse gas emissions in the energy sector in Greece. Parrish & Tommelein (2009) applied CBA for choosing the appropriate wastewater treatment technologies. Furthermore, MCDM has been applied in business and financial management as a decision support tool. In Taiwan,(Wu et al. 2009) employed various methods, including Fuzzy AHP-SAW-TOPSIS-VIKOR, to evaluate banking performances using the Balanced Scorecard. MCDM was used extensively in the Architectural Engineering and Construction (AEC) industry, where Paucar-Espinoza et al. (2021) used CBA for the selection of new member for a project team. Doloi (2008) used AHP for improving productivity in construction. Moreover, Schöttle & Arroyo (2017) showcased that Weighting, Rating, and Calculating (WRC) is among the most widely used methods within the AEC sector. In the manufacturing sector, Fuzzy MCDM was used in a Swedish study to find the most effective maintenance approach (Al-Najjar & Alsyouf 2003). Furthermore, AHP was used by Singh et al. (2011) to aid in the design of a flexible manufacturing system. Moreover, MCDM has been applied in other sectors ranging from healthcare to military and mechanical.

The literature has demonstrated the application of MCDM techniques in conjunction with simulation, lean methodologies, or a combination of both. These approaches assist decision-makers in reaching informed conclusions. For instance, Badreddine et al. (2022) used fuzzy-AHP and the House of Quality to incorporate lean construction concepts into offsite construction. The objective of the study is to rank the top lean concepts and to see the combinatorial impact. The findings revealed that the best two lean concepts are 5s and One-piece flow.Dehdasht et al. (2020) employed TOPSIS in the construction industry in order rank and identify the key drivers for successful and sustainable lean construction implementation. Li et al. (2013) identified, assessed, and ranked potential risks in OSC using Fuzzy AHP and simulations with the utilization of fuzzy. Simulation has also been employed to assess project risk.

2.2.4 Choosing by Advantages

CBA, a contemporary MCDM approach, was developed by Jim Suhr in 1999. CBA differs from traditional methods of MCDM, which typically involves pairwise comparisons or criterion weighting, by evaluating the benefits of decision alternatives (Arroyo et al. 2014).

One advantage of using CBA is that the cost is treated as a separate factor that is considered only after evaluating the importance of the benefits associated with each decision alternative. This means that cost is viewed as a limitation rather than a benefit, it is an element that is considered in the decision-making process independently, subsequent to the determination of other values. Moreover, by adopting this approach a more consistent and less subjective decision-making process can be achieved. This improves the implementation of lean thinking and optimizes workflow efficiency during the transition from design alternatives to operations, enhancing the evaluation and selection of available alternatives. Arroyo et al. (2012) notes the increased consistency, whileJim Suhr (1999) has highlighted the decreased subjectivity of this approach.

The decision to employ CBA as the MCDM method in this study was based on an evaluation of various MCDM methods employed in comparable scenarios. CBA was chosen due to its practical framework and user-friendliness, both of which have been highlighted in recent research as key factors for its application in decision-making. CBA has been used in many different areas, such as construction, maintenance, and manufacturing. The necessity for a systematic and structured method of making decisions in OSC is the main reason behind choosing CBA.

The CBA system is premised upon four principles, which are as follows: (1) decision makers should acquire and proficiently apply effective decision-making techniques; (2) decisions ought to be grounded on the significance of the benefit; (3) decisions should be anchored to pertinent facts;

and (4) distinct types of decisions necessitate diverse sound decision-making approaches. It is also important, when deciding, to give special attention to cost, since it is a constraint rather than a factor. CBA prioritizes decisions based on the differences in benefits between alternatives, rather than the relative importance of individual factors, which distinguishes it from other conventional MCDM techniques (Suhr 1999). Furthermore, research has shown that when compared to other MCDM methods, such as the AHP, WRC, and Best Value Selection (BVS), CBA outperforms in promoting stakeholder collaboration, maintaining transparency and consistency, and reducing subjectivity. Studies conducted by (Arroyo et al. 2014; Arroyo et al. 2016; Arroyo et al., Tommelein, &Ballard 2014; Schöttle &Arroyo 2017) have confirmed these findings.

Steps of CBA

Step 1: Generate possible alternatives for decision making where these alternatives are the potential choices for the ultimate selection during the decision-making process.

Step 2: Define factors that are components that have an effect on the ultimate decision. These factors where identified from stakeholders and literature review where it will assist the stakeholders in choosing the best alternative. However, the focus is not on which factor is the most important. The factors affecting a decision may vary based on the attributes of the available options and the significance given to their advantages. Some factors may not have been considered during the decision-making process if the options possess related attributes in relation to those factors.

Step 3: Define the criteria stakeholders are to use in order to reach a consensus, as these criteria will serve as the foundation for assessing the alternatives. The term "must criterion", it should be noted, pertains to a particular value established based on a standard, specification, or other such reference point. Certain attributes adhere to a standardized evaluation, and determining a criterion becomes a straightforward process. However, some attributes are difficult to identify. This why stakeholders must explain their needs.

Step 4: Provide a detailed account of the attributes. Attributes are features or results that are associated with each alternative option built on factors. Manufacturers' technical documents and expert opinions are both examples of sources where the attributes of a product can be obtained.

Step 5: Evaluate the advantages for alternatives. The advantages are calculated by comparing the least attribute to other attribute with respect to the criteria.

Step 6: Determine the significance of each alternative. CBA calls for the advantages to be weighted, unlike other methods such as AHP, where the weight is given for factors and not advantages. Moreover, the weights of these advantages are calculated by sending a questionnaire to Industry Managers. This will aid the process of showcasing the most significant advantage.

Step 7: Assess the cost versus the significance of the alternatives. After calculating the total importance of each alternative, the importance is compared to the cost. This allows decision makers to select the best alternative taking into consideration the cost.

2.3 Simulation

2.3.1 Introduction

A key focus of lean thinking is the elimination of waste and the improvement of quality within production processes. Moreover, the implementation of any lean adjustments is considered a high-risk process, especially when adjustments are not properly investigated before implantation and investment. Lean as a standalone tool is not sufficient since it is deterministic in nature, meaning that it is incapable of addressing variability and evaluating the performance of future states (Marvel & Standridge 2009). Therefore, simulation can be considered as a vital tool for stakeholders to check the accuracy and quality of modifications prior of implementation (Hajjar and AbouRizk 2000;Ekyalimpa et al. 2012). Moreover, the simulation was proven to give valuable information regarding new ideas or business analysis before taking decision to invest in new technology or disrupting actual system (Mourtzis et al. 2014). It can also be used as quantitative tool that tests and validates lean concepts and applications before implementation. For instance, the simulation was able to show that the implementation of the pull concept instead of the push concept in material delivery provides a better performance (Tommelein 1998).

2.3.2 Simulation Classification and Tool

Simulation models can be categorized into different types based on their characteristics. One classification is based on the nature of the model, which can be mathematical, physical, or computer based. Mathematical models use equations to depict the simulated system, while physical simulations, such as flight simulators, require the physical presence of an operator for execution.

Simulation models in computer bases depend on how entities change over time. If the entities in the simulation require time input, the simulation can be categorized as either dynamic or static. In a static simulation, the entities remain constant. In contrast, a dynamic simulation involves entities that change over time.

Dynamic simulations can be further divided into continuous and discrete simulations. In continuous simulations, the entities change continuously, representing systems where changes occur smoothly. On the other hand, discrete simulations represent systems where entities only change at specific points in time (Rosser et al. 1991). DES can be further categorized into event-driven and time-stepped simulations. In an event-driven simulation, entities change at specific predetermined points in time (Banks et al. 2010). This type of simulation focuses on modelling events and their effects on the system. In a time-stepped simulation, entities change after fixed time intervals. The simulation progresses in discrete time steps, and changes in the system occur at each step. This can be seen in Figure 1.

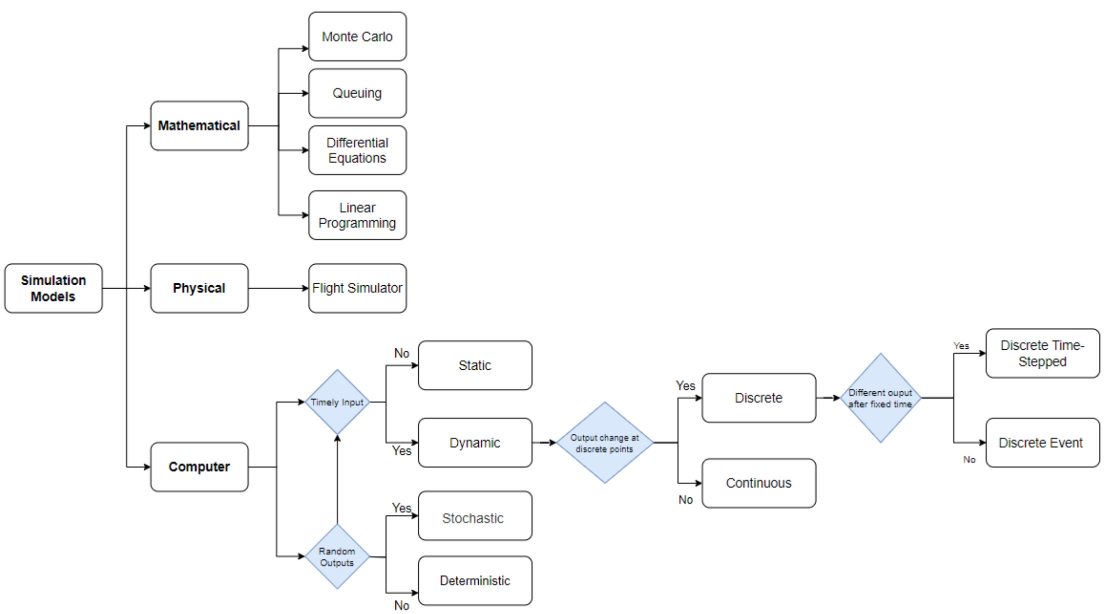


Figure 1.Simulation Classification

In this research DES is chosen to model the process. It is a well-suited approach that can describe OSC production lines with ease where every station can be considered as an activity and materials only change when passing through a specific station. DES is a tool that is considered insightful for understanding the process and improving its performance. DES can assist in the decision-making process by assessing different options of system configuration and operating strategies (Negahban and Yilmaz 2014). DES has the capacity to add intuitive visualization and animations, including the ability to represent a system's uncertainty and dynamicity, and to produce realistic (valid) representations of the real system.

There are different types of simulation software, such as Plant Simulation, Simphony, AnyLogic, and Auto Mod, all of which serve a similar purpose.

Simphony, a software developed at the University of Alberta, serves as a valuable tool for modelling manufacturing processes and assessing the impact of improvements on the new process. It offers real-time simulation capabilities and has been widely used in the construction-manufacturing domain to minimize process waste, reduce cycle time, and optimize resource utilization. Researchers such as Hajjar and AbouRizk (2000) and Ekyalimpa et al. (2012) relied upon Simphony to facilitate their studies in this field.

The utilization of Simphony in simulation proves particularly useful in addressing challenges related to the vague durations of activities and repetitive processes, as highlighted by AbouRizk et al. in 2010. By leveraging Simphony's features, researchers can customize and adjust various production process parameters, providing flexibility in modelling assembly stations based on allocated resources. Additionally, Simphony enables real-time simulation, allowing researchers to analyze results by regulating the number of simulations runs.

One of the key advantages of Simphony is its role as a modelling hub, combining simulation services with a user-friendly modelling interface. This software provides users with the ability to develop their own programming code using languages such as Visual Basic and C#. This flexibility empowers researchers and users to tailor the software to their specific needs and explore different scenarios efficiently.

2.3.3 Application of Simulation

Simulation is widely used in a number of fields, including supply chain(Terzi and Cavalieri 2004), marketing (Negahban and Yilmaz 2014), and healthcare (Mielczarek & Uziałko-Mydlikowska 2010). It has also been found to be a powerful tool by which to design, analyze, and understand the behaviour of construction systems (AbouRizk 2010), and it has been applied to both onsite (Temidayo et al. 2018) and offsite (Barkokébas et al. 2020) operations.

DES has been employed, for instance, to evaluate and enhance the process flow within a cabinet offsite manufacturing facility. The primary findings of this study were increased productivity, minimized idle time, and decreased WIP (Mohsen et al. 2021). Darwish et al. (2020)used DES and lean thinking to improve a prefabricated panelized offsite facility, where some of the solutions resulted in a 42% reduction in cycle time and a 35% reduction in idle time. Goh and Goh (2019) applied DES in prefabricated prefinished volumetric offsite construction facility. This helped in improving the process where cycle and process times decreased by 81.27%, resource utilization rate increased by 17.91%, and WIP decreased by 74%. Alcanchi et al. (2012) employed DES to accurately replicate the offsite steel construction process, specifically focusing on attaining conflicts that arise between the fabrication and erection phases of bridge construction. The study helped in reducing 10% of the total project duration by adjusting fabrication plans. Yuan et al. (2020) used LP and DES for optimization of offsite precast component production. This study played a crucial role in enhancing the production plan by effectively capturing uncertainties during the precast phase, leading to improved accuracy in production time estimation. Furthermore, it successfully eliminated waste in the system by addressing issues of underutilization. Pabloet al. (2020) employed DES to different designs of wood framing machines in OSC. The study helped in reducing costs by 40%, and 10% more productive than current processes that showcased the importance of simulation in OSC. Wang et al. (2018) used DES to optimize the offsite production scheduling of precast components. As a result, it achieved a remarkable 90% on-time delivery rate and substantial savings of 40% in daily activities. These outcomes demonstrate the effectiveness of DES in improving scheduling efficiency and enhancing overall productivity in the offsite production process.

2.4 Manual Material Handling

Despite the versatility and abundance of material handling equipment such as different types of conveyors, cranes, automated guided vehicles and others (G. Kay2012), manual material handling (MMH) that does not involve the use of any equipment is still considered a common task in many workplaces (Ontario.ca2022). MMH is defined as the process of “moving or handling things by lifting, lowering, pushing, pulling, carrying, holding, or restraining" (Canadian Centre for Occupational Health and Safety 2016). It often requires workers to bend and stretch their bodies when carrying heavy loads (Health and Safety Authority 2005). As such, MMH is recognized as a leading cause of occupational fatigue and musculoskeletal disorders, leaving approximately three out of every four Canadians whose job involves MMH with back pain resulting from injuries (Canadian Centre for Occupational Health and Safety 2016). In fact, the largest portion of workers' compensation claims are associated with MMH (Dempsy & Hashemi 1999). In Canada, MMH-related back injuries contribute to roughly one-third of all lost work and even more than one-third of total compensation costs (Canadian Centre for Occupational Health and Safety 2016).

The impacts of MMH are not limited to physical injuries of workers and the respective compensation claims. Improving work ergonomics has been shown to have many benefits, such as increased worker productivity, reduced skill requirements necessary to perform the job (e.g., a strong musculoskeletal system is needed to lift heavy items), reduced employee turnover, and more (Hendrick 2003). Moreover, besides the ergonomic aspect of it, material handling is generally considered a non-value-added task from a lean perspective, as it does not directly contribute to the transformation of raw materials into a saleable commodity (Liker 2004b). Despite not contributing any value to the final product, non-value-added tasks, including material handling tasks, can account for a significant proportion of the total manufacturing time. For instance, in a recent case study undertaken in a tannery facility, non-value-added tasks were found to account for 17.42% of the manufacturing cycle time, with the material handling tasks being the primary contributor (Wangari et al. 2018). As these non-value-added tasks consume time and resources, they lead to an increase in the operating costs of factories. In fact, material handling alone is responsible for 20% to 50% of the operating costs in manufacturing (Tompkins et al. 2014). Therefore, effective material handling strategies play a pivotal role in enhancing the overall performance of manufacturers.

Given the significant impact MMH can have on the operational performance of manufacturers and the health of workers, researchers endeavoured to analyze various aspects of MMH tasks. For instance, Yang et al. (2020)focused on the ergonomics aspect of MMH tasks in the manufacturing of motor vehicle parts. They studied 236 injured workers who were registered for occupational incidents and musculoskeletal disorders associated with MMH tasks. The study findings revealed that the majority of injuries (52.5%) were attributed to lifting and lowering tasks, while the second highest percentage of injuries (39.0%) were associated with pulling and pushing tasks. Meanwhile, Charistheo et al. (2020) evaluated the effect of material handling strategies on productivity within the automotive manufacturing sector. Specifically, they studied MMH tasks such as manually transporting bumpers from one location to another and investigated the productivity implications of utilizing trolleys or carts for material transportation. The findings demonstrated that using carts could result in a 19.6% improvement in productivity. These studies underscore the importance of analyzing material handling strategies implemented in various facilities and exploring ways to enhance their efficiency.

2.5 Conclusion:

In summary, the implementation of LP has supported the understanding and improvement of production systems in offsite construction. Specifically, the VSM provides valuable visual insight into the entire production line to highlight the associated issues. MMH was found to be among the most critical issues in offsite construction, whereby it accounts for a significant portion of nonvalue-added time. Given that there can be several possible solutions for the identified issues, an MCDM tool should be used to determine the most favourable solution. Both simulation and experimental approaches were chosen to test the proposed solutions. The selection of the approach depends on the ease of implementation.

Based on the conducted literature, several studies have used lean and simulation tools to improve the production line performance in offsite construction. However, there are not many studies that have integrated these tools with MCDM. The studies that do exist focus on limited applications including ranking top lean concepts, drivers for sustainable lean construction, and top risk factors in OSC. As such, existing studies did not incorporate decision-making tools when selecting potential solutions. Such an application can limit the number of potential solutions prior to implementation (theoretical and experimental) which, in turn, reduces the effort needed in implementation, verification, validation, and analysis. Additionally, this application is crucial for decision makers where their input on potential solutions is already considered through the MCDM questionnaire. Moreover, the decision maker can select a more favourable solution from a smaller set.

The MCDM tool that is selected in this research is the CBA because it is a user-friendly tool that focuses on collaboration and adding value to the end user, while treating the cost as a separate factor. It is worth noting that the application of CBA. along with lean and simulation in OSC, has been limited. Thus, the need to highlight its successful implementation is beneficial in this industry.

Additionally, the literature has not given enough attention to experimental testing of the solutions compared to simulation modelling. Considering that theoretical simulation modelling cannot always mimic real-life conditions, experimental approaches become useful in this case. It shall be noted that not every solution can be tested through experiments, given the implementation constraints.

CHAPTER 3: METHODOLOGY

3.1 Overview of Methodology

The research methodology adopted in this study is Design Science Research (DSR). DSR is a research approach that focuses on the development of artifacts or solutions to address specific problems (Dresch et al. 2014). This methodology is particularly suitable for bridging the gap between theory and practice by addressing problems of interest to both professionals and academics (Holmström et al. 2009). In the present work, the DSR approach is used to develop practical solutions that effectively address the identified problem. DSR, it should be noted, has been applied in various research domains, including information systems (Peffers et al. 2007) and management (Carlsson et al. 2011), and it also holds potential value in construction management research in terms of its ability to address practical challenges with scientific reasoning (Tommelein 2020).

The DSR includes three stages:

1. Identifying the problem
2. Developing the artifact
3. Evaluating the solution

3.1.1 Problem Identification

In the pursuit of improving the production system, researchers often tend to focus on isolated improvements rather than studying multiple objectives simultaneously. This strategy could yield less than optimal outcomes as it fails to consider the interdependences of the improvements which can have a tremendous impact. Therefore, when improving a production system, it is imperative to adopt an approach that collectively considers all the problems as opposed to looking at them in silos. However, this aspect not commonly discussed in the literature. To address this issue, a variety of metrics that reflect the performance of the overall system, such as wait time, WIP, production, and PLT, must be considered.

3.1.2 Artifact Development

In order to address the problem at hand, it is necessary to develop various methods, tools, and models as part of the artifact development process (Johannesson &Perjons 2014). For this purpose, lean manufacturing was used as one of one of the key aspects in this improvement. Moreover, this framework aims to improve the production system in terms of higher production and less PLT, wait time, and WIP. It also aims to enhance the well being of workers while doing specific tasks (less fatigue and injuries), which, in turn, will reduce the wastes in the system and will improve the system as a whole.

Figure 2 represents the framework that is followed in pursuit of the above-mentioned objectives. The initial stage of this framework involves evaluating the current state of the production process. The first step in this stage is data collection, which involves conducting a time study to record the duration and pace of individual task elements performed under specific conditions. The cycle time is divided into two components: processing time and idle time. During the measurement of processing time, activities that add value are considered, while non-value-added activities are excluded. Essentially, only value-added activities are considered as part of the processing time, while non-value-added activities are not included. On the other hand, idle time is collected in fragments and consists of various components, all considered non-value-added activities, and categorized as waste in lean manufacturing. These components align with the seven types of waste: defects, overproduction, waiting, transportation, motion, extra processing, and inventory. In order to collect the data, stopwatch timing, formal and informal interviews, observations, material counting, site visits, and company database analysis were employed. The collected data is critical in understanding the process and achieving the research objectives effectively.

The second step of the framework is creating a VSM of the production line. In order to develop a VSM, both value-adding and non-value-adding activities were identified and represented in a diagrammatic structure to give a visual depiction of the production process. The VSM encompasses only internal operations, and includes the inventory between stations, cycle time of activities, available time, and uptime of the stations. Once the VSM is developed, the problems and sources of waste can be identified. Based on this analysis, solutions are proposed and categorized into two types: operational and technological solutions. Operational solutions, also known as "quick hits", are aimed at addressing issues promptly, whereas technological solutions are solutions that need considerable planning and might require considerable investment before implementation. Since certain problems may have multiple solutions, a CBA is conducted to determine the most viable option.

Before implementing an operational or technological solution, a testing phase is carried out using theoretical and experimental approaches. The selection of the approach depends on the ease of implementation. If the solution presents a relatively straightforward implementation process, the experimental approach will be selected. However, if the solution involves significant challenges such as high investment, extensive preparation, potential work disruption, or if the factory prefers to avoid implementing it for various reasons, the theoretical approach will be favoured instead. The theoretical approach begins with developing a discrete-event simulation (DES) model based on data and process studies of the existing process. The model is then verified and validated using various techniques, such as face validity and event validity. Next, the bottleneck in the process is identified, and potential solutions are tested within the model. The solution with the highest improvement is selected for implementation. On the other hand, the experimental approach involves a detailed evaluation of the current practice of the existing problem to gain a deeper understanding. An experimental plan is then developed, outlining the necessary steps for proper solution implementation. The plan is executed on-site, and the results are analyzed to further investigate the benefits and payback of the solution and its impact on system improvement.

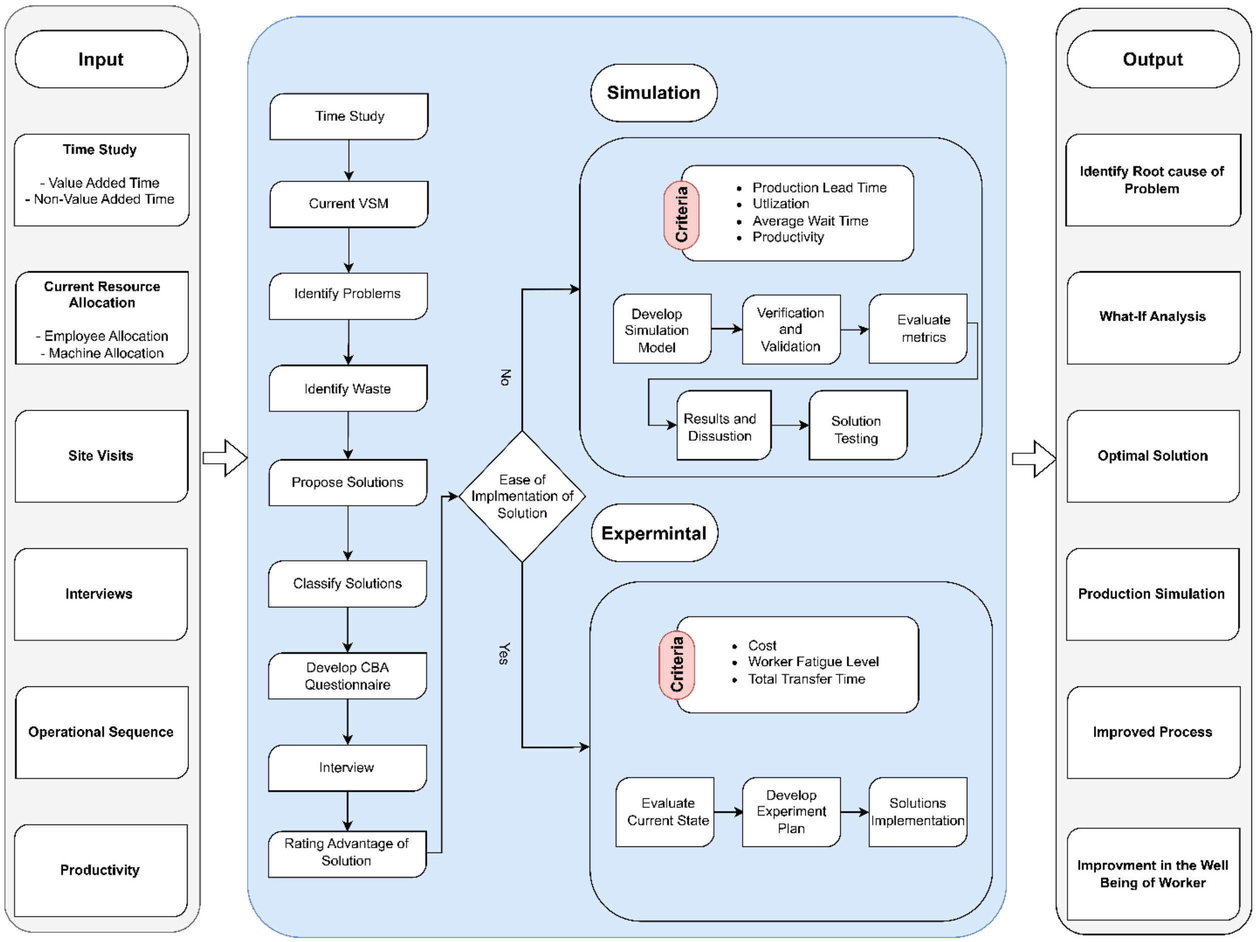


Figure 2.Framework

3.1.3 Evaluation

The framework is evaluated through a case study conducted in a window and door manufacturing company in Edmonton, Canada. With three branches, this manufacturer serves more than 10,000 customers every year. The case study involves gathering hands-on data from the OSC facility, which specializes in manufacturing windows for construction projects. By implementing each step of the framework and collecting feedback from the company, the evaluation provides the necessary evidence to validate the effectiveness of the framework. This feedback is obtained through interviews with the management team.

CHAPTER 4: IMPLMENTATION OF SUGGESTED FRAMEWORK

4.1 Glass Process

The selected case study involves a window and door manufacturing company located in Edmonton. This company has been operating in the market for over 40 years and features a factory spanning over 10,000 sq ft, making it the largest privately-owned window and door manufacturer in Canada. With a network of approximately 800 dealers across the country, this company has established a strong presence.

At the collaborating company’s manufacturing facility, the production process for manufacturing glazing units is organized into three distinct production lines. The first production line, known as the "Atlas line," specializes in the production of triple-glazed glass specifically designed for small to medium-sized windows. The second line, referred to as the "Linthard," focuses on manufacturing double and triple-glazed units primarily used for large windows. The third and final production line is called the "GED," which is dedicated to producing double glazing units. For the purpose of this study, the GED line is examined, as it is considered the most crucial and largest production line among the three. It is also the line that faces the most challenges and requires improvements, as identified by the company. Figure 3 displays the three lines, each equipped with identical cutting machines and loaders, to provide support for the production processes.

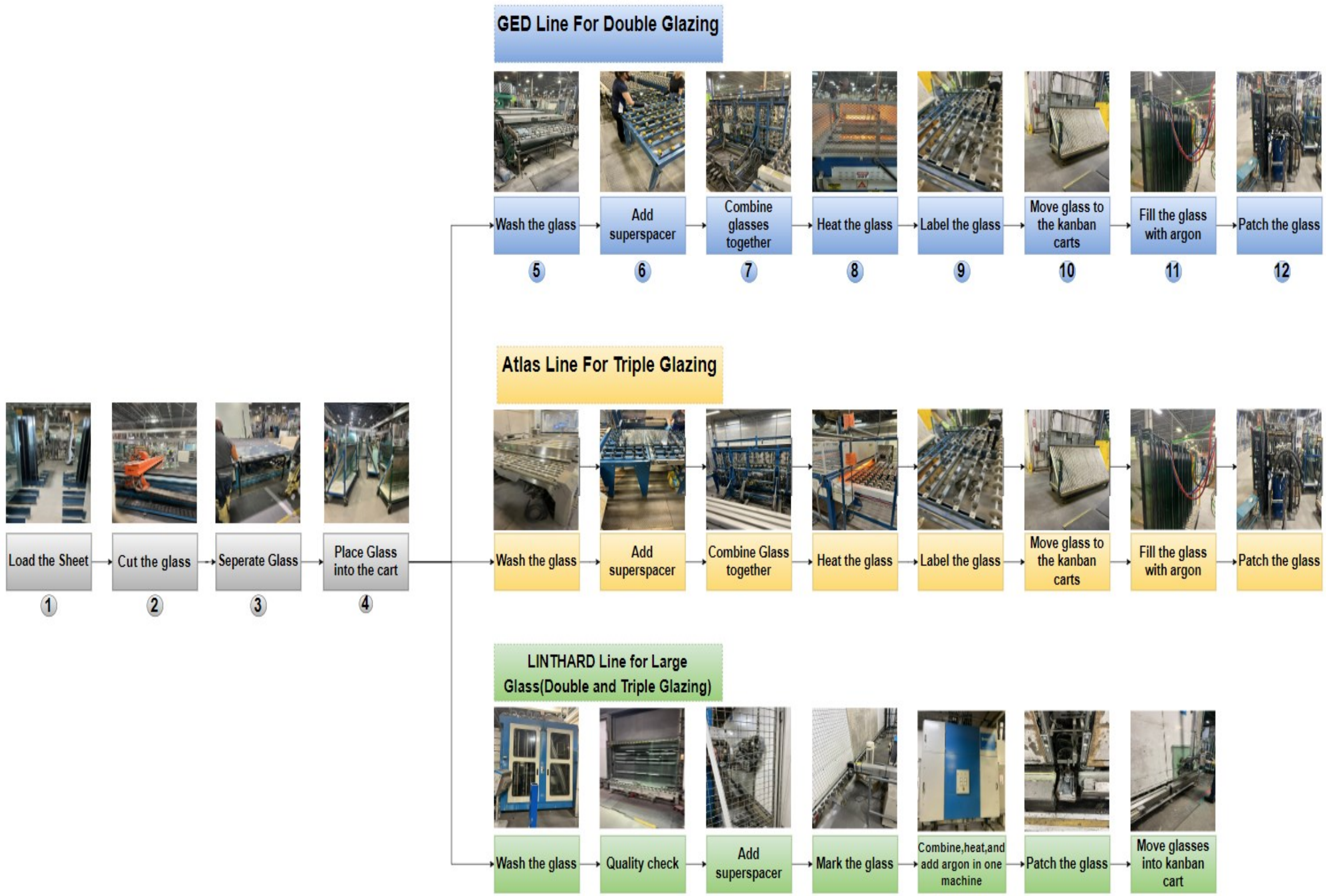
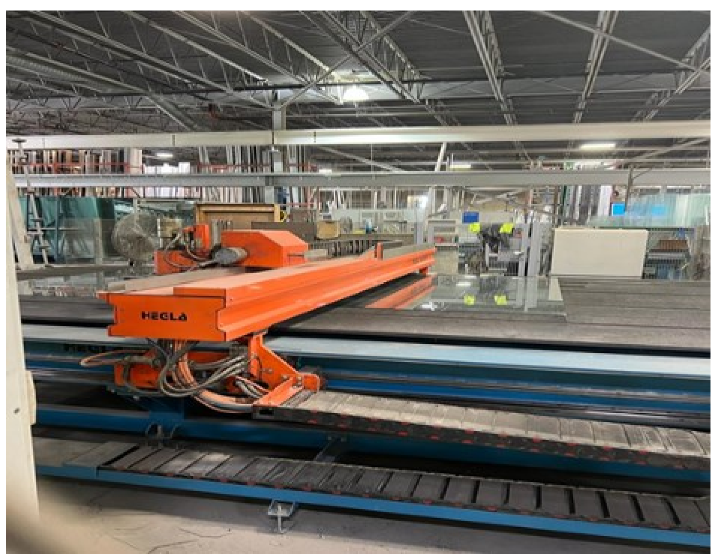
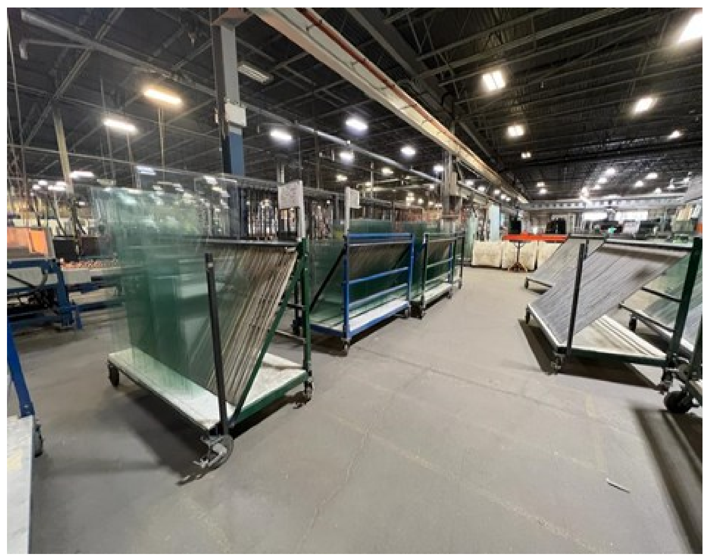


Figure 3.Production lines

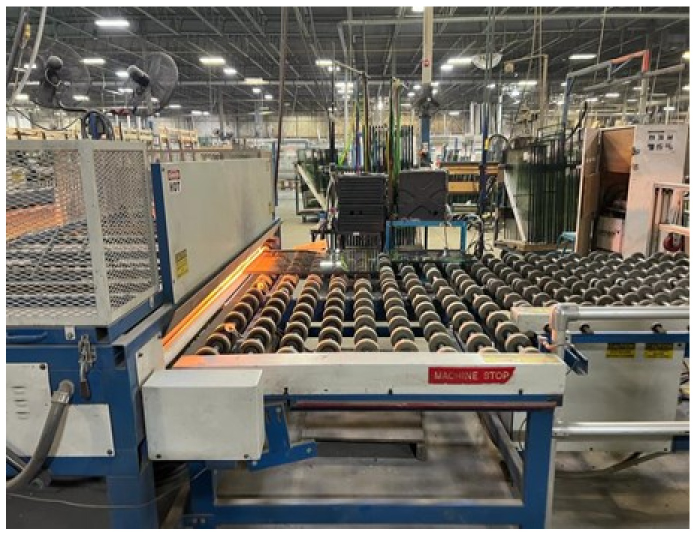
The focus of this study is on the largest and most intricate production line, which is “GED”. The work operations of GED are listed below.

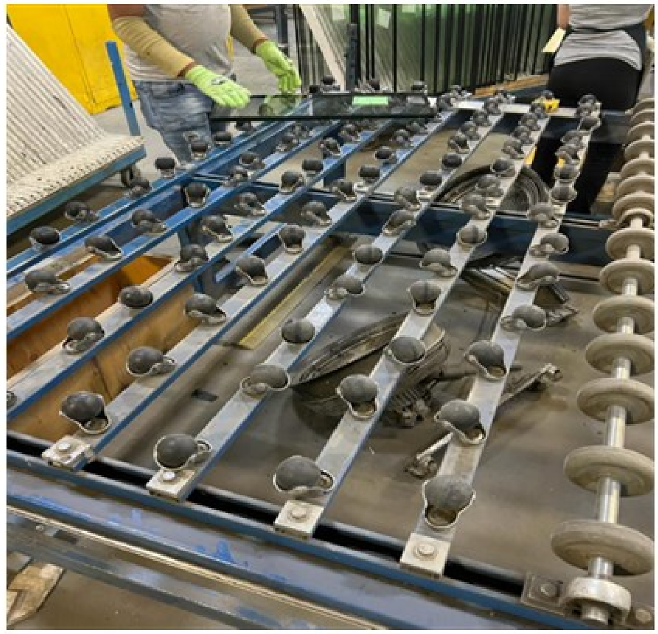
Table 1.Glass Process

Activities	Pictures
Loading: A gantry system is used to transfer glass sheets from the storage area to the loading area, where the glass sheets are loaded.	
Cutting Machine: After being loaded, the glass is transported to the cutting machine, where it is precisely cut based on the orders provided by the worker.	

Separating and Loading: After cutting, the workers will separate the glass pieces from the sheet. Each individual glass piece will then be placed in a designated slot within a 100-cart unit. Any excess glass from the cutting process is discarded into bins. This sequence is repeated until the cart is fully loaded.	
Transporting: Once the cart is loaded, the separating and loading worker transports the Kanban cart with the rest of the carts, which are subsequently moved to other production lines.	

Washing: The washing worker will retrieve the cart and position it in close proximity to the washing machine. The worker then will collect each glass piece and transfer them onto the washing machine until the cart is emptied.	
Adding Super Spacer: Workers place the super spacer on the glass after retrieving spacers from the cart.	

Combining: The two pieces of glass are then transported to a combining machine by conveyor and are combined via butterfly table.	
Heating: The glass is fed into the oven through ceramic rollers to guarantee uniform heat distribution throughout the heating phase. The temperature is raised to about 1100 degrees Fahrenheit during this process.	

Labelling: Each glass is labelled by the worker to indicate its type, order number, destination, size, whether it is filled with argon or not, and the date it was manufactured.	
Loading: The glass units are loaded into carts and, once a cart reaches a capacity of 50 units, it is transported to the filling and argon station.	

Filling the argon: The process involves injecting compressed Argon gas into one end of the sealed unit, and measuring the air that exits from the second hole until the argon concentration reaches 90%. Once this concentration is achieved, the holes are sealed with screws.	
Patching the Glass: After filling the argon, workers use a patching gun to apply a sealant corner where the hole was made. The patching gun is a tool that allows for precise application of the sealant. They carefully dispense the sealant on the drilled hole. Once the patching is complete, the workers move on to smoothening the sealant on the corner of the glass where they spread the sealant, making it even and consistent across the surface. In this case, the workers have specific dimensions to consider. They need to ensure that the sealant extends 4 cm both horizontally and vertically from the corner of the window.	

4.2 Data Collection

Various types of data were gathered during the study, including time data (value-added and non-value-added), observations, and interviews. The collection of data took place over several months, and in order to capture the variability in the system. It should be noted that no historical time study was available for the company prior to this research.

4.2.1 Interviews

There were two categories of interviews conducted: formal and informal interviews, both of which played a crucial role in collecting data. The formal interviews involved the production manager and production supervisor. During these interviews, a detailed explanation was given concerning the double-glazed window manufacturing process, from loading the glass sheet to the patching process. They clarified the functions and purposes of each station involved. They also explained how orders are generated and scheduled, and the required preparation time.

In addition to the formal interviews, an informal interview was conducted with the line superintendent and workers. These interviews proved to be highly valuable as they provided a comprehensive understanding of each activity and shed light on specific issues that needed resolution. The superintendent's and workers' insights were particularly significant since they possessed extensive hands-on experience and had been with the company for over 10 years. Their practical knowledge and expertise helped identify production problems and contributed greatly to the research.

4.2.2 Time Study

The Time Study technique involves recording the duration of individual task elements performed under specific conditions. This data is then analyzed to determine the time required to complete the task accurately. Collecting this data requires careful consideration of various variables in order to accurately replicate the shop floor environment. The collected data is essential for making improvements and conducting future analyses. As mentioned earlier in Section 4.1, the GED line consists of 12 operations. It should be noted that the time required for each activity may vary depending on the size of the window being processed. The process of conducting the time study adhered to the rules outlined by Kanawaty (1992) and Barnes (1968).

- The collection of time data was conducted without interfering with the workers' tasks or causing any distractions.
- Time data was collected on various days and shifts to ensure a diverse range of workers was included in the study.
- Instances such as machine breakdowns and idle time, along with any other events that affected the time measurements, were carefully recorded.
- All the time data was recorded during periods when highly trained individuals with over 5 years of experience on the line were performing the tasks.

As mentioned previously, there are seven types of waste: defects, overproduction, waiting, motion, extra processing, inventory, and transportation. One form of non-value-added activity is when a cart has to wait until it is full before being transferred from one station to another. This waiting time is observed at three different instances: between the separating and washing stations, between the loading station and the argon-filling station, and between the argon-filling station and the patching station. Additionally, incidents of glass breakage during the processes of filling argon, separating and loading were also recorded as defects. Another example of waste is the time workers spend searching for the appropriate super spacer for each glass, which can be categorized as waiting waste. Transportation of carts between stations is also considered a form of waste (motion).

The glass line undergoes production from Monday to Friday with two operational shifts. The first shift operates from 7:00 a.m. until 3:30 p.m. The second shift runs from 4:40 p.m. until 1:00 a.m. Both shifts include a 30-min unpaid lunch break and two 15-min paid breaks, resulting in an effective work time of 7.5 h per shift.

During the time study, a considerable degree of variability of products was observed. To account for this variability, a random sample of time periods was chosen for the time study. This ensured that a broad range of windows would be covered.

Glass products are tracked along the glass line, with each piece being closely monitored and documented at each station. The measurements were taken on multiple occasions to capture a range of timings and to accommodate any potential variations. The duration of tasks was gauged in seconds with the aid of a stopwatch. Using this approach, the stopwatch is initiated at the beginning of the first task and halted once the task concludes (i.e., upon completion of the task). The value-added activities and non-value-added activities were documented, and the timings for each activity were recorded. The data, including the timings for each operation, was compiled and included in Table 2, *Table 3*, and *Table 4*. However, these tables do not provide a complete set of data: a sample of 10 was used for value-added time, and a sample of 5 was used for non-value-added time, as seen in *Table 5*.

Table 2.Value-Added Time

Sample	Loading	Cutting	Separating and Loading	Washing				Adding Super spacer
				Window Entry (Small Glass)	Window Exit (Small Glass)	Window Entry (Large Glass)	Window Exit (Large Glass)	
1	87	100	123	7	23	-	-	30
2	77	200	110	7	23	-	-	35
3	83	170	78	6	21	-	-	30
4	90	200	90	6	21	-	-	30
5	77	170	110	11	19	-	-	33
6	84	193	72	-	-	27	10	33
7	75	130	95	-	-	27	10	40
8	88	110	110	-	-	20	8	28
9	81	100	74	-	-	20	8	33
10	74	217	100	-	-	22	10	30

Table 3.Value-Added Time (cont'd)

Sample	Combining	Heating			
		Window Entry (small)	Window Exit (small)	Window Entry (Large)	Window Exit (Large)
1	25	8	22	-	-
2	25	8	22	-	-
3	26	10	24	-	-
4	28	8	20	-	-
5	28	8	20	-	-
6	25	-	-	24	10
7	22	-	-	24	10

8	22	-	-	23	9
9	28	-	-	23	9
10	25	-	-	18	12

Table 4.Value-Added Time (cont'd)

Sample	Labeling	Loading		Argon		Patching	
		Small Glass	Large Glass	Small Glass	Large Glass	Apply	Patch
1	7	11	-	60	-	7	17
2	7	11	-	60	-	6	16
3	5	22	-	80	-	5	17
4	8	11	-	80	-	6	12
5	6	11	-	60	-	6	12
6	8	-	44	-	180	7	16
7	8	-	43	-	180	6	15
8	9	-	47	-	115	7	12
9	5	-	42	-	115	6	9
10	9	-	42	-	130	7	8

Table 5.Non-Value-Added Time

Activities	Description	Type of Waste	Sample 1(sec)	Sample 2(sec)	Sample 3(sec)	Sample 4(sec)	Sample 5(sec)
Cutting	Manual input of the Data	Waiting	180	188	260	177	190
Separating and Loading	Breakage of the Glass while separating it from sheet	Defects					
	Filling cart till it reaches 100	Waiting	900	1,080	1,200	960	1,320
	Transferring Cart	Transportation	25	30	25	21	27
Washing	Unclean glasses	Defects	35	25	30	22	33
	Transferring Cart	Transportation	45	33	40	48	42
Adding Super spacer	Workers spend a considerable amount of time identifying the correct super spacer for a given pane of glass	Waiting	25	22	15	30	22
Loading	Filling cart until it reaches 50 windows		1,080	1,200	1,320	1,140	1,080
Argon	Breakage of glass while filling the argon	Defects					

	Filling cart until it reaches 50 windows	Waiting	1,500	1,620	1,800	1,320	1,200

4.2.3 Resources

Table 6 displays the quantity of resources required at each station, where M is for male workers and F is for female workers.

Table 6.Resources

	Workers						Machine	
Station	No. Worker		No. Supervisor		Total number of workers	Years of Experience	Type	Number of machines
	M	F	M	F				
Loading Glass	0	0		0	1	10	Gantry crane	1
Cutting Glass	0	0	1	0	1	10	Cutting Machine	1
Separating and loading	2	0		0	3	7	-	
Washing	0	0	1	0	1	15	Washing Machine	1
Add super spacer	0	2	0	0	2	5	-	
Combining	0	0	0	0	0	0	Butterfly table	1
Heating	0	0	0	0	0	0	Oven	1
Label	0	1	0	0	1	8	-	
Loading	1	0	0	0	1	5	-	
Fill up argon	1	0	0	0	1	6	Argon Machine	1
Patching	1	0	0	0	1	8	Patching Machine	1
Total	5	3	2	0	10	-		7

4.3 Value Stream Mapping

The production of double-glazed units involves the utilization of various materials in order to be created. The process begins with the loading station and progresses through several stations until it reaches the patching station. Each station contributes to production by processing different inputs and generating specific outputs, making it challenging to create a comprehensive value stream map.

In Figure 4, the material flow on the production line is illustrated. The first three stations (loading, cutting, and separating) handle whole glass sheets as inputs. After the separating and loading station, the output is 10 sheets of glass, as will be discussed in further detail later.

Next, the washing machine simultaneously washes two glasses, taking two glasses as the input and producing two washed glasses as the output. The same input and output pattern applies to the super spacer station. After the super spacer is applied, the glasses are combined, resulting in a double-glazed unit. From this point onward, the input and output remain the same for all subsequent activities until the patching station, where the input is also a double-glazed unit. After passing through this station, the product becomes a finished unit, ready for use on another line where it can be installed onto a window frame.

It is important to note that, following separating and loading, products at the loading and argon-filling stations remain stationary until the cart is loaded with 100 and 50 products, respectively.

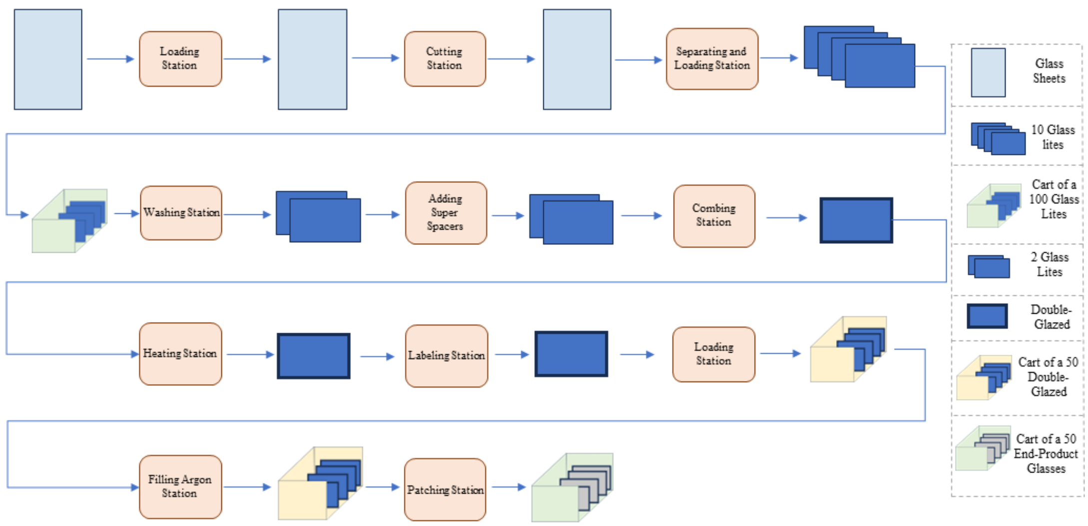


Figure 4.Material Flow

Unify the Units of the Whole Line:

In order to create a comprehensive value stream map, it is necessary to standardize the material flow throughout the production line. All outputs within the system should be aligned and measured in terms of one double-glazed unit. Therefore, the creation of a value stream map begins with an examination of the loading, cutting, separating, and loading stations.

The input and output for these stations consist of whole sheets (except for separating and loading output). These sheets must be converted into double-glazed units to align them with the production line.

A thorough observation and data collection were conducted within the company to determine the number of double-glazed units produced from a single sheet. Table 7 showcases a selection of orders that were examined to ascertain the number of glasses generated from each sheet.

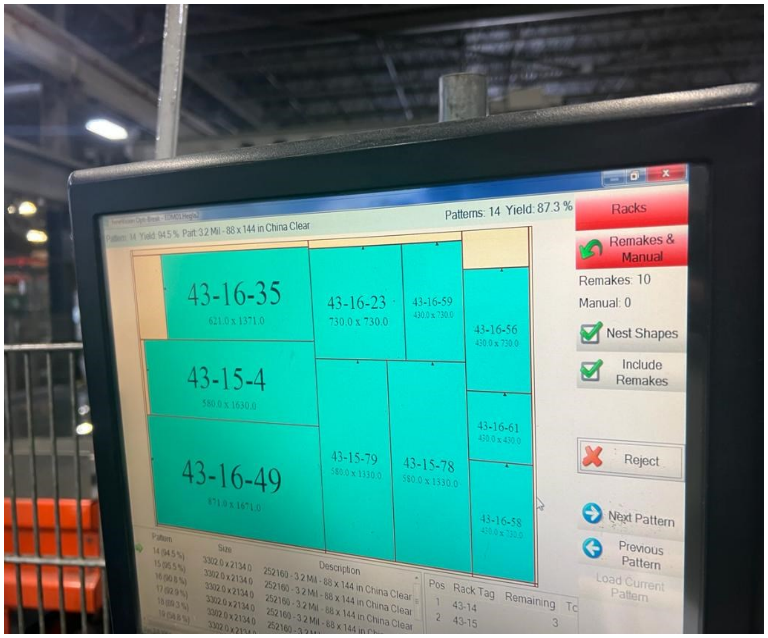


Figure 5.Cutting Order

Table 7.Number of Glasses

Job number	Sheet	Number of Glasses
167####	1	8
167####	1	12
167####	1	10
167####	1	4
167####	1	10
167####	1	8
167####	1	14
167####	1	12
167####	1	10
167####	1	8

Based on the analysis of orders and observations conducted on the shop floor, it was determined that, on average, each sheet yields approximately 10 single panes of glass, resulting in approximately 5 double-glazed units. This average value is used in both the VSM and the simulations.

The recorded time for loading, cutting, separating, and loading is measured based on the whole sheet rather than the double-glazed unit. However, we can consider this timing to be the same for both the sheet and the double-glazed unit since the processing time remains consistent. For instance, if the average recorded time for cutting the sheet is 170 s and it generates, on average, 5 double-glazed units, it can be inferred that each double-glazed unit requires 170 s for production.

In the case of the washing, super spacer, and combining stations, the recorded timing corresponds to one double-glazed unit because the two single glasses are processed simultaneously on the machine. Therefore, the timing remains the same for both operations. Similarly, for the remaining activities, the recorded time also pertains to one double-glazed unit.

Implementation of VSM

The VSM serves as a visual representation of the information and material flow within the production line. Its primary purpose is to identify activities and waste within the system, guiding improvement efforts.

In the case study, VSM was not fully utilized, as certain aspects of the tool were deemed unnecessary for the specific analysis. However, the VSM components that were used effectively served their purpose. It should be noted that the storage area was omitted from the VSM since the company already has a significant volume of glass in storage. Shipments are received every two days, ensuring an adequate supply of materials.

Therefore, the VSM exclusively focuses on the internal production system, omitting the storage area. It is important to note that the shift time is 7.5 h (for a total of 4,500 min/week), including breaks, and scheduling is done on a weekly basis. The company produces an average of 5,000 windows per week (5 days) or, on average, 1,000 windows per day (2 shifts), as determined by the scheduling department. This average demand per week is considered within the VSM.

Upon conducting a thorough examination of the glazing manufacturing line and collecting and scrutinizing data, the current value stream map was created and can be seen in Figure 6. The current-state map preparation involved computations that exposed significant details about the process. The problems that were concluded from VSM are shown below.

- WIP was seen before the washing, filling up the argon, and patching stations. It is important to note that this WIP is not a result of these stations being slow or incapable of processing the product efficiently. Instead, the reason for this WIP is that after the separating and loading station, the product must wait in the cart until there are 100 units present before proceeding to the next station. Similarly, after being loaded and then processed at the argon station, the product must wait in the cart until it reaches a count of 50 units before progressing to the subsequent station. These waiting points contribute to the accumulation of WIP in the production line. It should be noted that WIP was seen before the super spacer station.
- The processing time was found to be 642 s, and the production lead time was 230 min. This implies that there are several non-value-added activities, as previously discussed.

Ideally, it is recommended to minimize the leading time to be closer to the processing time for optimal performance.

- The cutting station was operational for the majority of the process. However, a significant number of products were waiting to be processed, as evidenced by their location before the station. These observations were reflected in the VSM, which indicated that the cutting station had the longest cycle time and the highest amount of WIP
- A percentage of orders were manually entered rather than being scheduled and sent electronically, which resulted in a delay in the transmission of orders to the cutting machine. The VSM illustrated this event through the manual information arrow from production control to the cutting station (waiting).

The Value Stream Map illustrated two crucial flows: material flow and information flow. The operation and data box documented the cycle time, number of workers, uptime, and shift time. The presence of the indicated WIP can potentially contribute to imbalances within the production system and result in discrepancies between the Total Processing Time (TPT) and PLT. These imbalances can hinder the overall efficiency and performance of the production line.

During the examination of the process, various issues were identified within the stations. These issues were thoroughly addressed, and potential solutions proposed to mitigate their impact on the production system. By resolving these issues and implementing effective solutions, it is expected that the overall performance and of the system can be improved.

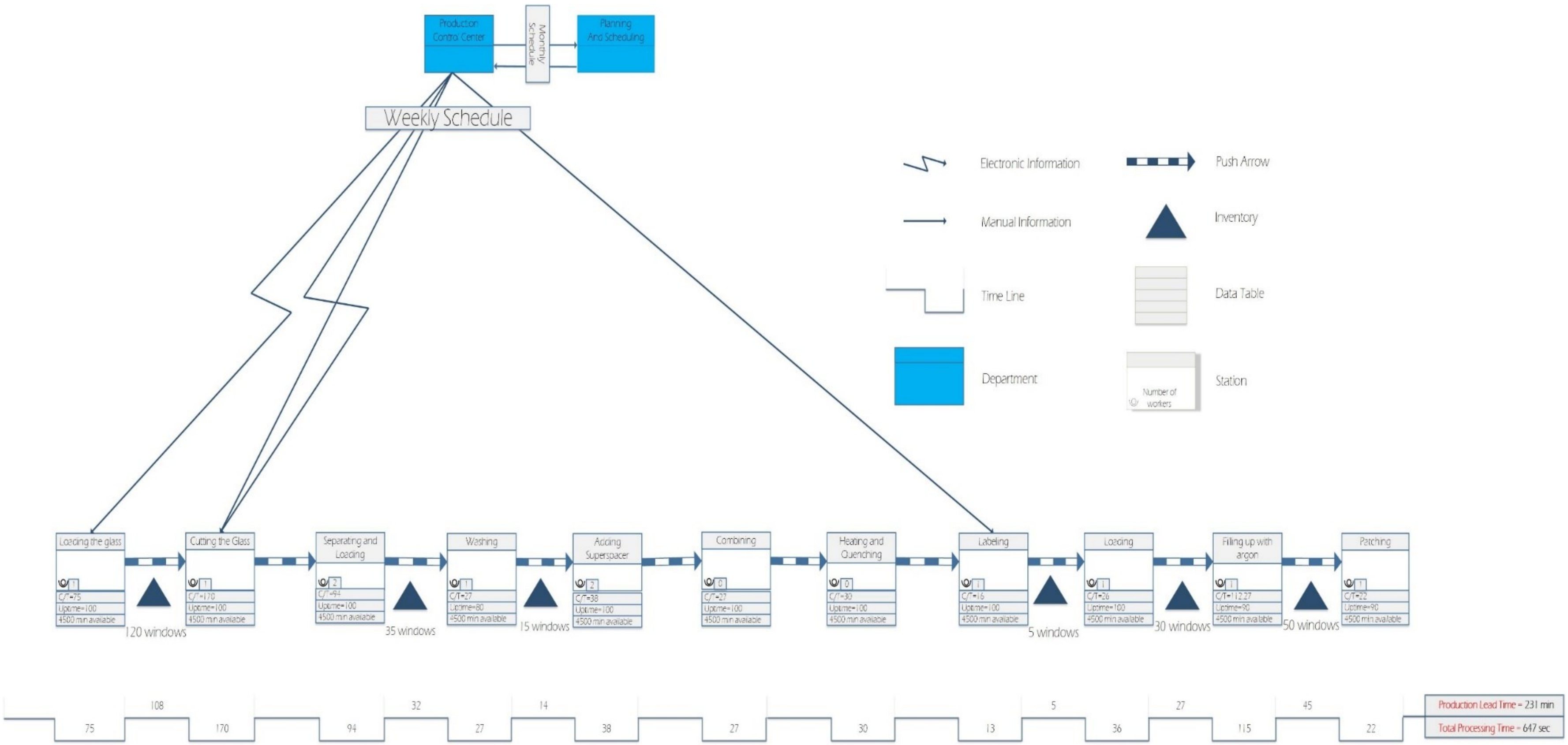


Figure 6. Value Stream Map

4.4 Further Understanding the Production Line

A meeting was held with the production supervisor after creating the Value Stream Map and pinpointing wasteful activities. This meeting was crucial as it provided an opportunity to address worker concerns, identify any problems they may be facing, and pinpoint areas with wasteful activities. Additionally, several line issues were documented after the input obtained during the meeting. However, there was a specific issue that demanded attention, which was the manual material handling carried out in the factory, specifically during the triple glazing process. It is important to note that this process is not within the scope of the GED line, but rather it was identified in the LintHard line, which is another line dedicated to handling double- and triple-glazed units. A written note by the workers was noticed on the cart, indicating that it is difficult to push. This observation sparked further interest in studying this aspect and discussing it with management. They acknowledged that addressing this problem is one of their concerns and indicated an openness to considering any promising solution. The problems are shown in Figure 7.

Activity	Glass Loading	Glass Cutting	Separating and Loading	Transport	Washing	Adding super spacer	Label and Loading	Transport	Argon filling
Problem	Inefficient feeding system	Slow Process	Breakage of Glass	Heavy Cart	Glass being washed repeatedly	Wrong spacers dimensions	Time wasted to lift the glass	Products must wait	Glass shattering, time consuming process
Type of Waste	Transportation	Waiting	Defect	Waiting, Transportation	Defect	Waiting	Waiting	Waiting, Transportation	Defect
Description	Time wasted in moving glass panels placed far from the machine	Low capacity of machine and manual input makes the system as bottleneck	Glass slippage while moving from station to cart	Transportation of heavy loads and waiting at station until the cart reaches 100 glasses	Smudges on glass due to residue of minerals that were in the water.	Workers takes a lot of time to identify right super spacer	Heavy panels require more than one worker to be moved	Products must wait until the cart reaches 50	Glass shattering due to overfilling with argon and dirt on the needle.
Operational Solutions	Most used glass nearer to the station	Eliminate manual input	New Gloves, Suction Cups	Less glasses per cart	-	Kanban Cart with numbers	-	Less glasses per cart	Create a preventive maintenance check
Technological Solutions	Rapid Loader, Rapid Store	New algorithm, New machine.	Conveyor	Conveyor	Reverse Osmosis	Conveyor	Suction Machine	Conveyor	-

Figure 7.GED Problems

4.4.1 Discuss Problems

A total of ten issues were identified following the meeting. The first issue was related to the loading station. In the current state, the loading process for glass onto the machine is time-consuming for two reasons. First, the glass is randomly placed in the storage area without considering the most used type of glass required by the machine. Consequently, the crane loads the glass into the machine in a haphazardly manner, sometimes within a 20-m range and other times within a 40-m range. Secondly, the crane is a slow-moving machine that requires significant time to maneuver between the storage area and the cutting machine, particularly when travelling long distances. As a result, the loading process is inconsistent.

The second challenge has to do with the cutting station, which acts as a bottleneck in the production line that affects the overall pace of the system. This is primarily attributed to its longer cycle time in comparison to the other stations. Additionally, the manual entry of specific orders (large glasses), instead of having them pre-scheduled, further contributes to the difficulties encountered. This manual process introduces delays and inefficiencies, inhibiting the smooth flow of operations.

The third problem is in the separating and loading station. It faces a significant problem related to glass breakage during the separation process from the whole sheet and when placing it in the Kanban cart. This issue results in rework, material waste, and loss of time. The leading causes of this problem are the use of deteriorated gloves that lack sufficient friction and unsafe handling practices by the workers.

The fourth problem pertains to the transportation of the cart to the subsequent station, which involves non-value-added time in the production process. This task poses challenges due to the heaviness of the cart, placing strain on the workers and potentially causing health issues. Additionally, the subsequent stations are often left waiting for products, even when there are ready-to-process items available. This occurs because the cart cannot proceed unless it reaches full capacity, which consists of 100 slots. These inefficiencies in transportation and cart management result in delays, reduced productivity, and potential bottlenecks in the production line.

The fifth problem lies with the washing machine, in that, in some cases, the glass needs to be cleaned multiple times before it can proceed to the next station. This requires the worker to stop the washing machine and leave their station to retrieve the smudged glass from the super spacer station, and then pass it through the washing machine again. This process involves rework and double handling, which are non-value-added activities.

The sixth problem is in the super spacer station, where a significant amount of time is consumed as workers struggle to identify the appropriate super spacer for each window. This results in increased placement time for the super spacer on the window. Currently, all super spacers are prepared in advance at a different station and stored near the super spacer station. However, they are stored in a cart without any specific sequencing, leading to inefficiencies.

The seventh problem pertains to the label and loading station, where it was observed that workers sometimes have to wait for assistance from another worker when carrying large glass. However, it is important to note that this specific problem is not addressed in this thesis. This is because the production line studied in this thesis does not generate a significant number of large glasses, so the production volume is not sufficient to significantly affect the station's overall efficiency. Furthermore, the station already operates at a faster pace compared to other stations in the line. As a result, this particular issue is not a major concern for the current research focus. However, it is worth considering potential future improvements or alternative solutions for situations where large glass production becomes more prominent within the production line.

The eighth problem shares similarities with problem four. In this case, the cart is transferred over a relatively short distance, so the physical strain on workers is reduced. However, the issue arises when subsequent stations have to wait for products until the cart is loaded with 50 sheets of glass.

The ninth problem is at the argon station, which encounters an issue where certain glass windows crack during the process of being filled with argon. Resolving this problem is crucial due to its position at the end of the production line. Any flaws present in the window at this particular stage can lead to substantial costs and time investments in order to manufacture replacement windows. The lack of regular maintenance for the machine is the root cause of this problem, leading to various issues. One example is the malfunctioning of the meter that measures the amount of argon being filled, resulting in overfilling and subsequent cracking of the window. Another factor is the presence of dirt on the needle that enters the glass, leading to the closure of the argon inlet and ultimately causing the glass to crack.

The tenth problem is the manual material handling in the factory. The case company specializes in manufacturing double- and triple-glazed window units. The process of manufacturing a sealed glass unit entails various activities, beginning with loading the glass onto a cutting table. The glass is then cut into desired sizes, and the workers load the glass pieces onto rolling carts located in Area A shown in Figure 8. They are then transferred to a production line, which starts at Location B in Figure 8**,** where double-glazed and triple-glazed glass is formed. The formed glass is then loaded onto rolling carts at the end of the production line positioned at Location C, which are transferred to another workstation located in Area D for the window framing process.

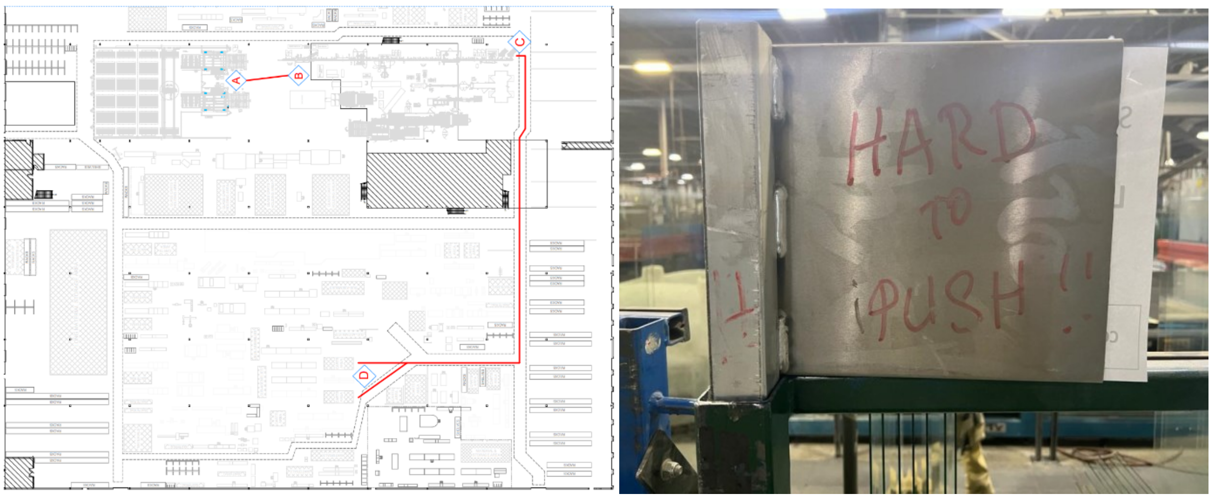


Figure 8.Material Flow

The rolling carts used at the facility, as shown in Figure 9, are manually transferred by workers between workstations. This manual transport of material stood out as a notable challenge in the manufacturing process due to the often-heavy weight of carts and the need for multiple workers to handle a single cart. For instance, the trip from Location C to Location D requires two to three workers to manually push carts loaded to their full capacity of 35 double- and triple-glazed glass units over about a 100-m-long route. The weight of such carts could reach 1,102 lb, and workers transfer loaded carts along this route more than twenty times a day, increasing the risk of injuries that can affect their well-being. This cart system has led to numerous workers developing back problems and has forced the company to incur significant workers' compensation costs to address the health issues arising from the present conditions. The impact of such material handling conditions is not limited to the safety risks imposed on workers—they also consume a significant number of labour hours, as will be discussed later in the thesis.

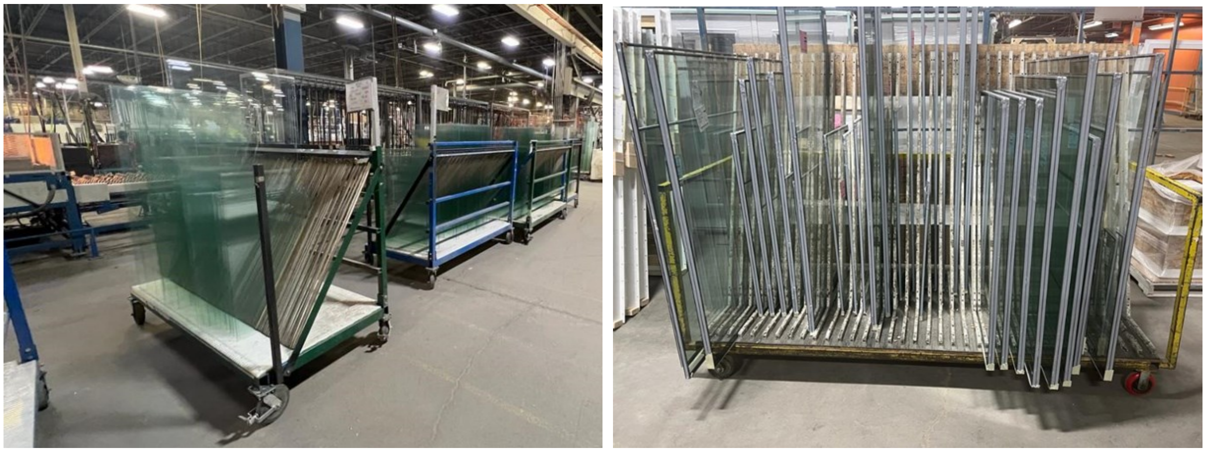


Figure 9.Rolling carts

As such, there is a need to quantify the effect of the current material handling practice on transfer time and labour costs, and to investigate alternative strategies that could mitigate the inefficiencies associated with the current practice. The present study focuses on the trip needed from Location C to Location D, which is the longest trip involving the heaviest carts at the factory.

4.4.2 Solutions

Two potential solutions were suggested, classified as operational and technological solutions. Operational solutions are relatively straightforward to implement on the production line. These solutions, often referred to as "quick hits", do not require significant investments and have the potential to yield significant improvements, although the results may vary. Their advantage lies in their ease of implementation and its benefits. However, whether or not they are implemented ultimately depends on the factory's discretion. On the other hand, the second type, referred to as the technological solution, requires careful consideration as it entails significant investments and may require temporary suspension of specific operations. The factory management is cautious about implementing the technological solution. They are committed to seeing a thorough assessment of its potential benefits, including improvements in the production line, increased productivity, and enhanced well-being of employees. This careful evaluation will consider various factors such as cost-effectiveness and the potential impact on the workforce's overall working environment and job satisfaction. Workforce management always seeks solutions that aligns with their objectives and will contribute positively to the overall success of the factory.

Operational Solutions:

The operational solutions are listed as follows:

- Most used glass closer to the station.
- Eliminate manual input.
- New Gloves, Suction Cups.
- Less glasses per cart.
- Kanban Cart with numbers.
- Create a preventive maintenance check.
- Reducing cart size.

Technological Solutions:

Below is the list of proposed technological solutions:

- Rapid Loader, Rapid Store.
- New algorithm, New machine.
- Conveyor.
- Reverse Osmosis.
- Suction Machine.
- Power Jack.

Further details and discussions on these solutions are presented in subsequent sections. It is important to mention that certain problems may have multiple solutions, and the best solution is determined based on the results of the CBA. The CBA aids in evaluating the potential impact and feasibility of each solution before making a final decision.

4.5 Choosing by Advantages

CBA is employed in decision-making scenarios to identify the optimal solution for the challenges encountered in the production line. Multiple iterations of CBA were conducted to address each specific problem at the respective stations. The implementation of CBA was facilitated by the Production Manager, who has over 20 years of experience.

Prior to the implementation of CBA, a comprehensive explanation of the CBA process was provided, utilizing a practical example to demonstrate its effectiveness and user-friendliness in the given context. This step was crucial in ensuring that CBA was implemented in the most efficient and effective manner. The Production Manager expressed satisfaction with the user-friendliness of CBA, particularly when the step-by-step approach was presented.

4.5.1 Alternatives Identification

Different alternatives were considered for each problem encountered in the production line, with each alternative tailored to address the specific challenges at hand. In subsequent sections, the various alternatives associated with each problem are presented and discussed in detail.

Loading Glass:

The loading process for glass onto the machine is inefficient, and the reason for this inefficiency is discussed in Subsection 4.4.1 Discuss Problems. To address this issue, two new technological solutions have been introduced as alternatives. These solutions involve replacing the current crane with either a rapid loader or a rapid store.

The rapid loader is a butterfly table designed to automatically load the glass onto the cutting table. It operates on specific rails, allowing for lateral movement of the glass before being placed on the cutting table. This machine is equipped with up to 10 positions, enabling it to accommodate and handle 10 different types of glass. A representation of the rapid loader can be seen in *Figure 10*.

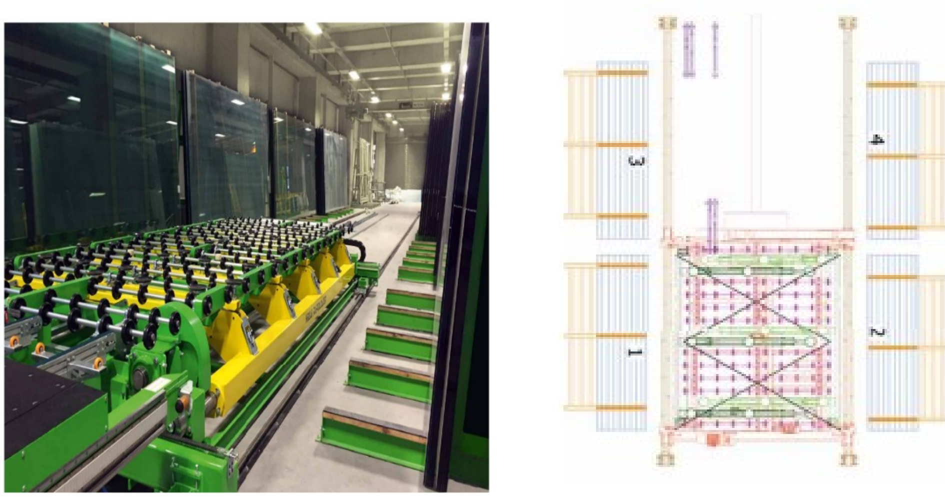


Figure 10.Rapid Loader. Source: “https://www.hegla.com/”

Rapid store is an additional feature that is added to a rapid loader and allows for a wider variety of glass to be fed into the loading machine. It then adds a shuttle that changes the type of racks used by the rapid loader that is fed to the cutting table, as shown in Figure 11.

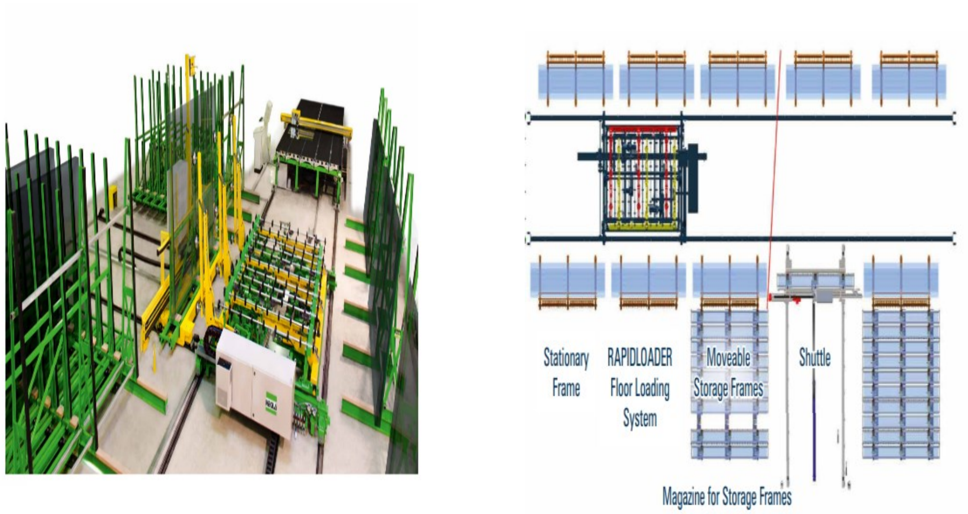


Figure 11.Rapid Store. Source: “https://www.hegla.com/”

Cutting Station:

The cutting station poses a significant challenge in the production line, serving as the bottleneck and determining the overall pace of the system. This is primarily due to its longer cycle time compared to the other stations. To address this issue, two potential technological solutions are proposed.

The first solution involves adding a new cutting machine. By adding a new cutting machine, it is expected to increase the overall production rate. This solution aims to enhance the cutting process and optimize the utilization of the cutting station.

The second solution suggests implementing a new algorithm in the cutting machine. This algorithm is designed to improve the speed and accuracy of finding the optimal cutting patterns for the glass. By optimizing the manner in which the glass pieces are cut and maximizing the number of glass pieces that can fit within each sheet, the production line can generate a higher number of finished glasses. This solution focuses on improving the cutting process and maximizing the output of the cutting station.

Both solutions aim to address the challenges posed by the cutting station and improve the production efficiency of the overall system. The choice between the two solutions depends on cost, feasibility, and potential impact on other aspects of the production line.

Separating and Loading:

The separating loading station is facing a significant problem related to glass breakage during the separation process from the whole sheet. The main cause of this problem was previously discussed in Subsection 4.4.1.

To address this issue, two operational solutions are proposed. The first solution involves introducing new gloves that provide higher friction, reducing the chances of glass slippage during the separation and loading processes. The improved gloves would enhance worker grip and control, minimizing the risk of breakage.

The second solution suggests utilizing suction cups when loading the glass into the Kanban cart. The suction cups would provide a secure hold on the glass, reducing the likelihood of breakage during the transfer process. This solution aims to improve the handling of the glass and ensure its safe placement in the cart.

However, it is important to note that the implementation of the new gloves should be accompanied by clear instructions and guidelines for the workers. This includes carrying the glass using both hands to ensure safe handling and, in the case of large glass pieces, involves two workers to handle the load. Although this may slightly increase the processing time for this activity, it is not a significant concern as the station has a low cycle time.

By implementing these technological solutions and reinforcing safe handling practices, the separating loading station can effectively reduce glass breakage, minimize rework, and waste, and enhance overall efficiency in the production line.

4.5.2 Identification of Criteria and Factors

The production manager at the factory identified various factors of interest when comparing alternatives. He focused on factors that would enable him to differentiate between options. However, some factors were not considered during the analysis because the alternatives possessed similar attributes. For example, when considering loading machines, all of the alternatives had the same safety certification, so the team could not include safety certificates as a factor. In CBA, it should be noted, cost is considered a constraint rather than a factor.

The key factors that where considered are as follows:

1. **Speed:** Measures the proposed alternative's speed, i.e., how quickly it can perform tasks.
2. **Maintenance:** Measures the impact of maintaining the machine over time.
3. **Safety:** Measures the alternative's safety, taking into account potential risks and hazards. Safety is a crucial factor in this case study since the material being dealt with is hazardous.
4. **Installation Time:** Measures the duration and resources needed to install and implement the new solution effectively. Installation time is important since any interruption of production can lead to considerable losses for the factory.
5. **Accuracy:** Measures the alternative's precision and correctness in performing its designated tasks. For example, in the case of a cutting machine, it refers to how accurately it cuts the glass.
6. **Accessibility:** Determines the extent to which a machine can interact with various types of glasses.
7. **Durability:** Measures the functionality of the solution without the need for repair or maintenance.

By evaluating these factors, the production manager aimed to assess the strengths and weaknesses of each alternative and to make an informed decision.

To judge the alternatives, specific criteria were established for each factor, all of which were agreed upon by the production manager. Criteria, it should be noted, can be categorized as either "want" or "must." "Must" criteria are those that are linked to a code or specification, whereas in this particular case study, all the criteria were considered as "want" criteria.

Table 8.Factors and Criteria

Factor	Criterion
Speed	The higher the speed is, the better
Ease of Installation	The easier the installation is, the better
Maintenance	The less maintenance is required, the better

Safety	The fewer threats caused by failure of equipment there are, the better
Accuracy	The higher the accuracy is, the better
Footprint	The smaller the footprint is, the better
Durability	The higher the durability is, the better
Accessibility	The higher the accessibility is, the better

4.5.3 Determining the Attribute

The attributes for each factor, which are associated with their respective criteria, are obtained from the manufacturing information whenever available. If the necessary information is not found within the manufacturing data, the attributes are derived from expert opinions. These experts possess the relevant knowledge and insights to provide the required attribute values for the factors based on their expertise in the field.

4.5.4 Determining Importance of Advantage

Once the criteria, factors, and attributes have been assigned and the individual IOA (Importance of Alternative) for each option has been determined, the total IOA is calculated by summing the attributes of each factor. It is important to mention that the importance scale ranges from 0–100, with each alternative assigned a specific value. The alternative that is most favoured in terms of factors and criteria receives the highest value of 100. Additionally, all the IOA were determined by the production manager.

4.5.5 Results and Discussion

CBA was used in three distinct scenarios (loading, cutting, and separating stations) as described in the following subsections in order to determine the most favourable solution.

4.5.5.1 Loading Station

The total IOA for the alternative of the rapid loader was calculated to be 225, whereas for the rapid store, it amounted to 85. Table 9 presents the corresponding results:

Table 9.Loading Station Alternative Results

Factors and Criteria		Alternatives					
		Rapid Loader			Rapid store		
		Attribute	Advantage	Importance	Attribute	Advantage	Importance
1	Factor: Speed m/min Criterion: Higher speed is better	60	25 higher speed	100	35		
2	Factor: Maintenance Criterion: The easier to maintain, the better	Requires minimal maintenance	Much easier to maintain	60	Requires sporadic maintenance		
3	Factor: Safety Criterion: Fewer threats caused by failure of equipment	Low threats	Slightly less threats	20	Medium threats		
4	Factor: Installation Time (days) Criterion: Less installation time is better	3 days	2 days less for installation	15	5 Days		
5	Factor: Footprint (sq ft) Criterion: A smaller footprint is better	10	5 sq ft less	30	15		
6	Accessibility Criterion: Higher Accessibility the better	Medium			High	Slightly more accessible	85
Total IOA				225			85

Determining the Cost of Each Alternative:

After obtaining the total IOA for each alternative, the cost of each alternative is calculated. To determine the cost of each alternative, multiple quotations are obtained from manufacturers, and the amount paid by the factory is determined. The cost is divided into two parts: one-time payment and monthly payments, both of which include direct and indirect expenses. The one-time payment includes expenses such as machine cost, employee training, disruption of work, and machine installation. Monthly payments include costs for maintenance, space, software, and energy. Table 10 illustrates these costs.

Table 10.Cost Rapid Loader versus Rapid Store

Rapid Loader			
#	Item Description		Value ($ CAD)
A	Total cost (Direct + In-Direct Expenses) one time		$162,290
B	Machine (Installation and Testing)		$1,890
	↳	Hourly rate	$30.00
	↳	Number of workers	3
	↳	Time (days)	3
C	Disruption of work		$80,000
	↳	Profit per window (Glass Portion)	$40
	↳	Number of windows produced per day	1,000
	↳	Time (days)	2
D	**Employee training**		$400
	↳	Hours needed to train	8
	↳	Hourly rate	$25
	↳	Number of employees	2
E	Machine Cost (cost machine + transportation)		$80,000
F	Total Cost (Direct + In-Direct Expenses) per month		$4,011
F1	Maintenance cost per month		$2,000
	↳	Spare parts and labour	$2,000
F2	Space cost per month		$604
	↳	Space (sq ft)	10
	↳	Rent paid per sq ft per month	$60
F3	Energy cost		$1,007
	↳	Price of 1 kWh (c/kWh)	16.49
	↳	Power consumption (kWh)	18.5
	↳	Time (h)	15

Rapid Store			
#	Item Description		Value ($ CAD)
A	Total cost (Direct + In-Direct Expenses) one time		$233,550
B	Machine (Installation and Testing)		$3,150
	↳	Hourly rate	$30.00
	↳	Number of workers	3
	↳	Time (days)	5
C	Disruption of work		$120,000
	↳	Profit per window (Glass Portion)	$40
	↳	Number of windows produced per day	1,000
	↳	Time (days)	3
D	**Employee training**		$400
	↳	Hours needed to train	8
	↳	Hourly rate	$25
	↳	Number of employees	2
E	Machine Cost (cost machine + transportation)		$110,000
F	Total Cost (Direct + In-Direct Expenses) per month		$5,374
F1	Maintenance cost per month		$2,850
	↳	Spare parts and labour	$2,850
F2	Space cost per month		$900
	↳	Space (sq ft)	15
	↳	Rent paid per sq ft per month	$60
F3	Energy cost		$1,224
	↳	Price of 1 kWh (c/kWh)	16.49
	↳	Power consumption (kWh)	22.5
	↳	Time (h)	15

In order to compare the alternatives together the Present Worth (PW) was calculated. The Minimum Attractive Rate of Return (MARR) for the factory was set at 20%, indicating that the factory would only invest if a 20% return was achieved. Furthermore, it was assumed that the analysis would cover a time period of 5 years (N). CW refers to the capitalized worth, which represents the initial investment, while A denotes the monthly cost. It is important to note that the PW was calculated solely based on costs, and no consideration was given to revenues in the calculation. The PW values are presented in the Table 11:

Table 11.PW Rapid Loader versus Rapid Store

	CW	A	P/A	MARR	N	PW
Rapid Loader	$162,290	$4,011	2.9906	20	5	$270,248
Rapid Store	$233,550	$5,374	2.9906	20	5	$378,194

$$PW = CW + A(^{P}/_{A}, i, j) \tag{1}$$

Selecting the Best Alternative:

Once all the IOA and costs for each alternative have been computed, the decision-maker can proceed to select the most suitable alternative based on specific cost considerations. This process aligns with the essence of CBA. Figure 12 presents the total IOA and costs for each alternative:

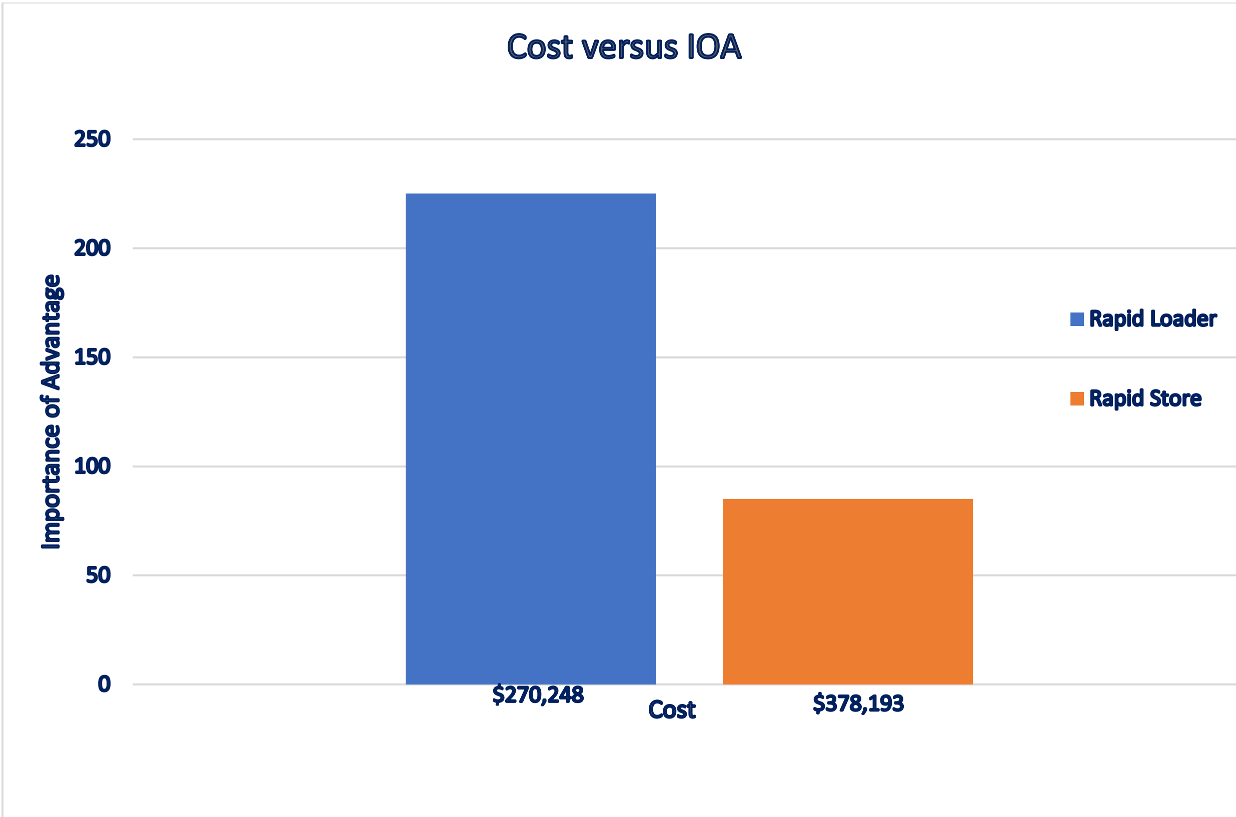


Figure 12.Cost versus IOA

Among the alternatives, the rapid loader option demonstrates a total IOA of 225, while the rapid store option has an IOA of only 85. Additionally, the cost associated with the rapid loader is calculated to be $270,248, while the cost of the rapid store amounts to $378,193. Therefore, based on the analysis, the optimal choice would be the rapid loader alternative. This option offers the highest value generation while having a lower cost compared to the rapid store alternative.

4.5.5.2 Cutting

For the first alternative, which is the new algorithm, the total IOA is 65. In contrast, for the second alternative, which involves implementing a new machine, the total IOA is 100. The results are summarized in the *Table 12*:

Table 12.Cutting.

Factors and Criteria		Alternatives					
		New algorithm			New machine		
		Attribute	Advantage	Importance	Attribute	Advantage	Importance
1	Factor: Speed Criterion: Higher speed saving is better	Low			High	Much higher speed	100
2	Factor: Footprint (sq ft) Criterion: Less Footprint is better	Low	Smallest footprint	15	High		
3	Factor: Installation time Criterion: Less installation time is better	2 Days	6 days less for installation	10	8 days		
4	Factor: Accuracy Criterion: Higher accuracy is better	High	Slightly more accurate	40	Medium		
Total IOA				65			100

Cost of Each Alternative:

After determining the IOA of each alternative, the total cost of implementing each alternative in the factory is calculated to aid the decision-maker in selecting the best option. The cost of alternatives is based on multiple quotations obtained from suppliers and the expenses incurred within the factory. The cost is divided into two parts: one-time payment and monthly payments.

For the new machine solution, the one-time payment includes expenses for the machine, disruption of work, and machine cost. On the other hand, the monthly payments comprise costs for maintenance, space, and energy consumption.

Similarly, for the new algorithm, the one-time payment consists of expenses for software installation and testing, disruption of work, software cost, and data migration. The monthly payment, however, only includes the maintenance cost of the software. The costs are illustrated in Table 13.

Table 13.Cost of New Machine versus New Algorithm

New cutting machine			
#	Item Description		Value ($ CAD)
A	Total Investment (Direct + In-Direct Expenses) one time		$335,040
B	Machine (Installation and Testing)		$5,040
	↳	Hourly rate	$30.00
	↳	Number of workers	3
	↳	Time (days)	8
C	Disruption of work		$160,000
	↳	Profit per window (Glass Portion)	$40
	↳	Number of windows produced per day	1,000
	↳	Time (days)	4
D	Machine Cost (cost machine + transportation)		$170,000
E	Total Investment (Direct + In-Direct Expenses) per month		$5,961
E1	Maintenance cost per month		$2,500
	↳	Spare parts and labour	$2,500
E2	Space cost per month		$720
	↳	Space (sq ft)	12
	↳	Rent paid per sq ft per month	$60
E3	Maintenance of software per month		$1,000
	↳	Software update and upgrade	$1,000
E4	Energy cost		$1,741
	↳	Price of 1 kWh (c/kWh)	$16.49
	↳	Power consumption (kWh)	32
	↳	Time (hr)	15

New algorithm			
#	Item Description		Value ($ CAD)
A	Total Investment (Direct + In-Direct Expenses) one time		$140,840
B	Software (Installation and Testing)		$840
	↳	Hourly rate	$30.00
	↳	Number of workers	2
	↳	Time (days)	2
C	Disruption of work		$80,000
	↳	Profit per window (Glass Portion)	$40
	↳	Number of windows produced per day	1,000
	↳	Time (days)	2
B	Software cost (Lump Sum)		$60,000
D	Total Investment (Direct + In-Direct Expenses)		$3,620
D1	Data migration (one time)		$1,620
	↳	Hourly rate	$45
	↳	Number of workers	3
	↳	Time needed (h)	12
D2	Maintenance of software per month		$2,000
	↳	Software Update and Upgrade	$2,000

To facilitate a comprehensive comparison among the alternatives, PW was computed. The MARR for the factory was established at 20%, indicating that the factory would only pursue an investment if it yielded a minimum return of 20%. Furthermore, the analysis assumed a time of 5 years (N).

However, it is important to note that the PW calculations were based solely on costs, and no consideration was given to revenues in this assessment. The PW values for each alternative are presented in Table 14:

Table 14.PW Cutting Machine versus Algorithm

	P	**A**	**P/A**	**MARR**	**N**	**PW**
Cutting Machine	$335,040	$5,961	2.9906	20	5	$477,664
New Algorithm	$140,840	$3,620	2.9906	20	5	$227,448

Selecting the Best Alternative:

Analyzing the IOA and cost of each alternative allows decision-makers to determine the best option. *Figure 13* represents the cost and total IOA of each alternative.

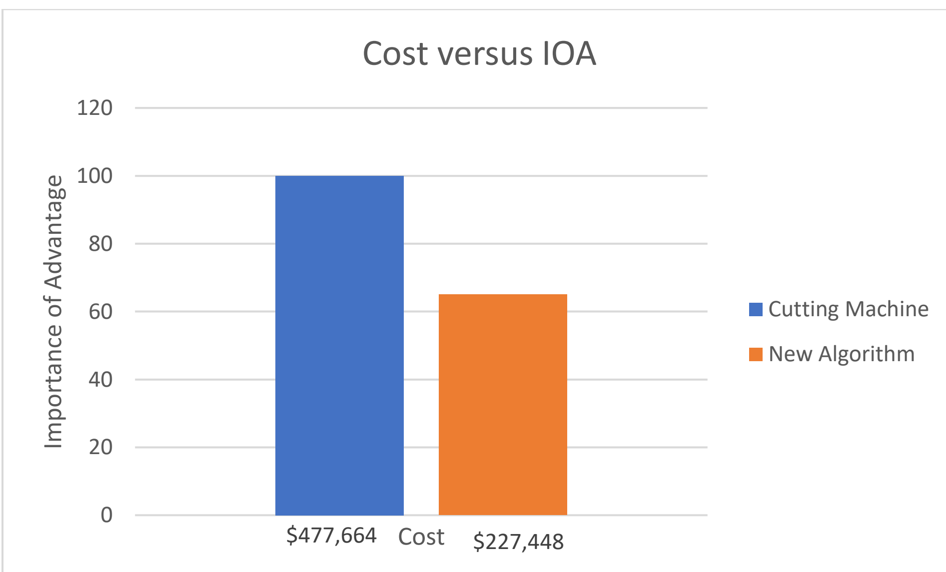


Figure 13.Cost versus IOA

For the cutting machine alternative, the total cost is recorded as $477,664, with a total IOA of 100. On the other hand, the new algorithm alternative has a total cost of $227,448 and a total IOA of 65. The decision was challenging for the decision-maker due to several factors.

First, implementing the cutting machine involves a significant investment compared to the new algorithm, which costs approximately half the price. However, the cutting machine has a higher IOA.

After careful analysis, the decision-maker chose the cutting machine, despite its higher cost. The VSM showed that the cutting machine was a bottleneck in the system, significantly slowing production. Their main concern was to enhance the process's speed, even if it meant incurring additional expenses.

By implementing the cutting machine, they anticipated a significant acceleration in production, leading to increased revenue generation. Therefore, the decision-maker concluded that the higher IOA and improved speed offered by the cutting machine outweighed the higher cost, making it the preferred alternative.

4.5.5.3 Separating and Loading

For this particular station, there are two solutions being considered. The first solution involves acquiring new gloves, which resulted in a total IOA of 170. On the other hand, the second alternative is the implementation of suction cups, which obtained a total IOA of 100. The results are presented in Table 15.

Table 15.Separating and Loading

Factors and Criteria		Alternatives					
		New Gloves			Suction cups		
		Attribute	Advantage	Importance	Attribute	Advantage	Importance
1	Factor: Speed Criterion: Higher speed saving is better	High	Much higher speed	90	Low		
2	Factor: Durability Criterion: Higher	High	Slightly more durable	35	Medium		

	durability the better						
3	Factor: Safety Criterion: Fewer threats the better	Medium			High	Slightly less threats	100
4	Factor: Ease of use Criterion: The easier to use, the better	High	Much easier to use	45	Medium		
5	Factor: Footprint Criterion: Less footprint is better	NA			NA		
6	Factor: Accuracy Criterion: Higher accuracy is better	NA			NA	NA	NA
Total IOA				170			100

Determining the Cost:

The cost of each alternative for this station is solely based on the initial investment, as there are no recurring monthly costs associated with either option. Table 16 displays the total cost for each alternative:

Table 16.Cost Suction Cups versus New Gloves

Suction Cups		
#	Item Description	Value ($ CAD)
A	Total cost (Direct + In-Direct Expenses) one time	$700

New Gloves		
#	Item Description	Value ($ CAD)
A	Total cost (Direct + In-Direct Expenses) one time	$800

Choosing the Best Alternative:

After determining the IOA and cost of the alternatives, the decision maker is able to select an alternative. The total cost and IOA of the suction cups are displayed in Figure 14 below:

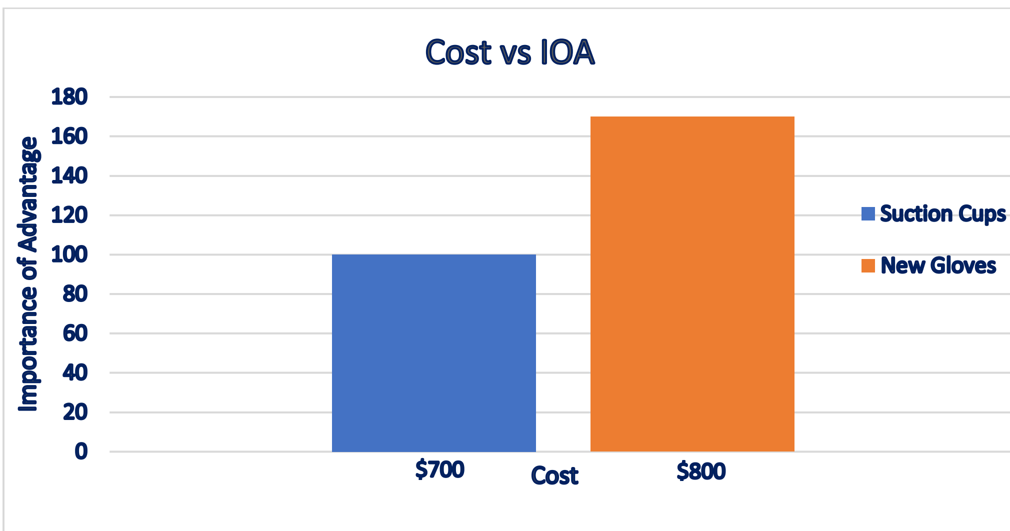


Figure 14.Cost versus IOA

The total cost for the suction cups alternative was $700, with a recorded total IOA of 100. On the other hand, the new gloves alternative had a total cost of $800 and a total IOA of 170. Based on the total IOA values, the new gloves alternative is the superior option due to a higher IOA. Although it comes with an additional cost of $100 compared to the suction cups, the higher cost is not a significant drawback considering the substantial benefits provided by the higher IOA. Therefore, for these reasons, the decision-maker prioritized the new gloves alternative.

4.6 Simulation

4.6.1 Introduction

After conducting VSM and CBA to identify and address waste and choosing the most favourable solution, a simulation model is developed. This simulation model replicates the current state of the window manufacturing process and provides a detailed analysis of its performance in terms of utilization, WIP, average wait time, production rate, and production lead time. Unlike VSM, which has certain limitations in terms of the information it can provide, simulation offers a more comprehensive view of the current state.

Simulation is a valuable tool that can provide insights into various lean metrics such as WIP and production lead time, enabling the examination of the proposed solutions' impact and determining which are most effective for improving production. Simulation helps stakeholders understand the outcomes and make informed decisions by showcasing the solutions' effects.

4.6.2 Fitting the Data

The previously collected data from the factory is incorporated into the simulation model, which encompasses both value-added and non-value-added time. Each activity within the model is based on data points that includes both types of time. To ensure the accuracy of the data, probabilistic distributions are fitted to all the data points. Additionally, the goodness of fit for each data point is tested using the Kolmogorov-Smirnov (K-S) test, which is performed in Simphony.

4.6.3 GED Line Simulation Model

This section introduces a simulation model that replicates the current state, as illustrated in *Figure 15*, and presents the obtained results. The simulation model initiates the process by creating entities using the "create entity" function at the beginning of the simulation. The number of entities created is determined by the schedule department in order to produce 5,000 units per week. Initially, the entities created are sheets, and after passing through the separating and loading station, they are transformed into glass panes. As previously explained, the number of glass panes produced after the separating and loading station is 10.

It is important to note that there are three batches in the system. The first batch occurs after the separating and loading station, where the glasses cannot proceed unless the cart is loaded with 100 sheets of glass. The next two batches occur after the loading and argon station, where the glass cannot proceed until the cart is loaded with 50 sheets of glass.

Moreover, there are multiple probabilities incorporated into the model. The first probability relates to the cutting station, where workers manually input the orders instead of having them ready 20% of the time. Another probability pertains to the separating and loading station, where 3% of the glasses are broken on average each day when the worker separates and loads them. The third probability also applies after the separating and loading station, indicating that 65% of the glasses produced are medium-sized, while 35% are large-sized. Furthermore, 75% of the glasses produced are directed to the GED line, while 25% go to the atlas line and linthard line. Additionally, there are two more probabilities considered: 4% of the glasses are washed twice, and 4% of the glasses break at the argon station. All these probabilities are collected from the company and from observations that have been conducted. For example, the number of medium and large glasses is calculated based on the schedule provided by the company, while the number of broken glasses is determined through observation using the equation below:

$$\%\,Broken\ Glass = \frac{Quantity\ of\ broken\ glass}{Total\ number\ of\ glasses\ Produced} * 100$$

The Production rate of the entire line was evaluated by using global variables in order to assess the performance of the line. This production rate was calculated using global variables.

GX(1): Time Now

GX(2): Number of windows produced

GX(3): GX(2)/GX(1)

Another important data point collected in the model is the production lead time. Each glass is time stamped with a local variable just before entering the loading glass station and after exiting the patching station. By doing this, the time spent can be tracked by each window in the system, providing valuable information about the production lead time for analysis. Moreover, the daily glass count shows the number of glasses produced every 54,000 s (i.e., how many glasses are produced daily).

Moreover, this section helps to identify the bottleneck in the system and address the problems discussed earlier by implementing solutions. However, resolving one bottleneck may give rise to a new bottleneck, which will also be addressed in this section.

It is worth noting that new solutions are not always a benefit for production. For instance, reducing the time spent on an activity may not always be the best option, as it could result in an increase in WIP and a decrease in overall production. This aspect is demonstrated in the discussion of the simulation model.

After analyzing the results, the model is validated, and the solutions derived from CBA and others are implemented to enhance the line's performance.

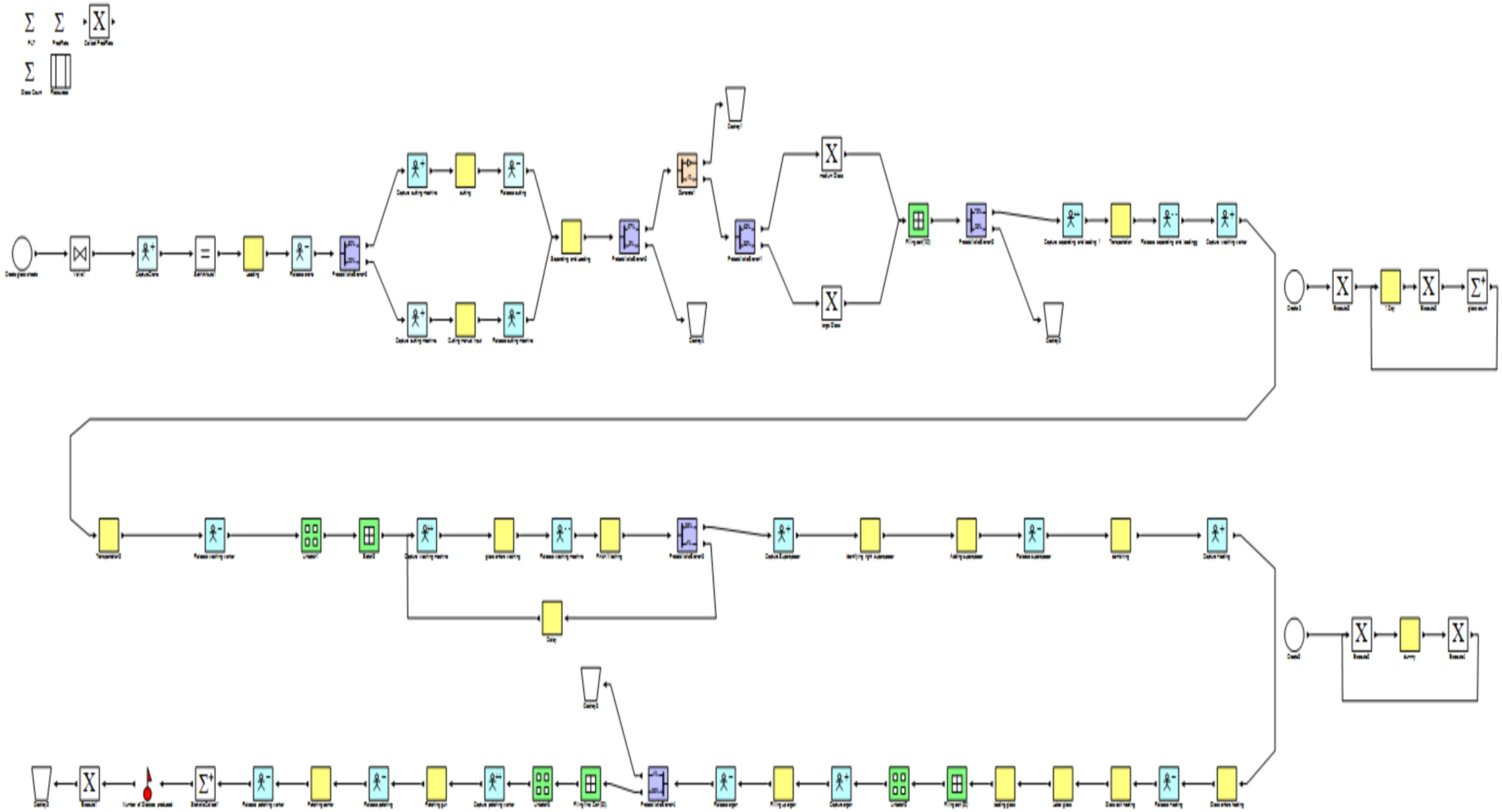


Figure 15.Simulation Model

4.6.4 Verification and Validation

4.6.4.1Verification:

Prior to extracting any results, the simulation model needed to be verified and validated. Various approaches were used to verify the model. First, all syntax, data, experimental, and logical bugs and errors were addressed. Data error, for instance, is one sort of error that was fixed by modifying the distribution of the activity duration. When attempting to fit the best distribution, the normal distribution was best fit (least K-S value). an error was encountered indicating that the distribution might result in a negative value, as shown in Figure 16.

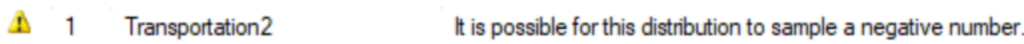


Figure 16.Duration error

This outcome is illogical because activity duration cannot be negative. To resolve this issue, an alternative distribution was fitted that demonstrated a better q-q plot and finite boundaries, with a K-S value that closely resembled the least K-S value (normal distribution).

Black Box Testing and Desk Checking were used to validate the model, both of which are tests adopted from Whitner and Balci (1989).

Black Box Testing is a testing method that focuses on studying the model based solely on its input and output, without considering the internal processes. In this case, the black box testing involved simulating a certain number of sheets to evaluate if the model was performing correctly. During the simulation, the output of windows generated by the model was logically consistent, meaning that the numbers produced were in line with the expectations. Moreover, the output obtained from the simulation aligned with the expected results, which were also confirmed by the company itself. Through Black Box Testing, the model's ability to generate accurate and expected output was assessed, providing confidence in its performance and reliability.

Desk Checking involves evaluating and examining the logic and consistency of a model. In the case of the developed model, its logic is straightforward and easy to comprehend. The model's logic is relatively simple: sheets are loaded, cut, and separated. These glass pieces are then placed into carts (batches) and cannot proceed until the cart is full. The glass goes through multiple stations to be transformed into a double-glazed window, which is then placed in another cart that must be full before it can proceed. Next, the glass goes through the argon-filling station, followed by the patching station, to which the glass cannot proceed until the cart is full. Overall, the logic of the model follows a clear and sequential process that aligns with the manufacturing operations and requirements. This logic was also validated by the line superintendent.

4.6.4.2 Validation

Model validation is essential to ensure the simulation model accurately represents reality and that the system is being modelled correctly. Validating the model is crucial because, without validation, the model may produce inaccurate outcomes. This section employs various validation techniques, including face validity, degenerate tests, internal validity, and event validity adapted from Sargent (2010).

First, the face validity was assessed by consulting experts to determine if the model made sense. The superintendent of the line was consulted to ensure that all activities were sequenced in the correct order and that the model accurately reflected the duration of each activity. The average time of each task was also determined using the data gathered, and its logical coherence was examined with the superintendent. The model was also evaluated for its representation of WIP, where the WIP in model was shown in the factory, and the superintendent was shown all of the resources assigned to each activity. After presenting the model, the superintendent confirmed that the model is mimicking the real factory. It is worth noting that the superintendent has more than 10 years of experience.

The second validation technique involved performing degenerate tests, where the parameters of the model were altered, and the model behaved as predicted. These tests are discussed later in the thesis.

The third validation test, internal validity, was conducted to assess the variability of the model and ensure that it falls within an acceptable range. Since the model is stochastic in nature, it was necessary to examine its internal validity. This was accomplished by comparing the outcomes of multiple runs to determine if the results were consistent or reasonably close to each other. Parameters such as WIP, PLT, utilization, and average wait time were evaluated, and it was observed that the variability across the runs was approximately 3%. This indicates that internal validity has been achieved, as the results demonstrate a consistent level of similarity.

The final validation test was event validity, where the model was centered on comparing the present state to the simulation model. The simulated production rate ranged between 900 and 1100 windows per day, which closely aligned with the current state. Notably, the model accurately represented the utilization patterns observed in reality, with the cutting station having the highest level of utilization, just as it never ceased operations in practice. Additionally, the simulation captured the WIP between cutting, washing, the super spacer, argon, and patching, mirroring the quantities found in the actual production environment.

4.6.5 Identification of Bottlenecks

Based on the utilization rate, waiting time, and WIP, the cutting station is identified as the bottleneck of the system. This is because there are a significant number of products waiting to be processed at the cutting station, totaling around a substantial 25 sheets, given that a sheet yields an average of 10 glasses. Furthermore, the cutting station has the longest waiting time of 4,380 s, indicating that each entity must wait approximately 4,380 s to be processed. The station is fully utilized at 100%.

4.6.6 Scenarios

This subsection discusses the simulation of various scenarios and is divided into two parts. The first part focuses on the simulation of operational solutions. The second part discusses the testing of technological solutions once all operational solutions are implemented. These scenarios are evaluated based on factors such as production rate, utilization, average wait time, WIP, and PLT.

4.6.6.1 Operational

These solutions are categorized as "quick hits" due to their ease of implementation in the system and their minimal investment requirements. Implementing these solutions can result in an improved system state.

Scenario 1: Most Used Glass Near the Loading Station

In this particular scenario, we are examining the loading station where the storage area for the glass lacks proper organization. Currently, the glass is randomly placed in the storage area without considering the type of glass that the machine predominantly uses. The crane loads the glass into the machine randomly, sometimes within a 20m range, and other times within a 40m range. As a result, the loading process varies and takes a considerable amount of time depending on the position of the glass.

To address this issue, a suggested solution is to strategically position the most frequently used glass near the station. In this case study, the most commonly used glass is the 3mm low-e glass. By placing this type of glass near the loading station, the time required for the loading process can be significantly reduced.

To determine the cycle time for loading the glass, a specific approach was implemented. First, the daily usage of glass was measured by assessing the amount of glass cut in the factory. It was determined that approximately 45% of 3mm low-e glass is used per day on average, as reported by the production team. Based on this information, it becomes evident that having this type of glass readily available near the machine is necessary. The remaining 55% of the glass was loaded with various types, and their timing was assumed to be similar to the average time previously collected during the time study.

Furthermore, the manufacturer provided the speed of the crane, indicating that it loads at a rate of 50m/min. In the current setup, the closest possible range to place the glass is within 20m of the loading table. However, it is important to note that if a different layout is possible, it would be ideal to have the glass placed even closer to the machine for improved efficiency.

By employing these values, the time required for the loading process can be calculated using the equation below:

$$Total\ loading\ time\ = (T1 \times \%1 + T2) + (T3 \times \%2 + T2) \quad (2)$$

where:

T1 = Average travelling time for different types of glass

T2 = Time for loading glass

T3 = Distance travelled divided by the speed.

The results simulated are shown in Figure 17 below:

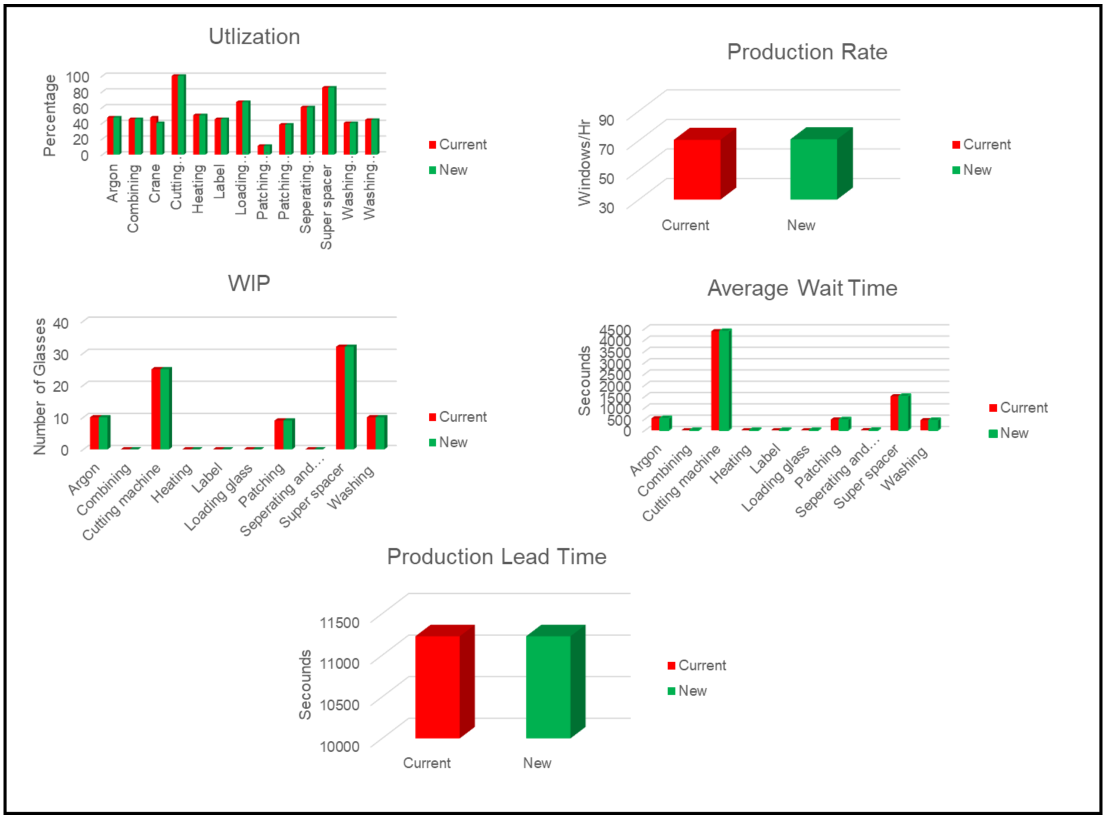


Figure 17.Most Used Glass Near the Station

After implementing the proposed solution, there was a marginal increase of only 1% in the production rate. Moreover, the PLT stayed the same. However, all other metrics under study stayed the same for all stations. This means that the solution did not have a significant impact, except on the utilization metric for the loading station, where it decreased by 5%. This occurred because the machine is now loading faster than it was previously, causing a reduction in the station cycle.

The observed increase in productivity appears to be reasonable, considering that it is primarily influenced by the station that follows. In this case, the station that follows is the cutting station. However, it is important to note that if the cutting station is not optimized, the improvements in this particular station may not be fully reflected. However, it is crucial to also focus on improving this station because it is considered the feeding station for cutting and holds the second highest process time after cutting. By addressing both stations, the overall system performance can be further enhanced.

Scenario 2: Eliminating Manual Input

The cutting station is identified as the bottleneck within the system due to its longest cycle time, highest utilization, WIP, and wait time. Consequently, this station requires significant attention and improvement efforts to enhance the overall system performance. One key issue with this station is that not all orders are directly sent from the schedule team. Instead, some orders are manually entered by workers into the machine, resulting in increased processing times.

To address this problem, it is crucial to ensure that all orders are completed in advance by the schedule team and sent directly to the machine. This adjustment will decrease processing times and ultimately improve the system efficiency. The results of this adjustment are shown in Figure 18.

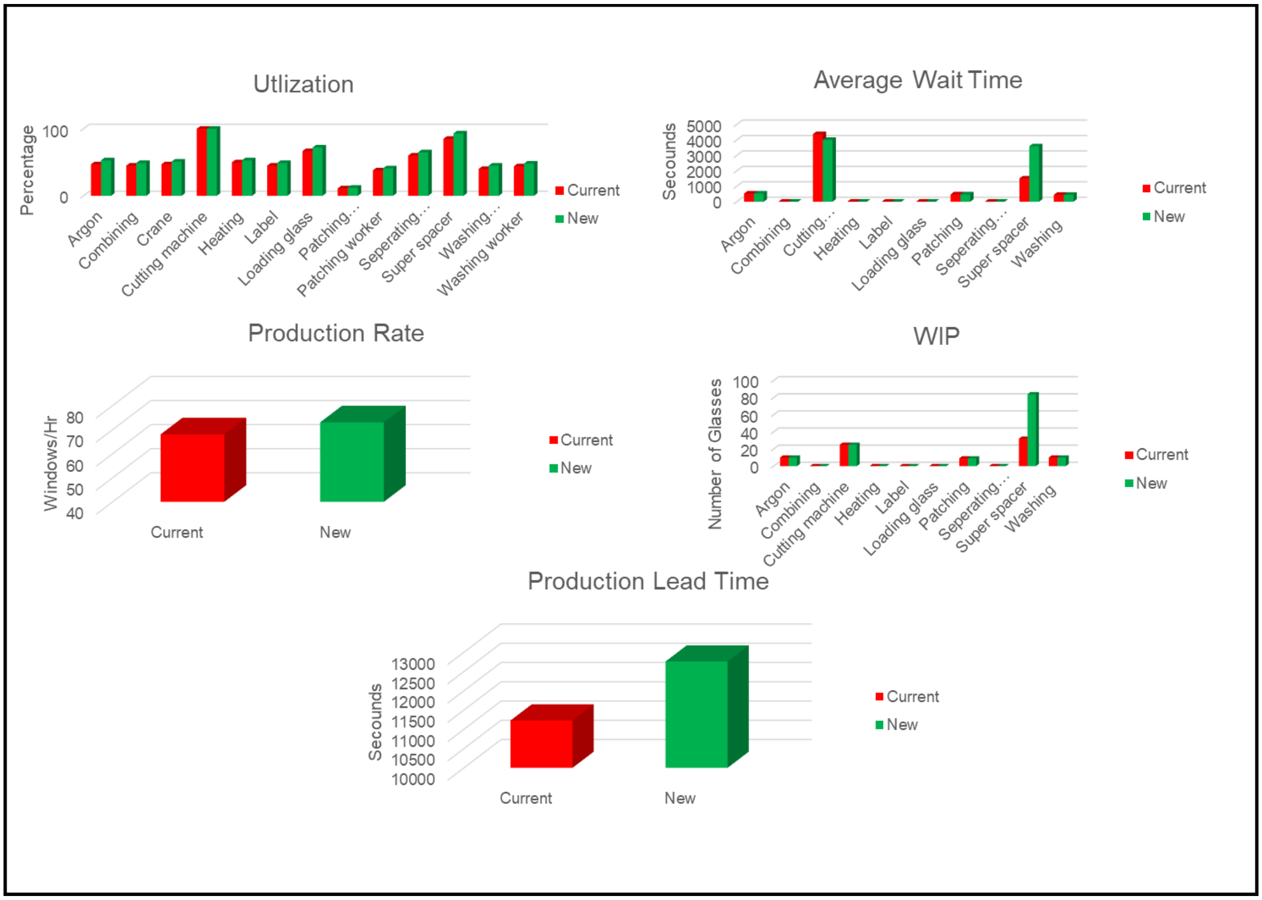


Figure 18.Elimination of Manual Input

After implementing the solution, there was an observed improvement of a 7% increase in the production rate. Moreover, the average wait for cutting stations decreased by 9%. Despite this improvement, the WIP and wait time for the cutting station remained relatively high, since the cycle time did not improve significantly.

It should be noted that the implementation of the solution led to an increase in WIP at the super spacer station by a significant 63%. This increase can be attributed to the higher production volume resulting from the improved system. The utilization rate at this station also rose to 93%, indicating that it is operating at a higher capacity. Consequently, the increased wait time at the super spacer station suggests that the solution overwhelmed the station's capacity to handle the increased product flow.

Moreover, the solution had a negative impact on the PLT, which increased by 14%. This means that the time required to obtain a finished product increased by 14%. The higher product volume, combined with the overwhelmed super spacer station, contributed to the product's wait time until completion, putting additional strain on the system. Furthermore, the increase in PLT will have adverse effects on the products. When products spend more time on the production line, the likelihood of defects occurring rises, potentially leading to a higher number of defective products. Additionally, the extended PLT reduces the system's flexibility. If a window, for example, takes a full day to be completed, it becomes challenging to reproduce the same window efficiently due to the accumulation of high WIP in the system.

It is important to highlight that the utilization rate remained unchanged at 100%, signifying that the cutting station still serves as the bottleneck in the process.

Scenario 3: New Gloves

In the separating loading station, there is a significant problem with glass breakage during the process of separating it from the whole sheet, as well as when placing it in the Kanban cart. This issue leads to rework, material waste, and time loss. The primary cause is often attributed to unsafe handling practices by the workers. For example, workers sometimes fail to wait for assistance when handling large glass pieces, resulting in breakage. Additionally, glass is occasionally carried with only one hand positioned just below the shoulder, which increases the risk of breakage. Moreover, the current gloves being used have deteriorated and do not provide sufficient friction with the glass, leading to slippage.

To address these issues, it is crucial for workers to always wait for assistance when carrying glass, regardless of its weight. Glass should be carried using both hands to ensure safe handling. Although this may slightly increase the processing time for this activity, it is not a significant concern as the process currently has low utilization. Finally, replacing the worn-out gloves with new gloves that offer higher friction will prevent glass slippage and reduce the occurrence of accidents. These measures will not only improve production efficiency and minimize waste but also prioritize the safety and well-being of the workers, which is of utmost importance. The results of this solution are shown in *Figure 19*.

Figure 19.New Gloves

The implemented solution yielded promising results, with a 3% increase in the overall production rate compared to the previous state. While the WIP and average wait time remained unchanged for most stations, there was a negative impact observed at the super spacer station. The average wait time at the super spacer station increased by 18%. Additionally, the WIP at the super spacer station increased by 25%, suggesting a higher accumulation of WIP. This shows that this intervention adversely affected the super spacer station, causing it to become overwhelmed with products.

However, it is important to note that the utilization of separating and loading increased by 8%. This increase can be attributed to the longer processing times resulting from the implementation of the new solutions. Despite the longer processing times, waste was successfully reduced by 6% through the implemented measures.

The PLT experienced a 3% increase, primarily due to the overwhelming workload at the super spacer station. This rise in PLT results in products waiting longer to be finished. This might lead to more defective products and less flexibility for the process.

Scenario 4: Reducing Super Spacer Searching Time

In the super spacer station, a significant amount of time is consumed as workers struggle to identify the appropriate super spacer for each window. This leads to an increased placement time for the super spacer on the window. All super spacers are prepared in advance at a different station and stored near the super spacer station. However, they are stored in a cart without any specific sequencing, leading to inefficiencies.

To address this issue, a suggested solution is to assign a numbering system to the Kanban cart, aligning it with the numbering system used for the washing Kanban cart. The glasses in the cart should be sequenced accordingly. For example, if a double-glazed glass is assigned the numbers 1 and 2, the super spacer cart should also be numbered as 1. This approach will significantly reduce the time required to identify the correct super spacer, as workers can easily match the numbering sequence between the glass and the super spacer.

By implementing this solution, the time spent identifying the appropriate super spacer will be reduced, improving overall efficiency. The results are shown in Figure 20.

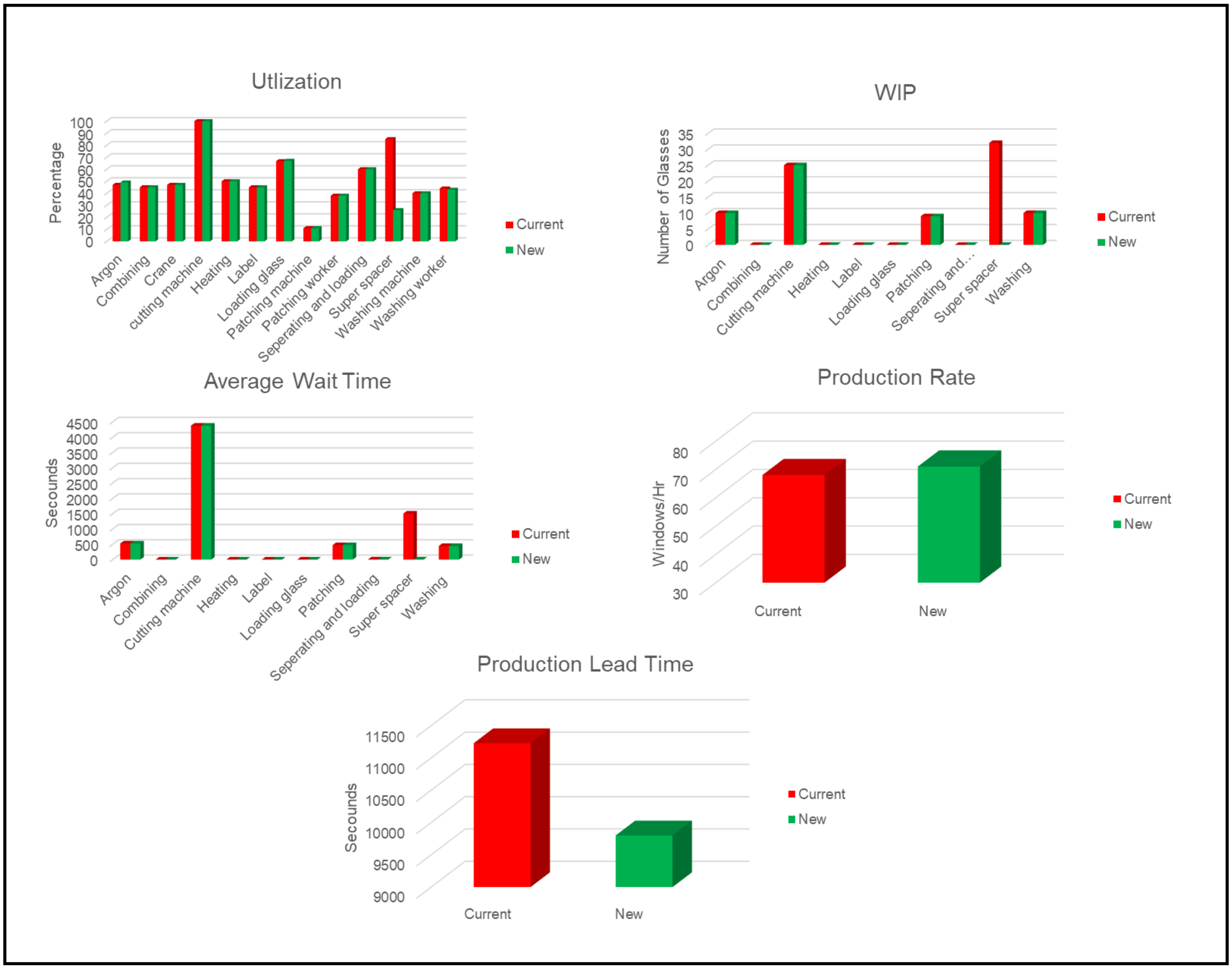


Figure 20.Reducing Super Spacer Searching Time

After implementing the suggested solution, there was a notable 4% increase in the production rate. Moreover, there was a significant decrease in WIP and average wait time, with an impressive 99% reduction in super spacer station. This reduction indicates a substantial decrease in non-value-added time and the absence of WIP between these stations. Consequently, the system has moved closer to achieving a one-piece flow and becoming more streamlined.

However, it is worth mentioning that the utilization rate decreased to 24.5%, meaning that the station is now underutilized and starving for work. This is because the solution sped up the process. Finally, the PLT decreased by 13%, indicating that the system is less overwhelmed. As a result, the products require less time to reach the finished state when compared with the previous methods. There will also be fewer defective items, since products are spending less time in line.

Overall, the implemented solution has led to positive results, including increased production, reduced WIP, PLT and wait time, and a move towards a leaner system.

Scenario 5: Preventive Maintenance

The argon station encounters an issue where certain glass windows crack during the argon-filling process. Resolving this problem is crucial due to its position at the end of the production line. Any flaws present in the glass containers at this stage can lead to substantial costs and time investments in order to manufacture replacement windows.

The lack of regular maintenance for the machine is the root cause of this problem, leading to various issues. One example is the malfunctioning of the meter that measures the amount of argon being filled, resulting in overfilling and subsequent cracking of the window. Another factor is the presence of dirt on the needle that enters the glass, leading to the closure of the argon inlet and ultimately causing the glass to crack.

To address this issue, it is crucial to implement a regular maintenance schedule for the machine to prevent such problems from occurring. By conducting maintenance at the start of each shift and during the mid-shift break, the machine will operate smoothly without malfunctions. The outcomes of this solution are demonstrated in Figure 21.

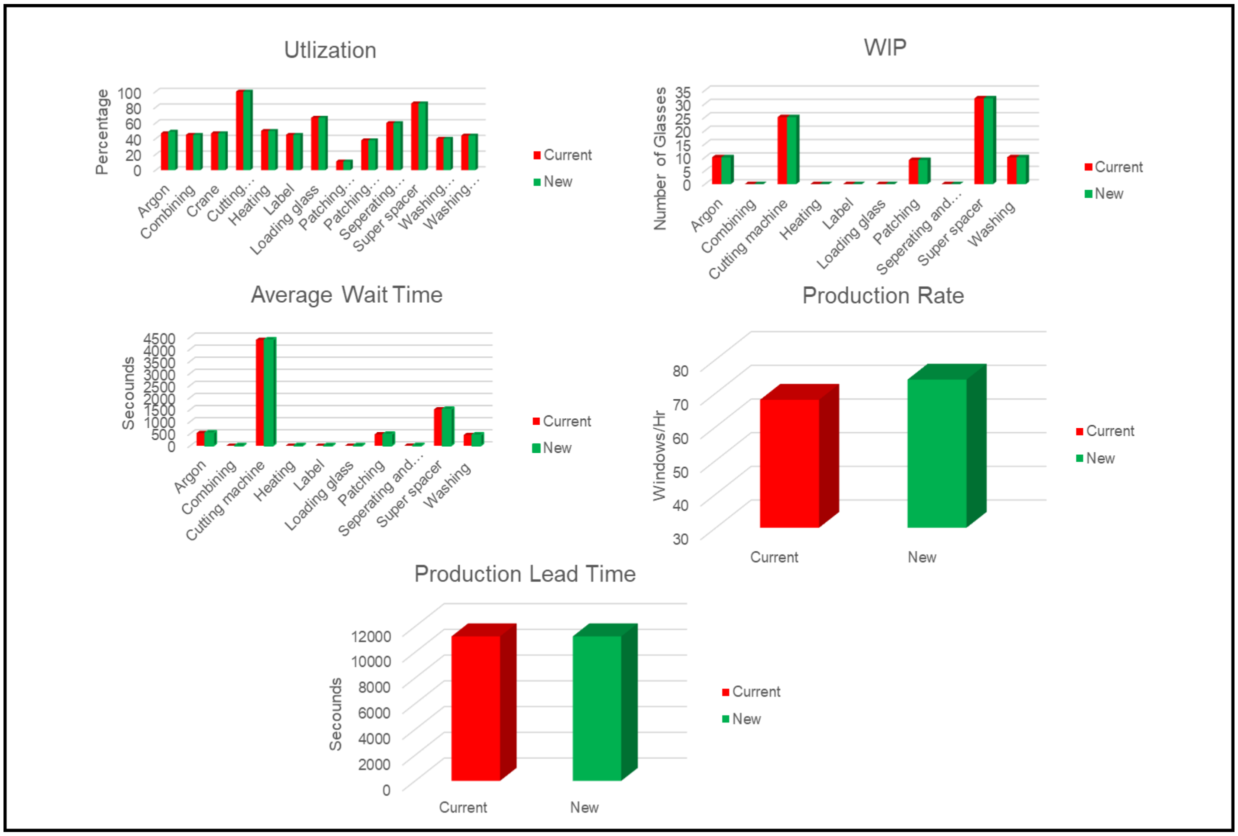


Figure 21.Preventive Maintenance

The findings indicated a 9% rise in the production rate. However, the utilization, WIP, PLT, and the wait time remained unchanged for the whole line, suggesting that this solution solely influenced the production rate.

Scenario 6: Reducing Cart Size

Throughout the production line, it was observed that there are three instances where carts need to wait until they are loaded before proceeding to the next station. These waiting positions are Locations A, D, and E, as seen in *Figure 22*.

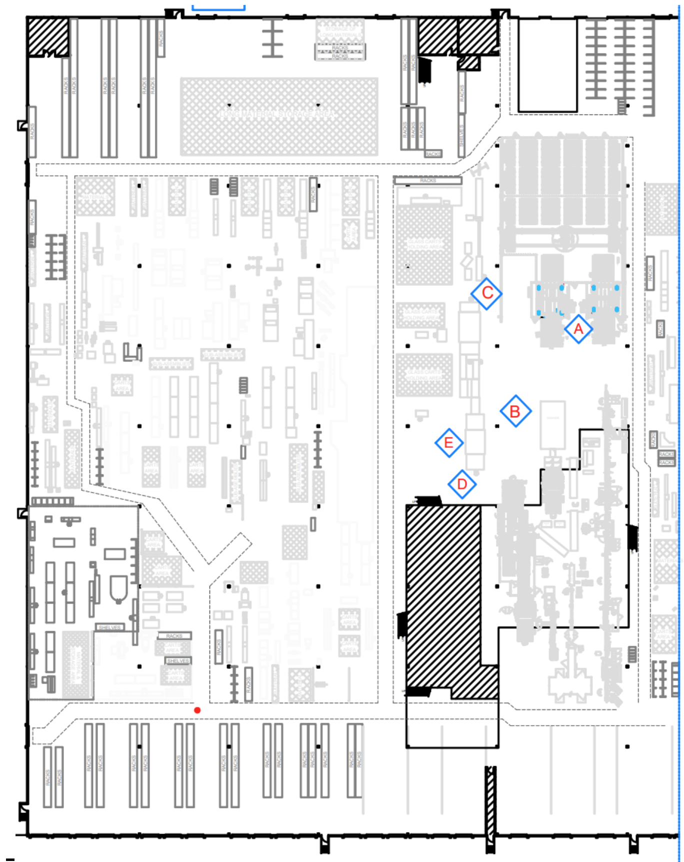


Figure 22.Cart Path

At Location A, workers separate glass from the cut sheet and wait until the cart is loaded with 100 sheets of glass before transferring it to Location B. The washing worker then takes the cart from Location B to Location C for washing the glass pieces. The loading worker at Location D loads double-glazed windows onto a 50-glass-sized cart and waits until it is full before proceeding. Once full, the cart is transferred from Location D to Location E, the argon station, to be filled with argon. The worker must then wait again for the cart to be loaded (50-sized cart) before proceeding. This waiting on carts at different locations causes certain stations to experience starvation, leading to wasted time.

To address this issue, different numbers of units inside the carts were tested to evaluate their impact on the system's overall performance. A simulation was conducted, considering nine different cart sizes, to analyze the effect of reducing the cart size on cost. The objective was to identify the optimal cart size that would enhance the production line's performance within reasonable cost.

In selecting the best cart size, the total cost of each option was analyzed. Reducing the cart size would decrease the WIP and the cost of materials between stations. However, it would also increase the number of trips made during the day, resulting in higher transportation costs. Therefore, a balance needed to be found between reducing WIP and minimizing transportation costs in order to determine the most suitable cart size.

The steps to calculate the total cost are shown below:

1) Extract from model the WIP from Locations A, D, and E

2) Calculate the Cost of WIP in three locations by using Eq. (3):

$$TC\ of\ WIP\ = WIP(A) \times Cost\ WIP(A) + WIP(D) \times Cost\ WIP(D) + WIP(E) \times Cost\ WIP(E) \qquad (3)$$

3) Calculate the number of trips required for each location:

$$Number\ of\ trips\ = \frac{Quantity}{Size\ of\ cart} \qquad (4)$$

4) Calculate the average time spent to transfer carts:

$$Average\ time\ spent = T_F \times N + T_R \times N$$

where (5)

T_F = Time needed to transfer full cart

N = number of carts

T_R = Time needed to return to station.

5) Calculate cost of transfer of carts:

$$Cost\ of\ transfer\ Carts = Average\ Time\ spent \times number\ of\ workes \times Hourly\ wage. \qquad (6)$$

5) Determine the total cost:

$$Total\ Cost = Total\ cost\ of\ WIP + Total\ cost\ of\ trnasfer\ of\ carts \qquad (7)$$

The total cost versus the size of the cart is shown below in *Figure 23*.

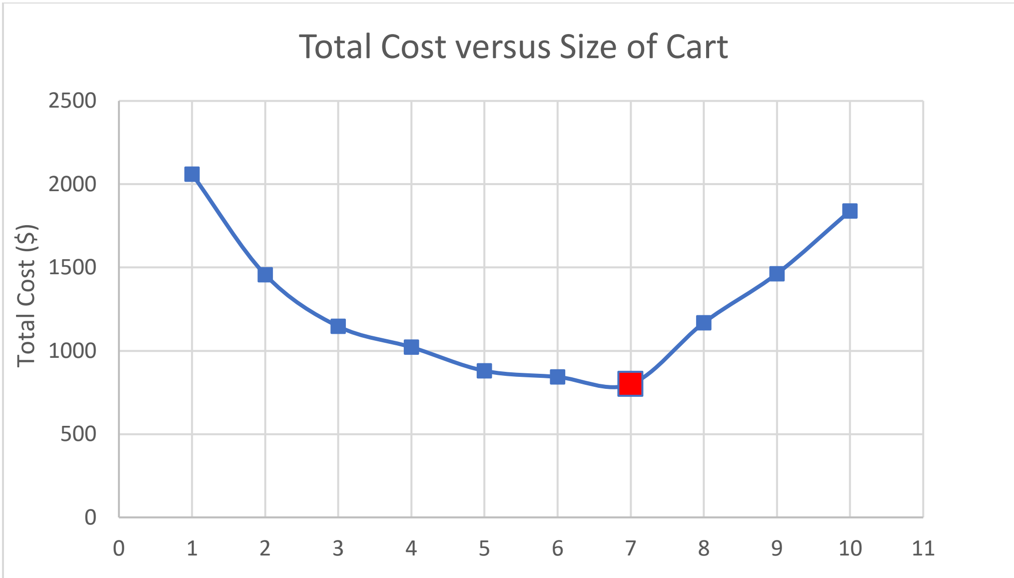


Figure 23.Total Cost versus Size of Cart

In *Figure 23*, it is observed that as the number of glasses in the cart is reduced, the total cost decreases. The main reason for this decrease is the reduction in WIP between stations, resulting in a decrease in the cost of WIP. This trend continues until reaching the point on the graph where the cart size is 20, 10, 10, which represents the lowest cost.

However, beyond this point, as the cart size decreases further, the cost starts to increase. The main factor contributing to this increase is the higher number of trips required to transfer the carts between stations. The cost associated with cart transportation becomes dominant in this region of the graph, outweighing the cost savings from reduced WIP.

Based on this analysis, the best cart size option is determined to be 20, 10, 10 as it corresponds to the lowest cost point on the graph. This size strikes a balance between reducing WIP and minimizing transportation costs, resulting in the most cost-effective solution for the system. The result of this solution is shown in Figure 24.

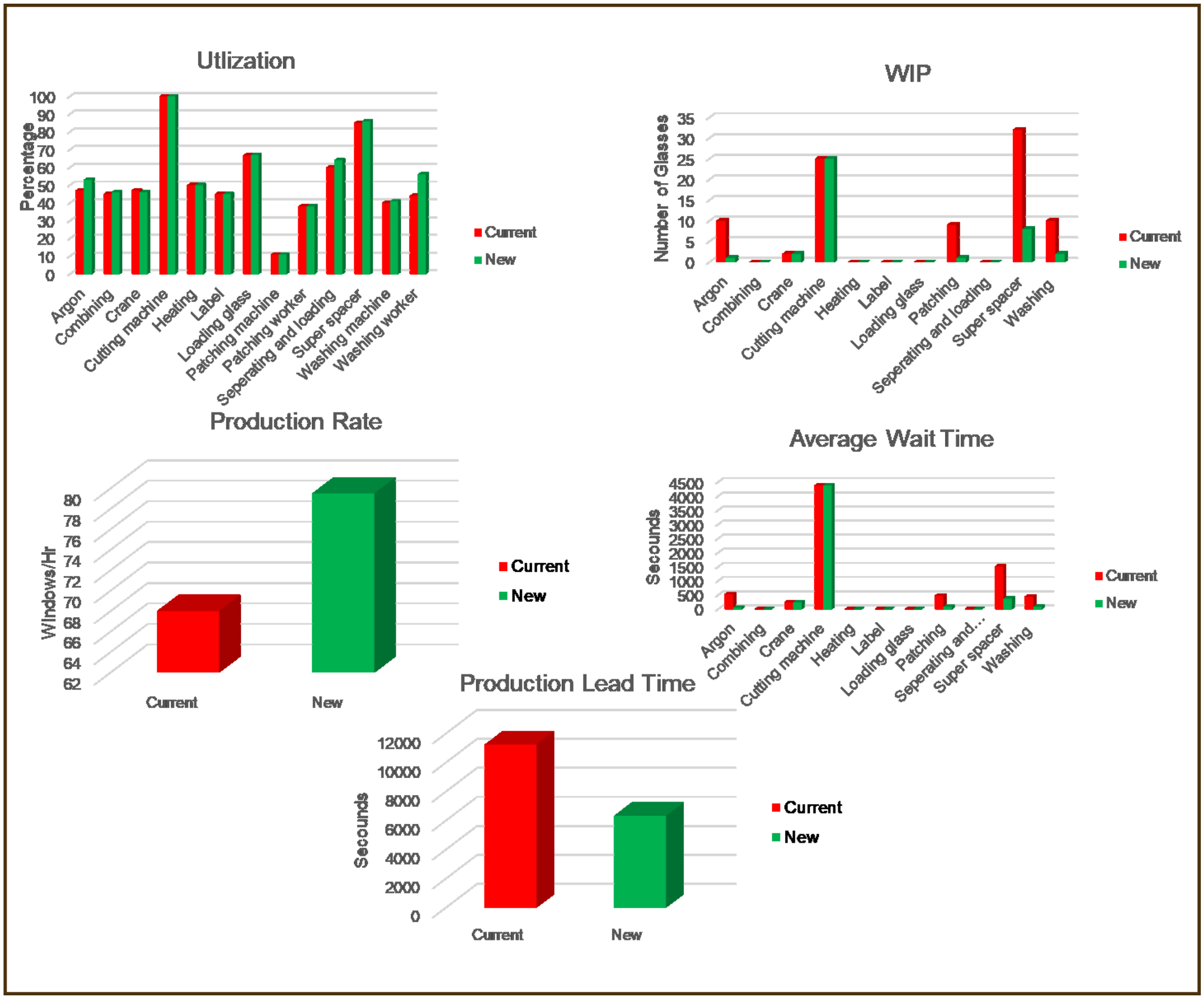


Figure 24.Reducing Cart Size

Regarding the reduction in cart size, the production line was found to experience a significant increase in production as a result of this change, with a 17% improvement. Additionally, the WIP at Locations A, D, and E decreased to 0, 2, and 2, respectively. Moreover, the WIP was reduced in argon, super spacer, washing, and patching stations by 90%, 75%, 80%, and 80%, respectively. This reduction in WIP is crucial, as it brings the system closer to achieving a one-piece flow, where products move smoothly from one station to the next without excessive inventory build-up. It also enables faster defect tracking, since fewer products are waiting to be processed. Having less WIP in the system facilitates the tracking of defects and makes taking immediate action easier. Less

WIP means that defects can be detected more quickly, allowing prompt corrective measures. In such cases, the defective product can be returned to the station responsible for its production and fixed, resulting in significant cost savings.

On the other hand, large amounts of WIP means that defects may go unnoticed for longer periods of time. This delay in detecting defects can lead to producing more defective products before the issue is identified. Consequently, a larger quantity of defective products will be wasted, resulting in increased costs.

Additionally, there was a notable improvement in the average wait time across the board. At Locations A, D, and E, the average wait time decreased significantly by approximately 90%. Moreover, wait time reductions were observed in the argon, patching, super spacer, and washing stations, with decreases of 89%, 82%, 75%, and 80%, respectively. This reduction indicates that products are being processed faster, resulting in a decrease in non-value-added time. Furthermore, there was an increase in utilization across multiple stations in the system, with most stations experiencing a utilization increase ranging from 2% to 3%. This beneficial increase indicates that workers and machines are being utilized more efficiently to a certain extent without causing significant delays in the production process. This higher utilization suggests a better allocation of resources. However, the most significant increases were in the washing work, which increased by 28%. This increase is logical because the washing workers are making significantly more trips than before to get the glass cart to load to the machine. The transportation time is also the highest out of all 3 locations. However, this increase did not make this station a bottleneck, since it lowered the highest utilization, which is 100% for the cutting station. The wait time to process products also decreased. For the average wait time and WIP, all stations in the system decreased significantly except for two stations that remained the same, which are the loading station and the cutting station, since the solution will only affect the stations after the separating and loading station. This indicates a positive impact on the line where now the system is more resembling one-piece flow. Defects can be detected faster, decreasing waste and making the system more efficient.

Finally, the implementation of this solution had a significant positive impact on the PLT, resulting in a remarkable decrease of 44%. This substantial reduction can be attributed to the decrease in WIP between the three stations, as previously discussed. Consequently, the product now spends less time waiting in the system before reaching the finished state, ultimately leading to a faster production of the glasses.

Overall, these improvements in WIP, wait time, productivity, and PLT indicate a more efficient and streamlined production process.

4.6.6.2 Technological:

Following the discussion of the operational solution, several technological solutions were explored and simulated to evaluate their impact. However, these solutions will be tested after the implementation of the operational solution, since the operational solution is considered to be a quick hit, does not have a high investment, and proved to have good benefits on the line. The technological solutions often impose a notable challenge due to the substantial investments and considerable time required for implementation.

Scenario 1: Rapid Loader

To address the issue of slow glass loading in this scenario, a new technological solution was introduced, involving the replacement of the crane with a rapid loader for loading the glass onto the cutting table.

The implementation of this solution offers significant advantages compared to the crane. First, it eliminates the need for delicate maneuvering in the storage area (more processing time), simplifying the loading process. Second, the rapid loader operates at a much higher speed compared to the crane, with a 30% faster performance according to the manufacturer. The results of this implementation are presented in Figure 25.

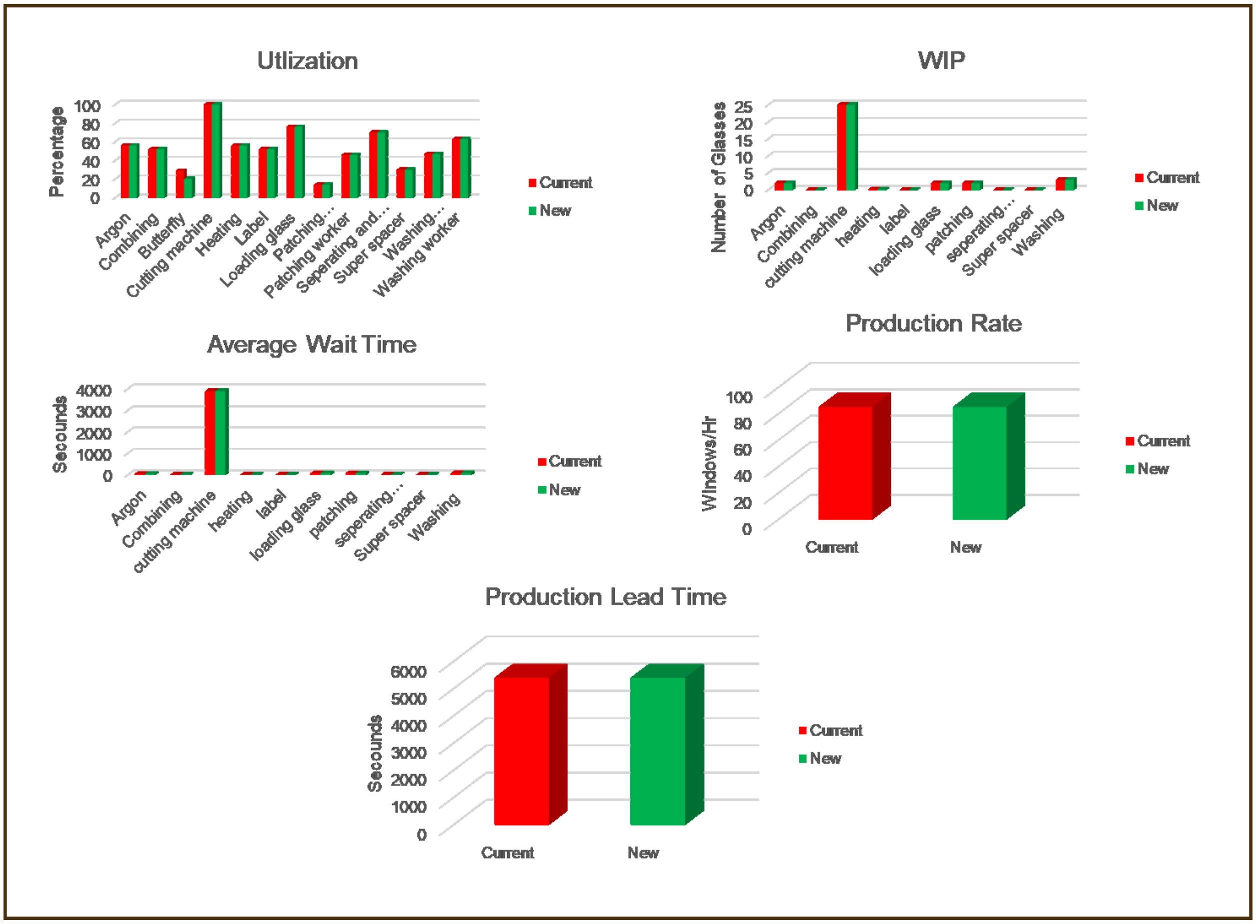


Figure 25.Rapid Loader

The implementation of the rapid loader resulted in a 1% decrease in overall production. This decrease indicates a negative impact on the production line's output. Furthermore, the utilization of the machine decreased significantly by 45%, indicating that the machine is underutilized and did not benefit the loading station. Moreover, all other metrics stayed approximately the same for average wait time, WIP, and PLT.

It appears that the solution focused on local optimization at the specific station, resulting in a suboptimal overall production performance. To achieve better results, it is crucial to consider the impact on the entire production line. Addressing the imbalance between the loading and cutting stations would be necessary to achieve a more efficient and balanced workflow.

Scenario 2: New Cutting Machine

As previously highlighted, the cutting station serves as the bottleneck in the system and plays a crucial role in controlling production. To enhance overall efficiency, it is imperative to focus on improving the cutting station. One solution to this challenge is to invest in a new cutting machine. Despite the high initial investment costs, a new cutting machine would promise a substantial return on investment. The results of implementing this solution are presented in Figure 26.

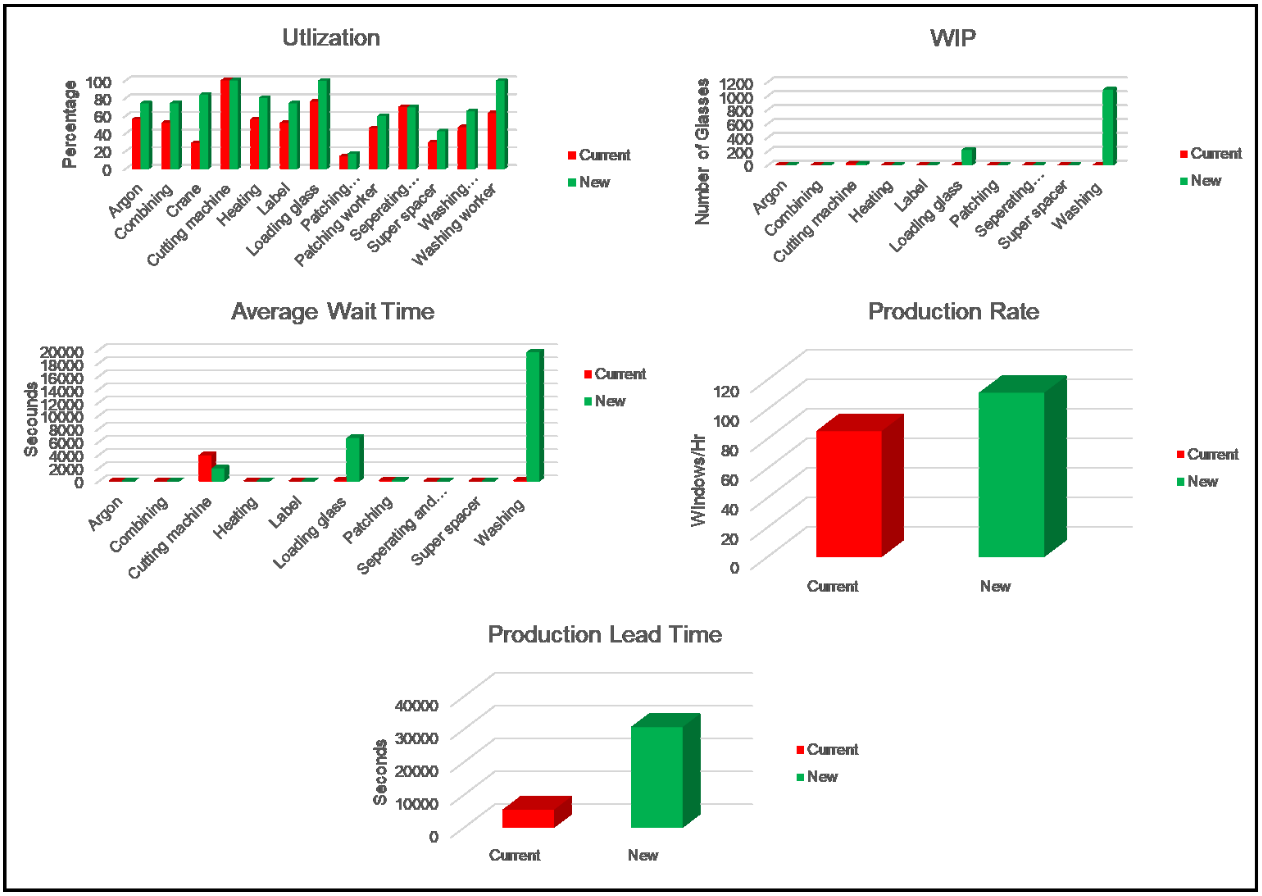


Figure 26.New Cutting Machine

The implementation of this solution had a significant positive impact on production, with a 31% increase in the production rate. However, this improvement in production had negative consequences for PLT increasing PLT values by more than 100%. This means that products spend more time in the production line before being processed, resulting in higher wait times and WIP in certain stations, leading to defects and reduced flexibility in the system.

Specifically, the "loading glass" and "washing" stations experienced a substantial increase in WIP and average wait time, both exceeding 100%. The utilization of these two stations also rose significantly, with a 65% increase for the loading glass station and an 82% increase for the washing station. On the other hand, the average wait time for the cutting station notably decreased by half its original value.

The high utilization, increased WIP, and wait time in the loading glass and washing stations are expected consequences. The solution addressed the bottleneck, resulting in a sharp increase in productivity. However, this increased flow of products downstream and revealed problems that were not previously apparent due to the cutting station controlling the flow.

With the increased production, the workers in the washing station had to make more trips to transport the carts, leading to higher utilization, WIP, and wait time. Similarly, the loading station became overwhelmed as the production moved faster, requiring the workers to load glass windows more quickly. This is reflected in the system's performance. To address these challenges, one approach is to transfer a worker from the super spacer station to assist in the washing station, since it is underutilized. Additionally, adding one worker to the loading station would help reduce wait time and WIP in that area. By redistributing resources in this manner, the system can alleviate the overwhelming load on the washing and loading stations. Despite these challenges, the wait time in the cutting station decreased by 48%, indicating that products spend less time waiting to be processed.

Scenario 3: Reverse Osmosis

The main issue with the washing machine is that occasionally, the glass must be cleaned multiple times before it can proceed to the next station. This requires the worker to stop the washing machine and leave their station to retrieve the smudged glass from the super spacer station, and then pass it through the washing machine again. This process involves rework and double handling, which are non-value-added activities.

The root cause of the problem was identified as the high amount of magnesium in the water used for washing the glass, resulting in smudges when the water evaporates. To address this issue, reverse osmosis was implemented to reduce the mineral content in the water, ensuring that the glass comes out clean from the washing machine. The outcomes of this solution are shown in Figure 27.

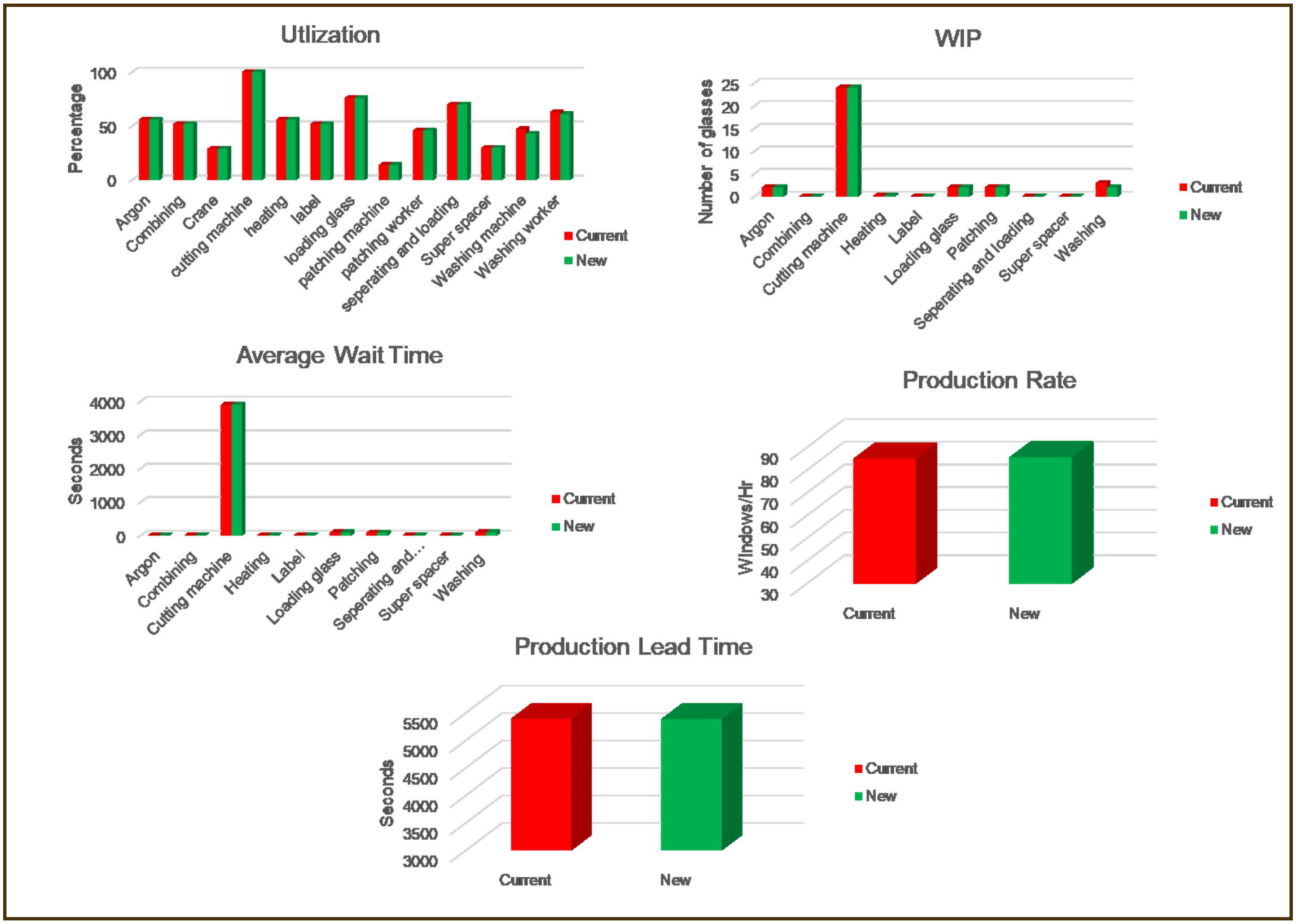


Figure 27.Reverse Osmosis

The implementation of reverse osmosis resulted in a 1% increase in production. Additionally, there was a significant decrease in WIP by 33%, and an average wait time reduction of 11% in the washing station. These improvements signify a decrease in the number of products waiting to be processed, as well as a reduction in WIP, indicating a move towards a lean system and a step closer to achieving a one-piece flow.

However, there was a decrease in utilization by 26%, indicating that the machine is now being underutilized. Additionally, the PLT decreased by 1%, implying that products spend less time waiting in the production line to be completed which will lead to higher flexibility in the system.

Scenario 4 (Reverse Osmosis + Cutting):

In this scenario we combined two technological solutions: the washing machine and the cutting machine solution. The results are shown in Figure 28.

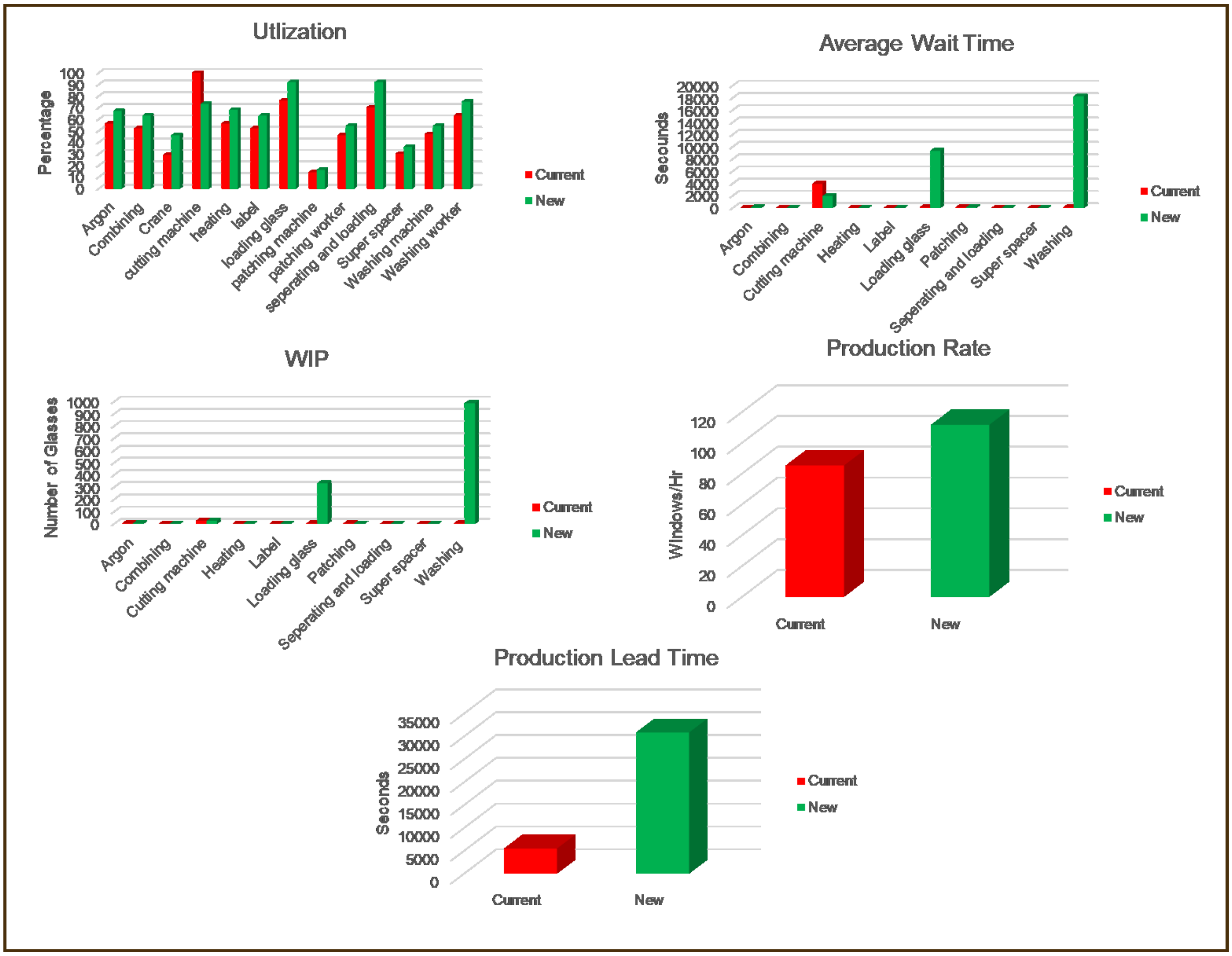


Figure 28.Reverse Osmosis and Cutting

The implementation of this solution resulted in a significant production rate increase of 24%. However, it also led to challenges in the loading and washing stations, where the WIP increased by over 100%, indicating that the system was overwhelmed and experiencing stress. Similarly, the average wait time in these stations showed a similar trend, surpassing a 100% increase. This means that products had to wait longer to be processed at these stations.

These changes can be attributed to the higher production volumes generated by the cutting station, which caused an increased workload that overwhelmed the washing and loading station. Moreover, the PLT also increased by over 100%, indicating that products had to wait longer before being completed. This means that a higher chance of having a defective product is possible.

Overall, the utilization of the entire process improved, suggesting better utilization of machines and workers. However, it is important to highlight that the loading and washing stations faced challenges and were identified as the bottlenecks of the system. To address these issues, further optimization efforts, as discussed in Scenario 3, may be required to improve the overall performance of the production line.

Scenario 5 (Reverse Osmosis + Rapid Loader):

In this scenario, washing and butterfly solutions were combined to observe the impact on the production line. The outcomes are presented Figure 29.

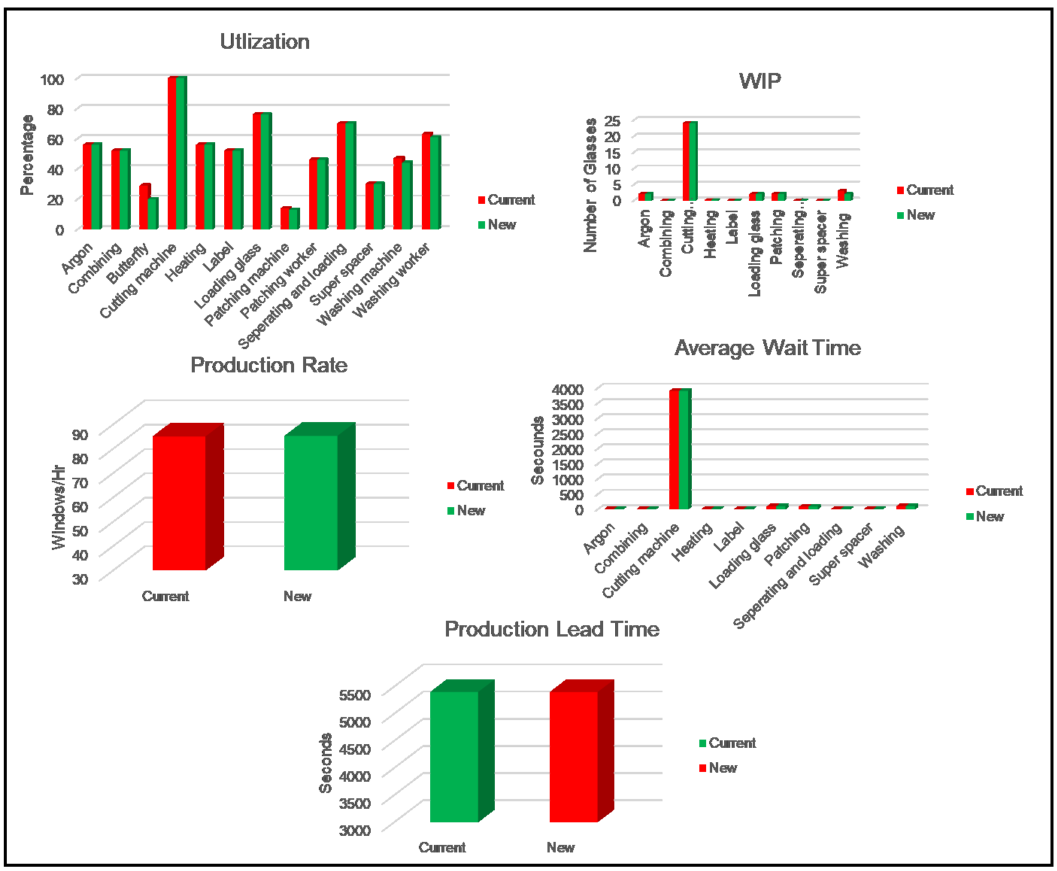


Figure 29.Reverse Osmosis and Rapid Loader

The overall production rate remained unchanged with a 0% improvement. Although the utilization rates for all stations were unaffected, a decrease in utilization for the washing machine station was recorded. The washing machine experienced a 2% drop in utilization.

As for the average wait time and WIP, a decrease in the washing station was recorded. The WIP dropped by 33%, and the average wait time decreased by 2%.

Scenario 6 (Cutting + Rapid Loader):

In this scenario, two technological solutions were implemented in order to study the effect they had on the system. The results are shown in

Figure 30.

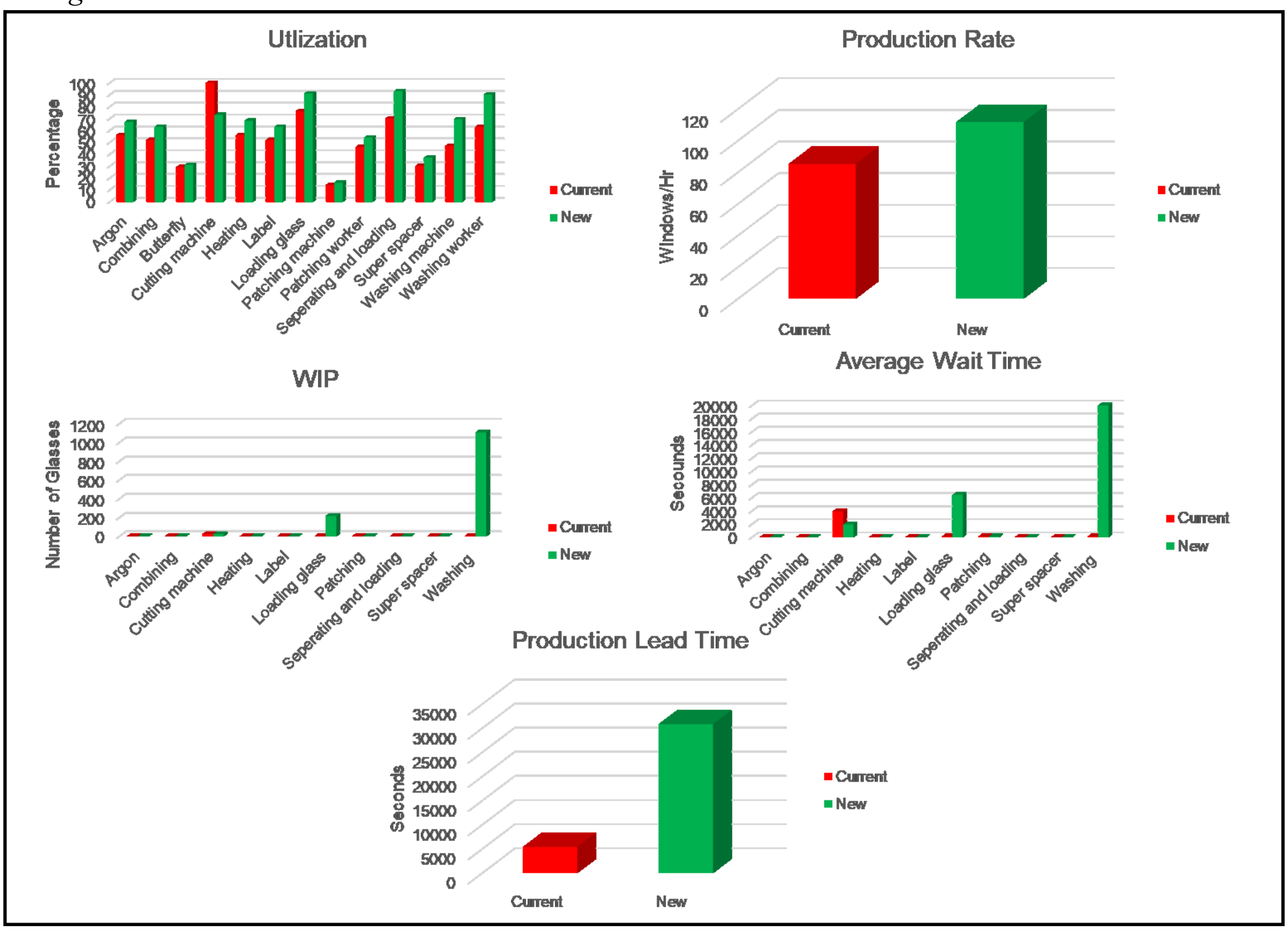


Figure 30.Cutting and Rapid Loader

The implementation of the solutions yielded significant improvements in the production rate, resulting in a 31% increase. However, the impact on WIP and average wait time varied across stations. The cutting station experienced a notable decrease in average wait time by 50%, indicating a reduction in unfinished work between stations. Conversely, the loading and washing stations observed a 100% increase in WIP and wait time, signifying a higher accumulation of work. These changes can be attributed to the higher production volumes achieved by the cutting station, which overwhelmed the separating and loading station, leading to increased wait times and higher WIP. Moreover, PLT increased by more than 100%. Despite these variations, the overall utilization of the entire process improved, indicating a better utilization of machines and workers. However, it is crucial to address the loading and washing station's higher utilization and bottleneck status to further enhance the overall performance of the production line. Additional optimization efforts may be necessary to address the challenges faced by these stations.

Scenario 7 (Cutting + Rapid Loader + Reverse Osmosis):

In this scenario all technological solutions were combined and implemented to see the impact of these solutions on the line. The results of these implementations are shown in Figure 31.

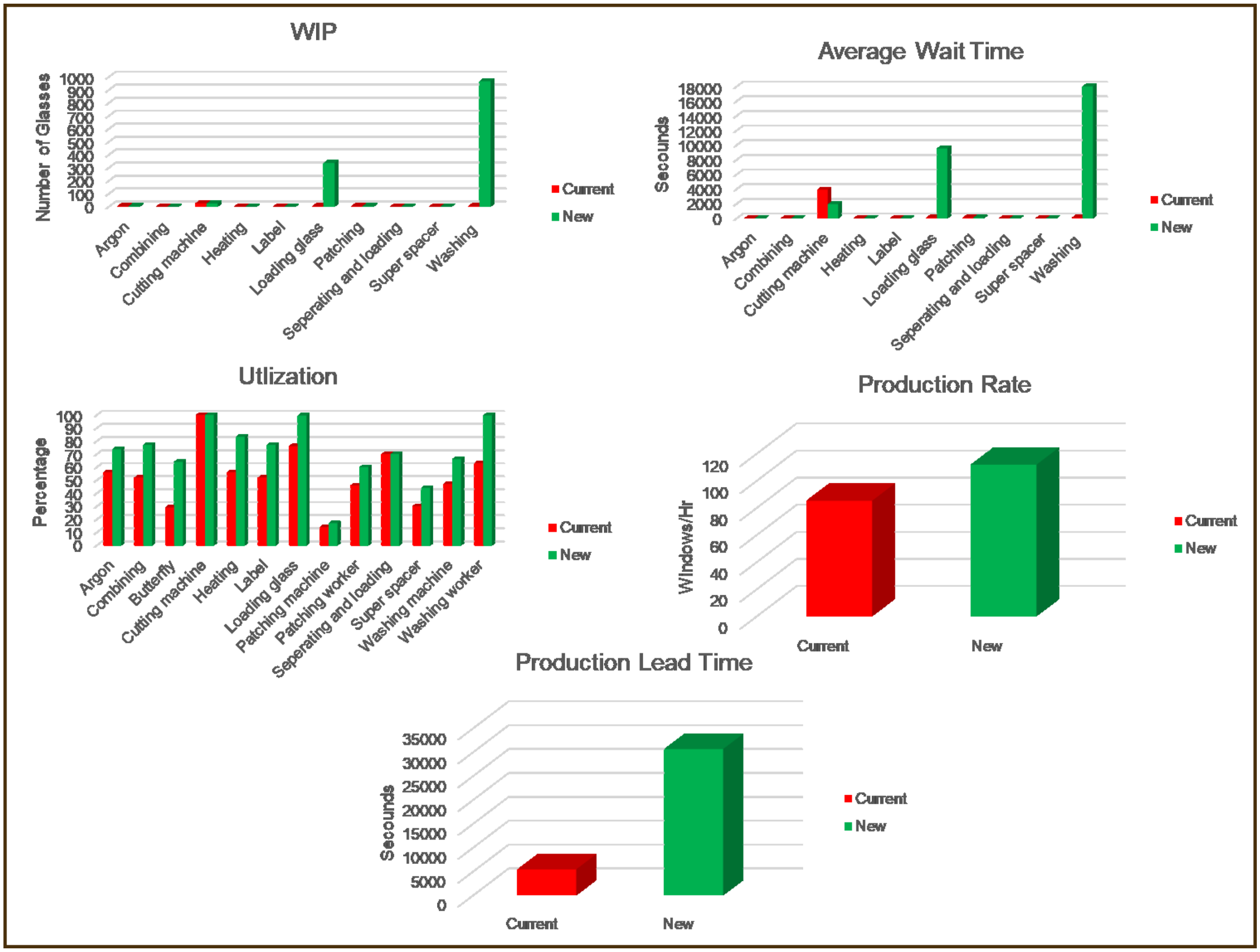


Figure 31.Rapid Loader, Cutting and Reverse Osmosis

The implementation of the solution yielded significant improvements in the production rate, resulting in a 31.5% However, the impact on the WIP and average wait time varied across stations. The cutting station experienced a notable decrease in average wait time by 50%. On the other hand, average wait time and WIP increased in two stations washing and loading stations—by more than 50%, meaning products are waiting to be processed. This indicates that the system is overwhelmed and stressed. Additionally, the PLT increased by over 100%, indicating that products are spending longer waiting to be finished. This prolonged waiting period can have negative consequences, such as an increased likelihood of defects in the products. Moreover, it reduces the flexibility of the system, making it more challenging to adapt and respond quickly to changes or produce specific products efficiently due to the accumulation of high WIP in the system.

Despite these variations, the overall utilization of the entire process improved, indicating better utilization of machines and workers (under 80%). However, the loading and washing stations had a high utilization (above 90%), causing these stations to be the new bottlenecks of the system.

It is crucial to address the loading and washing station's high utilization in order to further enhance the overall performance of the production line.

All Scenarios:

Table 18.All Combinations

Scenario		Production Rate (Windows/hr)	Improvement (%)
1	All	85	-
2	All scenarios + cutting	111	31%
3	All scenarios + Reverse Osmosis	85.6	1%
4	All + Rapid Loader	85	0%
5	All + Rapid Loader + cutting	111.2	31%
6	All Rapid Loader + cutting + Reverse Osmosis	111.6	32%
7	All Rapid loader + Reverse Osmosis	85.25	0%
8	All + Cutting + Reverse Osmosis	111.35	31%

When the analyzing the table above, it can be observed that Scenarios 3, 4, and 7 did not yield significant improvements. Scenarios 4 and 7 showed no improvement in the production rate and had negative impacts on average wait time and WIP in other stations, as previously discussed. Similarly, Scenario 3 had only a slight improvement of 1%, which may not justify the investment in a new machine considering its limited impact on other stations.

When comparing Scenarios 2 and 5, it is advisable to choose Scenario 2. Both scenarios had a similar production rate improvement of approximately 22%. However, Scenario 5 adversely affected the loading station since it made the station more underutilized than it was previously. Moreover, implementing Scenario 5 would require a higher investment due to the installation of a new loader, resulting in additional costs and potential disruptions in work processes. Considering these factors, Scenario 2 appears to be a better option for achieving higher production rates.

For Scenarios 6 and 8, there were improvements of 32% and 31% in the production rate, respectively. Scenario 6 involved the implementation of three solutions, resulting in higher costs. On the other hand, Scenario 8 implemented only two solutions, making it a less expensive option compared to Scenario 6. Therefore, Scenario 8 is a more favourable option.

In summary, the optimal scenario choice lays between Solution 8 and Solution 2. Both scenarios showed the same production rate improvement of 31%. However, Solution 8 had an impact on the WIP and wait time for the washing station, while Solution 2 did not. Additionally, implementing Solution 8 required a higher investment compared to Solution 2. Therefore, from an economical perspective, the recommended solution would be Scenario 2, as it requires less cost while achieving the same improvements. Moreover, it is expected to have the highest improvement in the production rate, since the cutting station serves as the system's bottleneck and has a significant influence on overall system performance. Furthermore, addressing the high PLT, wait time, and WIP in this scenario can be relatively straightforward. The main contributors to these issues are the washing and loading stations. By redistributing resources along the production line, these challenges can be mitigated effectively.

To address the high WIP in the washing station, one worker can be transferred from the super spacer station to assist in the washing machine. This redistribution would result in an 80% decrease in WIP, wait time, and PLT for the washing station. Since the super spacer station is currently underutilized (43%), this adjustment would not incur additional costs and would not adversely affect its performance.

Additionally, in the loading station, assigning a new employee to assist with the loading process would help reduce wait time, WIP, and production lead time. An additional worker could contribute to faster loading and alleviate the strain on the station, improving overall efficiency. By implementing these adjustments, the production line can effectively address the high PLT, wait time, and WIP.

4.7 Experiment

4.7.1 Experimental Plan

This subsection discusses the development of an experimental plan to find a solution to the ninth problem, discussed in Subsection 4.2.5.1 above. This plan consists of three approaches (discussed in the following subsections, along with the cost analysis section).

4.7.1.1 Evaluating the Current Strategy of using Fully Loaded Rolling Carts.

The first step consisted of identifying the different activities involved in the manufacturing process and observing the material handling system for some time. The number of glass units that need to be transferred between workstations on a daily basis and the number of workers required to transfer them were first recorded. Next, a time study was conducted to measure the time needed to transfer the fully loaded 35-slot carts along the 100 m-long route. A total of 24 data points were collected and were deemed sufficiently representative of the actual durations since low variability was found in the recorded data (as indicated by the obtained low standard deviation 0.5 min). The trip duration was measured using a stopwatch which, for every trip, was started when the workers began transferring the cart from Location C and stopped when the cart arrived at Location D.

Moreover, to quantify the fatigue level experienced by different workers when transferring the carts, the workers were asked to indicate a fatigue score for each trip on a scale ranging from 1, representing the lowest fatigue level, to 5, representing a severe fatigue level.

4.7.1.2 Experimenting with Using Partially Loaded Rolling Carts

In the first stage, the workers consistently selected the highest fatigue score when asked about their fatigue level primarily caused by the heavy weight of carts when they are fully loaded with double- and triple-glazed glass. In fact, the heavy weight of the carts has been a central topic of discussion during the course of this study. As such, the first alternative strategy that warranted experimenting with consisted of reducing the number of units loaded onto a single cart in order to reduce the total cart weight. This is although partially loading the carts translates to increasing the total number of trips needed to transfer the same number of units. Nevertheless, lighter carts may require a lower number of workers to handle it, may reduce the adverse effect of manual material transfer on the workers' fatigue level, and may necessitate a shorter trip duration compared to heavier carts. To test this hypothesis, three experiments were run with the number of glass units loaded onto the 35-slot carts reduced in increments of five in each experiment. Specifically, carts loaded with 30, 25, and 20 glass units were studied. However, to minimize interruptions to the facility operations, each experiment could only be repeated four times, meaning that the size of data collected on each load size was limited to four data points. In each experiment, the trip durations, the necessary number of trips, and the level of fatigue experienced by workers were recorded.

4.7.1.3 Experimenting with Using a Power Jack

After completing the first two stages of analysis, the case company opted to invest in one motorized power jack, shown in Figure 32, to test it for transferring glass units between workstations. The power jack can load up to 4,500 lb of glass and is operated by a single worker. The durations of four trips completed using the power jack were recorded, and the worker operating it was asked about their fatigue level.

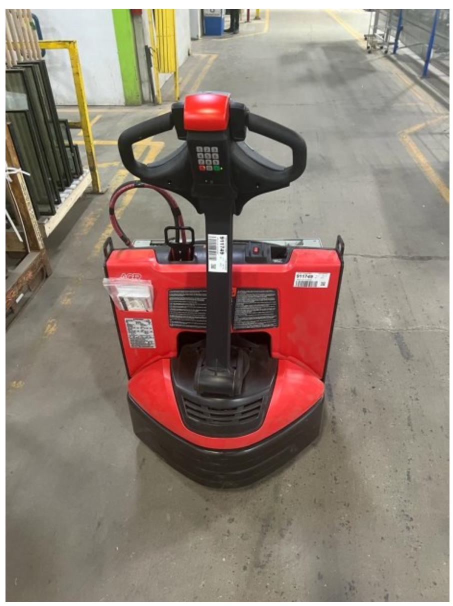


Figure 32.Power Jack

4.7.1.4 Conducting a Comparative Cost Analysis

Upon completing the data collection process for the three material handling strategies, the costs associated with each strategy were identified to gain a better understanding of their financial implications. Namely, the total labour hours spent on handling the same quantity of glass units using each strategy was computed and multiplied by a sample hourly rate of $25 to compute labour costs. Moreover, since using power jacks adds its purchase cost to the present costs, the net present values equivalent to the labour and capital costs incurred in each strategy were computed considering a minimum attractive rate of return (MARR) of 20%. This rate was chosen because the case company does not consider any investment that does not yield at least a 20% return. This analysis was mainly intended to determine whether buying the power jack was financially sound. The different material handling strategies were accordingly discussed and compared to each other.

4.7.2 Results and Discussion

This section discusses the results of the experiment plan discussed in Subsection 4.5.1 above, including the analysis conducted to find the optimal solution.

4.7.2.1 Fully Loaded Carts

Data was collected on 24 randomly selected fully-loaded carts transferred from Location C to Location D, as summarized in

Table *19* below. During the data collection process, four instances of transfer times (highlighted in red in Table 19) were identified as outliers due to events that interrupted the transfer of the corresponding carts. Specifically, workers occasionally had to navigate slowly while pushing the cart because other workers were simultaneously pushing different materials along the same path. Consequently, they had to pause and wait until the pathway cleared. In the case of these carts, the workers sometimes had to cease pushing the cart upon arrival at their destination, as there was a congestion of carts in the designated area, necessitating a rearrangement of the area to fit all the carts.

Most of the carts were transferred by three workers, as they were deemed too heavy to be handled by only two workers, which rarely occurred. It took the workers, on average, a total of 3.3 min to transfer each loaded cart to Location D. Moreover, the workers consistently indicated a fatigue score of 5, indicating that they were experiencing high levels of exhaustion while transferring the carts.

Table 19.Current State Results

Cart #	Transfer Time per Cart (min)	Cart #	Transfer Time per Cart (min)
1	3.5	13	3.0
2	4.4	14	3.3
3	3.3	15	3.2
4	3.1	16	3.1
5	3.2	17	4.5
6	3.2	18	3.4
7	4.5	19	3.1
8	3.4	20	5.1
9	3.4	21	3.1
10	3.5	22	3.3
11	4.2	23	3.0
12	3.0	24	4.4

Although the time spent on each trip may seem insignificant, the cumulative time spent on transferring carts from Location C to Location D alone is significant. To demonstrate this, consider the total time and labour hours needed to transfer twenty carts, containing 35 glass units each, which is a common size of glass batch scheduled for production on a given day. The total time and labour hours can be calculated, on average, by using Eq. (8) below. The total time and labour hours needed to transfer twenty carts amounts to 1.1 h and 3.3 h, respectively. A total transfer time of about one hour per day is equivalent to more than 10% of an 7.5-hour work shift spent by each of the three workers on manually transferring heavy carts, which is a significant amount of non-value-added work.

$$\begin{aligned} &Estimate\ of\ total\ transfer\ time\ per\ day \\ &\quad = average\ transfer\ time\ per\ cart\ \times\ carts\ per\ day \\ &\quad = 3.3\ \frac{min}{cart} \times\ 20\ carts = 66\ min \\ &\quad = 1.1\ hours\ \times\ (\sim 3\ workers\ per\ trip) \approx 3.3\ labour\ hours \end{aligned} \tag{8}$$

4.7.2.2 Partially Loaded Carts

As previously explained, the effect of reducing the cart weight on the cart transfer time and worker fatigue was studied. To evaluate the effect of the load size on the number of carts required to transfer a given batch of glass from Location C to Location D, a batch size of 700 glass units was considered. The total number of carts necessary to transfer this batch was then computed satisfying Eq. (9). The total transfer time and labour hours were also computed satisfying Eq. (8). It should be noted that for a load size of 30 units, the number of required carts would total to 23.3 based on Eq. (9). In this case, 23 carts would be loaded with 30 units and one cart would be loaded with ten units. The total transfer time corresponding to the 23 carts is calculated satisfying Eq. (8) using the average transfer time per cart loaded with 30 units. As for the time needed to transfer the remaining cart containing ten units, it was assumed to be equal to the time needed to walk freely (without pushing a cart) from Location C to Location D, which was measured at 1.5 min. As such, the total time needed to transfer the 24 carts was computed as the sum of the transfer time computed using Eq. (9) and 1.5 min.

The results are summarized in Table 20.

$$Number\ of\ required\ carts = \frac{700\ glass\ units/day}{Load\ size\ (units/cart)} \tag{9}$$

Table 20.Reducing Cart Weight Results

# glass units per cart	Transfer time per cart (min)	Average transfer time per cart (min)	# needed workers	Average fatigue score	# trips per day	Total transfer time per day (min)	Labour hours per day
35	-	3.3	~3	5.0	20	66.0	~3.3
30	2.8	2.8	2	5.0	24	65.9	2.2
	2.7		2				
	2.9		2				
	2.8		2				
25	2.3	2.2	2	4.0	28	61.6	2.1
	2.3		2				
	2.2		2				
	2.1		2				
20	1.8	2.0	2	2.3	35	70.0	2.3
	1.7		2				
	2.2		2				
	2.1		2				

The results revealed that decreasing the cart load size reduced the number of required workers from about three workers for carts with 35 glass units to two workers for carts with 30, 25, and 20 glass units. The average transfer time also decreased, with the lowest total transfer time of 61.6 min and total labour hours of 2.1 recorded for carts with 25 glass units. Reducing the load size from 35 units per cart to 25 units per cart reduced the total transfer time by about 7% and the total labour hours by about 38%. Further reducing the load size to 20 units per cart increased the total transfer time and total labour hours, as the increase in the number of required trips outweighed the reduction in the transfer time per cart. Such results are reasonable, since walking freely (without pushing a cart) from Location C to Location D at the factory takes about 1.5 min. As such, further reducing the load size will not have a significant effect on the transfer time as it approaches the average walking time needed to travel between the two locations.

The average fatigue score dropped from 5.0 for carts loaded with 35 and 30 units to 4.0 for carts loaded with 25 units and further dropped to 2.3 for carts loaded with 20 units. When the load size was reduced from 35 to 30 units, the fatigue score remained high because two instead of three workers were transferring the carts. Hence, this first reduction in load size only had a positive outcome on the total labour hours spent. Reducing the load size by additional five units dropped the average fatigue score to 4.0, realizing an improvement to the well-being of workers. However, an average fatigue score of 4.0 recorded on a scale of 5 is still high, but it could be further reduced as the results corresponding to the load size of 20 revealed. Even though reducing the load size beyond 25 units negatively affected transfer time and labour hours, it significantly reduced the average fatigue score, as the carts were significantly lighter. Therefore, a reduction in the load size that may negatively affect productivity may be necessary to mitigate the negative effects of manually transferring heavy carts on the health of workers.

4.7.2.3 Power Jack

The power jack was used to transfer fully loaded carts, each containing 35 glass units, from Location C to Location D. However, to drop off the carts at their intended position, it was more feasible to remove the cart from the power jack and manually maneuver it than to use the power jack, as the drop-off area is often congested with other carts. Despite this limitation, the data presented in Table 21 demonstrates promising results for this material handling approach. Using a power jack reduced the transfer time for each cart by about half on average. The effect on the total labour hours was even more significant, since a single worker is needed to operate the power jack. In fact, the total labour hours decreased by about 85%, from 3.3 in the case of manually-handled carts to 0.5 in the case of carts transferred using the power jack. The average fatigue score also significantly decreased from 5.0 to 2.0, but it did not drop to 1 because the worker manually maneuvers the cart at the drop-off location. In light of this, the power jack is the most attractive material-handling strategy in terms of time efficiency and the well-being of workers. However, understanding its financial implications on the company is worthwhile.

Table 21.Power Jack Results

Cart handling strategy	# glass units per cart	Transfer time per cart (min)	Average transfer time per cart (min)	# needed workers	Average fatigue score	# trips per day	Total transfer time per day (min)	Labour hours per day
Manual	35	-	3.3	~3	5.0	20	66	~3.3
Power Jack	35	1.3	1.5	1	2.0		30	0.5
		1.5						
		1.4						
		1.7						

4.7.2.4 Cost Analysis

The labour costs associated with each material-handling strategy and the respective net present value equivalent to twelve months of labour costs were computed. The results obtained for a MARR of 20% are presented in Table 22. Notably, the expenditures on transferring carts from Location C to Location D alone amounts to $1,815 per month. It is also important to note that a mere adjustment in the load size of these carts could lead to monthly labour cost savings of over $800 for the company. The power jack strategy was found to have the lowest present value among the tested strategies, with a recorded value of $10,177, resulting in 48% cost savings when compared to the current practice. The strategy of using a cart load size of 25 units was also found to be financially attractive, where a 36% reduction in costs could be realized without investing in new equipment. Still, despite requiring initial capital investment, the power jack strategy stands out as the preferable choice due to its significant time and cost savings, coupled with the reduction in the level of fatigue experienced by workers.

Table 22.Cost Results

Cart handling strategy	# glass units per cart	Capital investment	Monthly labour costs	Net present value	Cost savings
Manual	35	-	$1,815	$19,584	-
Manual	30	0	$1,210	$13056	33%
	25	0	$1155	$12462	36%
	20	0	$1,265	$13649	30%
Power Jack	35	$7,210	$275	$10,177	48%

Additionally, the company can realize its return on investment in a reasonable time frame. Using the power jack results in monthly savings in labour costs of $1,540. Considering the initial purchase price of $7,210, the number of periods (N) needed to recover the cost of the power jack can be calculated using Eq. (10) as follows.

$$PV = C + \frac{1-((1+\mathrm{r})^{-\mathrm{N}})}{\mathrm{r}} \times \mathrm{S} \rightarrow 0 = -7{,}210 + \frac{1-((1+0.0167)^{-\mathrm{N}})}{0.0167} \times 1{,}540 \quad (10)$$

where:

- PV is the present value, and is set equal to zero to find the breakeven point at which the company recovers the purchase cost of the power jack.
- C is the initial capital investment, which is the purchase price of the power jack.
- R is the monthly discount rate.
- S is the monthly savings in labour costs realized using the power jack.

Based on Eq. (10), it would take the company about five months to recoup the initial investment of $7,210. Beyond the breakeven point, the company would start saving $1,540 each month compared to the previous cost of $1,815 corresponding to manually pushing fully loaded carts from Location C to Location D.

CHAPTER 5: CONCLUSIONS AND FUTURE RECOMMENDATIONS

5.1 Research Summary

The research presents a comprehensive framework that integrates lean manufacturing, MCDM, simulation, and experimental analysis to enhance production lines in OSC. Various different lean tools were used to address waste in the system, and in-depth investigations (through interviews and observations) were conducted to identify the root causes of issues and devise appropriate solutions.

The selection of these tools was not arbitrary, as each tool was to play a significant role in enhancing the overall efficiency of the OSC production line. The VSM tool was employed to evaluate the current state, identify inefficiencies between stations, and gain a comprehensive understanding of the system, including the WIP. Lean metrics such as WIP, PLT, and average wait time were suggested and calculated through simulation to assess the system's performance.

Furthermore, lean principles were applied, such as the implementation of a Kanban cart to optimize material flow. For problems with multiple potential solutions, CBA was used to select the most favourable option.

It is important to note that many companies hesitate to implement lean or other solutions to improve their business, especially when substantial investments are involved and the payback calculation is not straightforward. To address this challenge, all proposed solutions were simulated to evaluate their effects on the system. Additionally, an experimental testing approach was adopted, provided that the solutions could be easily implemented in the system. This approach allowed for a thorough assessment of the solutions' potential implications, offering companies a tangible understanding of the proposed changes. By testing the solutions on the shop floor, while considering all variables, the reliability and practicality of the solutions were demonstrated.

In essence, this research significantly improved the overall state of the OSC production system by integrating various metrics and analyzing them collectively. This aligns with the core principles of lean thinking. Evaluating the system's performance is not solely reliant on the production rate; understanding the interplay between different metrics is essential. While a high output rate may initially seem indicative of a well-performing system, lean thinking emphasizes the importance of comprehending the underlying processes, as a high output rate could be accompanied by waste and an overwhelmed system. Therefore, an analysis of the system was conducted through the support of VSM to identify areas of waste such as overutilization, average wait time, average WIP, rework, transportation, and defects.

It should be noted that some of the solutions mentioned earlier may have improved metrics in some areas but harmed metrics in other areas. This shows how improving the production system in isolation can lead to suboptimal outcomes if the broader context is not considered.

Notably, one of the most effective solutions not only enhanced productivity but also improved worker well-being by reducing fatigue and saving significant amounts of time, resulting in substantial cost savings for the company. The combination of lean manufacturing principles, MCDM, simulation, and experimental testing facilitated waste identification and resolution, while also providing a forecast of the expected results and benefits prior to implementation.

5.2 Research Contributions

5.2.1 Academic Contributions

- Presents a framework to assess and improve the state of offsite production system and its impact on work environment using value stream mapping, discrete-event simulation (DES), experimental analysis, and MCDM.
- Offers a subjective and collaborative approach to reduce the effort needed in testing and analyzing any potential solutions. This is done by utilizing CBA to select favourable solutions for problems in OSC that were primarily identified using VSM.
- Enhances testing methods through the integration of experimental modelling and simulation to achieve a more comprehensive approach.

5.2.2 Industrial Contributions

- Provides the management with a valuable decision support system to improve the state of the production line, enhances the well-being of the workers, and makes the workplace more inclusive.
- Poses a desirable overview into the performance state of the production line in terms of a comprehensive set of criteria including material count, cycle time, production rate, resource utilization, value-added time, and non-value-added time.

- Improves the working environments to reduce the physical effort required, which, in turn, ensures the well-being of the workers, a more inclusive environment, less injuries, and less claims, consequently leading to higher productivity and lower costs.

5.3 Research Limitations

The research includes the following limitations:

- There was a limited amount of data available for the evaluation of the alternative material handling strategies, and this necessitated the use of average transfer times per cart in order to estimate the total transfer time corresponding to a batch of glass units.
- The value stream mapping included only internal operations and it did not include any supply chain problems which can further enhance the VSM. However, the assumption that was made for this research served the purpose and is good to apply but studying supply chain will give better accuracy of the results.
- Small sample size for the CBA questionnaire.

5.4 Recommendations for future work

- Test the alternative strategies for MMH over the course of days to get more accurate figures of the corresponding transfer times and costs.
- Look into examining the implementation of fully automated material systems such as automated guided vehicles to eliminate the reliance on human labour.
- Conduct an ergonomic study to assess the impact of MMH on different demographic groups, including males, females, and elderly individuals.
- Investigate if there are variations in strength, endurance, flexibility, or other factors that may influence MMH performance and potential risks among different demographic groups.
- Explore and develop more efficient algorithms for cutting glass sheets, aiming to reduce both the cutting time and waste generated during the cutting process. This improvement can lead to increased productivity and cost savings in the overall manufacturing process.
- Implement a real-time digital twin system that enables tracking of the glass windows throughout the production line. This approach offers the advantage of reducing the time required for data collection. However, it is important to note that implementing such a

system can be costly, as it necessitates the use of sensors to track the movement of the products accurately.

- Study the supply chain to enhance the process optimization from the supplier to the customer.

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