Simulation-based approach to improving Overall Equipment Effectiveness analysis in construction manufacturing

by

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ABSTRACT

This thesis describes productivity improvement at a window and door manufacturing company using DES (discrete event simulation) and OEE (overall equipment effectiveness) analysis. The primary goal of this research is to propose improvements to an existing manufacturing process and prove the effectiveness of the various scenarios using simulation software and performance indicators. The stations belonging to the production line under study are described in detail in order to understand the impact each has on the production line. Then, areas of improvement are identified, and changes are proposed using a simulation program developed by researchers at the University of Alberta. For the OEE analysis, the goal is to facilitate the identification of manufacturing wastes (material- and productivity-related) and to create a plan to approach and mitigate manufacturing wastes and observe the impact of resource availability, production performance, and final product quality improvement.

Acknowledgments

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DES: Discrete event simulation

OEE: Overall equipment effectiveness

JIT: Just-in-time

VSM: Value stream mapping

TPM: Total productive maintenance

P/F: Picture and fixed

A/C: Awning and casement

CHAPTER 1 – RESEARCH MOTIVATION AND OBJECTIVES

1.1 Research motivation

Manufacturing companies are responsible for 68% of Canada's merchandising exports (Government of Canada, 2019). Due to the manufacturing industry's high rate of participation, companies seek to improve their products by increasing the level of customization in their manufacturing processes.

Performance indicators require reliable data collection methods, and an understanding of process flexibility, manufacturing capacity, and resource availability for the assembling of the product. However, before adding new technology or implementing changes to their production lines, there is a need for feasibility studies and cost-benefit analyses. With the rise of simulation, sequential tasks can be analyzed and adjusted as the company desires, which makes it is possible to evaluate the impact of a change to the manufacturing process before implementing it in real life.

A significant amount of literature has been published that pertains to performance indicators aimed at increasing production line productivity. However, many companies adopt an approach that will often result in a performance improvement at a single workstation but will miss an opportunity to see the bigger picture. Workers availability, performance, and quality are interconnected and changing one of these will affect both the other factors.

This research aims to facilitate the calculation of the Overall Equipment Analysis (OEE) with the use of simulation model by observing its fluctuation within different scenarios before implementing changes in the current scenario.

1.2 Research objectives

This research tackles one production line of one window and door manufacturing company. The main objective is to create a method to evaluate current production capacity using simulations and known performance indicators, with the possibility to replicate the evaluation in the context of other manufacturing processes in different companies. This research follows the following steps:

- identify the main bottlenecks given the sequential tasks in a manufacturing company;
- observe performance fluctuations while testing different scenarios with the primary goal of improving productivity;
- understand which of the proposed scenarios have a significant positive influence on the production rate; and
- use of simulation for the assessment of the overall equipment effectiveness (OEE) and interpretation of results, while also explaining some misuses of this KPI

1.3 Research organization

This thesis is divided into six chapters.

- Chapter 2 (literature review) covers the evolution of productivity improvement in the manufacturing industry since the first implementation of the TPS (Toyota Production System), and the use of DES (discrete event simulation) models and OEE (overall equipment effectiveness).
- Chapter 3 (research methodology and data collection) details the production line chosen for this research, providing information such as the sequence of stations, the time study parameters and assumptions, how customization impacts production and how the database,

which contains windows with different characteristics, was created. This chapter introduces the methodological approach used for the research.

- Chapter 4 (simulation results and scenario analysis) presents the validation results for the simulation model that mimics production and also proposes some hypothetical scenarios to observe the fluctuation of production rates when the scenarios are tested in the simulation.
- Chapter 5 (OEE analysis) will assess how the OEE factor is calculated and how to use it to identify possible improvement areas.
- Chapter 6 (conclusions and future recommendations) summarizes all the results, discusses the observations made during this research, lists the contributions, and proposes future approaches and goals for future research.

CHAPTER 2 – LITERATURE REVIEW

2.1 Industrialized and lean manufacturing

In the 19th century with the beginning of the Industrial Revolution, companies were starting to understand the real meaning of mass production. Employing machines to perform human tasks meant the number of products that could be manufactured grew exponentially. However, factories that had a hybrid work system (automated and non-automated combined) were experiencing challenges because human labour could not be as productive and consistent as a machine, creating buffer times between stations. Consequently, managers started to analyze possible scenarios to avoid bottlenecks and to invest in ways to improve productivity in the most profitable way.

2.2 Lean manufacturing

Lean manufacturing's main goal is to reduce cost and waste while still maintaining quality and high production. There are many lean tools available to assist in achieving this goal, such as JIT (just-in-time), Kanban, and VSM (value stream mapping), and these tools are still widely used today.

The major goal of JIT is to produce and deliver finished products just in time to be assembled and sold to the customer (Mullarkey et al., 1985). By simple definition, JIT aims to avoid having unnecessary stocks of completed material by manufacturing goods only when they are required.

Kanban is a system that supports JIT. Kanban is a tool that assists in the feeding of the production line with materials only when they are required. Typically, a signboard is used on which the worker will indicate a station is running low on materials. This can solve inventory issues and help to understand material flow (Wang, 2019).

VSM is a tool that helps coordinating activities from manufacturers and suppliers, while also mapping material and information about the product (Shahrukh & Zhou, 2006). This tool contains information such as facility layout, station lead times, non-value-added timings and more. With all this data presented in a visual graph, the identification of bottlenecks and possible layout improvements becomes easier, while giving owners a better insight of the line behaviour.

2.2.1 Eliminate wastes

The Toyota Production System (TPS) was responsible for significant advancements in the context of manufacturing improvement. The concept of lean production, which was developed based on TPS, has spread widely among many other industries and has reshaped the way mass production is approached. According to the TPS, lean production's main goal is to minimize and/or eliminate all type of wastes without major changes to productivity rates, and these wastes include unnecessary material stocks or having idle products waiting to be worked on due to poor management planning. While developing the TPS, Taiichi Ohno, the Chief Engineer at Toyota, devised the eight typical wastes encountered in a manufacturing facility:

1) Defects: Defects are a normal problem all manufacturing companies deal with. There are many causes of defects during production: the material was already damaged coming from the supplier, material can get damaged if not handled properly during product assembling, or the material can get damaged while being transported to the end user. This generates unnecessary rework, since the time being spent on defects could be used to build new products.

2) Overproduction: Overproduction is producing more than what is needed to meet customer demand. JIT aims to reduce this type of waste specifically since it results in the need for storage to place goods that the customer has not yet required. This increases costs for the company since

they need a location to place these products and to maintain them to avoid damage. If the products are perishable (e.g., food items), they may even need to be discarded.

3) Waiting: Waiting refers to when a product is being queued to be worked on later at a specific station. Simulation software can be used to identify bottlenecks and help to reduce this waste, which is typically identified as occurring when a slower station is preceded by a faster one. Sometimes, due to the lack of space, a station will need to decrease its productivity until there is more room to work.

4) Non-utilized talent: Not taking full advantage of the workers' skills and knowledge results in non-utilized talent. Some manufacturers shift workers to various locations based on demand. However, keeping the worker at a station where he is familiar with the work can reduce station lead time and possibly boost productivity.

5) Transportation: Transportation in this context refers to the unnecessary movement of products and materials while the product is being assembled. This is often seen as necessary waste because the product needs to go to the next station. However, the transporting of materials consumes time and effort that could be used to instead to build another product.

6) Inventory: Inventory in this context refers to an excess of products not being processed, generating more storage requirements and cost for the company. JIT also aims to eliminate this waste since its main goal is to avoid inventory and to assemble products only when there is a demand.

7) Motion: Motion in this context refers to the unnecessary movement of people. One example is walking to a location to fetch material or having to bring the product to another work location.

Having a single place where everything is available for the worker and assigning someone to manage and control material flow would reduce this problem.

8) Extra-processing: Extra-processing in this context refers to undertaking additional work or producing a higher quality than is required by the customer. This can reduce defects but increase product takt time, which in consequence will reduce productivity and company profitability.

2.3 Mass customization

Manufacturing is when materials are transformed into goods to satisfy human needs (Mourtiz et al., 2014). Mass customization is the ability to simultaneously manufacture, in a cost-effective manner, a high volume of products that attend all customer needs (Quiang et al., 2001). Competitiveness between manufacturing companies will force them to produce more unique products, as they are trying to "stand out" and sell more. Sudden changes to processes or regulatory requirements need to be addressed quickly so production can be adjusted accordingly without major production losses (Renna, 2010). Changes in customization will not only affect respective stations, but the entire system. The following subsections highlight the most common areas investigated by manufacturing companies when studying the capacity of their manufacturing operations.

2.3.1 Lead time

Lead time is the time between when a product is ordered and the moment it is finalized (i.e., the total duration during which the product is in process). This information is crucial for the supply management team to learn production workflow and this data can facilitate changes to the product in the future (customization) (Business Dictionary, 2019).

2.3.2 Takt time

Takt time is the processing time that products should ideally have in order to meet customer demand or the company's goal (Business Dictionary, 2019).

2.3.3 Work conditions

Understanding work conditions, how stations are sequenced, how flexible the work is and how much work variation can be seen during active work are aspects that must be captured before starting any kind of analysis.

2.3.4 Machine maintenance

Conducting scheduled maintenance and deciding how often a machine should be checked, preferably during a time that there is no work being performed, helps to avoid unwanted scenarios such as production being delayed due to machinery stoppage.

2.3.5 Product customization

Product customization refers to the special manufacturing options created by the company. Although it gives uniqueness to the product, implementing customization while aiming for mass production is not an easy task, since lead times can change considerably.

2.4 Simulation analysis approach

Simulation can be defined as a tool used to mimic activities of certain operations that uses mathematical tools to analyze processes (Farlex, 2011). Resource utilization, material and resource queuing, and total time of an entire operation are some examples of what simulation models can achieve when properly used. AbouRizk et. al. (2010) stated that uncertainty of activity durations and repetitive processes are the best indicators that using simulation would be beneficial.

Simulations are very helpful for manufacturing companies because owners can propose hypothetical scenarios and observe the impact they would have on the pace of work and on the final output. Simulations also give insight into trending ideas or business analyses before making decisions to invest in new technologies or disturbing the actual system (Mourtiz et al., 2014).

For this research, Simphony.NET, a simulation software developed by researchers at the University of Alberta (AbouRizk et al., 1999), will be used. Using this software, the user can interconnect activities by using discrete event simulation (DES) and apply changes not only to task sequencing, but also to scheduling algorithms to improve resource utilization.

2.4.1 Time study

A time study is the analysis of a specific job performed by a qualified worker that measures the time required for job completion, which provides insights into the best method to follow to execute the task (Chandra, 2013).

According to McGraw-Hill Science & Technology Dictionary (2002), the definition of time study is:

"A work measurement technique, generally using a stopwatch or other timing device, to record the actual elapsed time for the performance of a task, adjusted for any observed variance from normal effort or pace, unavoidable or machine delays, rest periods, and personal needs."

A time study makes it possible to track possible areas for improvements, identify bottlenecks, and measure non-value timings. While capturing timings, it is also possible to better understand the flexibility of the line, which creates more areas to investigate.

2.4.2 Validating the simulation

In order to analyze changes to the manufacturing system under study, there is a need to confirm that the simulation matches reality, which is necessary since any inconsistencies in the model that do not accurately represent the tasks will result in false results.

Sargent (2010) suggests using the following techniques to validate a simulation model in order to generate accurate results:

1. **Comparison with previous models:** If there are existing validated models that simulate the same tasks as the simulation, compare the results provided by both and check for similarities.
2. **Historical validation:** Compare the results obtained from the simulation model with historical data provided by previous studies or by the company's database (when applicable).
3. **Face validity:** Talking to people that are familiar with all the tasks and their inherent variability and then walking them through the model is one of the best ways to check whether all possibilities and variations are covered.
4. **Internal validity:** When the model has many variables, the results from each run can be different. Therefore, running the simulation several times will give an average of the results, generating better overall simulation results.
5. **Event validity:** Compare current state processes with the built simulation.
6. **Parameter variability:** Observe effects by changing values of the inputs and confirm whether the simulation still matches reality.
7. **Operational graphics:** Observe whether the resource utilization output given by the simulation is reasonable compared with the current state process of the examined tasks.

8. **Degenerate tasks**: Test whether the simulation will respond as expected given the inputs and given the changes that are to be tested.
9. **Specify desirable accuracy:** All simulations will always vary slightly from real-life scenarios. Being aware of these differences and how much the simulation varies compared to reality will afford credibility to the simulation.

2.4.3 Scheduling algorithms

The order that products enter a system may influence productivity depending on the variability of products being produced on the production line. Scheduling the products in an order that reduces the amount of queuing (when many products are waiting to reach a busy workstation) can potentially boost productivity. Job sequencing aims to decrease the buffer time between stations, reduce queuing times, and reduce system inventory (Hammad, 2003).

There are many scheduling algorithms; the most common ones are as follows:

- **FIFO** (first in, first out): As the name suggests, resources will be queued in the same order as they arrive.

- **EDF** (early deadline first): Unlike FIFO, this approach prioritizes when queuing products. Generally, all products are sorted and the ones that must be finished urgently will be taken to the head of the queue. This may also generate waiting times between workstations since products are sorted by completion date and not lead time.

- **SRTF** (shortest remaining time first): In this approach, products that require the shortest processing times will go first into the system. For this analysis, it is critical to know with a certain amount of precision how long a part stays in the system, since they will be queued based on this information.

Those are only a few examples of sorting algorithms. To identify the best one that fits a specific system, a more profound study is needed. Each production line has it owns particularities and should be studied before deciding on the best approach. Choosing the wrong approach may create process starvation (one stations holds the product due to long processing time, causing all subsequent stations to be idle) and, therefore, not result in achieving optimum production. Identifying the best scheduling algorithm is very helpful in seeking balanced production lines.

2.4.4 Flexibility vs Sequencing

When looking for a productivity increase, the terms flexibility and sequencing are important; however, they are often misinterpreted as being the same concept. While sequencing refers to the order that products will be inserted into the system, flexibility refers to the capability of the workstations to work in a different order depending on the demand. In the context of a manufacturing system, Zelenovic (1982) describes flexibility as “a measure of its capacity to adapt to changing environmental conditions”. Figure 1 summarizes the difference between sequencing and flexibility.

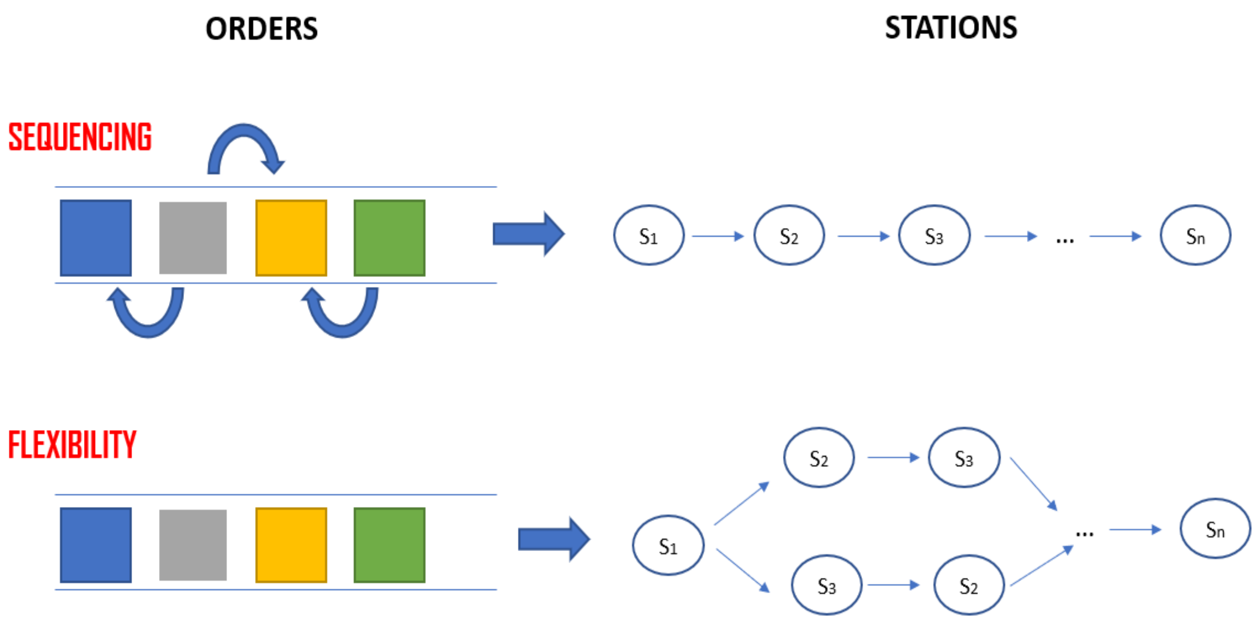

Figure 1 - Illustration flexibility vs sequencing

2.5 Overall Equipment Effectiveness (OEE)

Nakajima (1988) launched the total productive maintenance (TPM) and introduced a tool to measure the productivity of individual pieces of equipment in a factory: the OEE analysis (Muchiri & Pintelon, 2008).

Mostly used in the semiconductor industry, overall equipment effectiveness (OEE) is a metric that will quantify elements such as availability, performance, and quality for the purpose of measuring the performance effectiveness of an individual piece of equipment or of the entire process (Garza-Reyes, 2015).

OEE is often used to measure the performance of a single station, but it can also be used to observe the entire production line production. Usually under other names like OFE (overall factory effectiveness), OTE (overall throughput effectiveness), OPE (overall performance effectiveness) or OLE (overall labour effectiveness), all these measurement tools share the same background and are used for similar purposes. Oechsner et al. (2003) stated that OEE and OFE are correlated since both use parameters such as production capacity, resource utilization, and cycle time.

An OEE analysis will indicate how to create a balance between line value-added time, performance, and quality of the final product. Equation 1 illustrates how OEE is calculated:

$$OEE = Av * Eff * Q \qquad (1)$$

where:

Av = availability of the line (active time during which people are working, without the normal scheduled breaks and unplanned downtimes);

Eff = effectiveness of the line, which compares the actual production rate with the desired output for that specific product;

Q = quality of the final product, which measures the amount of rework that was necessary due to a defective product reaching the end of the production line.

More details on how to calculate each one of these indicators will be further addressed in Chapter 5 of this thesis.

Costa & Lima (2002) observed that many companies are employing an OEE analysis for the wrong reasons, such as:

- Using an OEE analysis to discuss capacity because capacity is a measurement of performance only. The goal of OEE is to compare current production with planned production. Moreover, a machine can have high performance but because it produces many defective materials or because it breaks down, the OEE score is lower and would not be representative of the machine's capacity.

- Using OEE to identify bottleneck processes. As stated before, OEE is an indicator that depends on three factors. A lower OEE score might be related to data not being properly collected or a machine producing waste. Identification of bottlenecks should be performed by other tools such as DES (discrete event simulation), after which OEE can be used to determine why that station is considered a bottleneck and how to mitigate it.

CHAPTER 3 – RESEARCH METHODOLOGY AND DATA COLLECTION

This chapter will introduce the methodology used during this research. The analysis presented in this thesis is performed using results from Simphony.NET, a computational software developed by researchers at the University of Alberta. This program can mimic repetitive activities, determine resource utilization and performance indicators, and also allows the user to make modifications to estimate the future state during hypothetical scenarios.

The simulation model is used to mimic the current state of the manufacturing system at a window manufacturing facility. All the necessary inputs, such as task sequencing, available resources, timings of activities, manufacturing capacity, and possible customization options for the product were collected and implemented to the program. Then, after running and validating the simulation, bottlenecks are identified and some future-state scenarios are tested with the goal to reduce or eliminate their impact on the manufacturing line, always aiming for productivity improvement and line balancing.

Although this research is focused on one specific manufacturing line, the methods can be replicated to any kind of manufacturing industry which shares similar processes.

The following sections in this chapter include descriptions of the stations, the time study, some assumptions made during the analysis, how the product customization was implemented into the simulation, and how the performance improvement is addressed. Figure 2 provides an overview of the methodology used for this research.

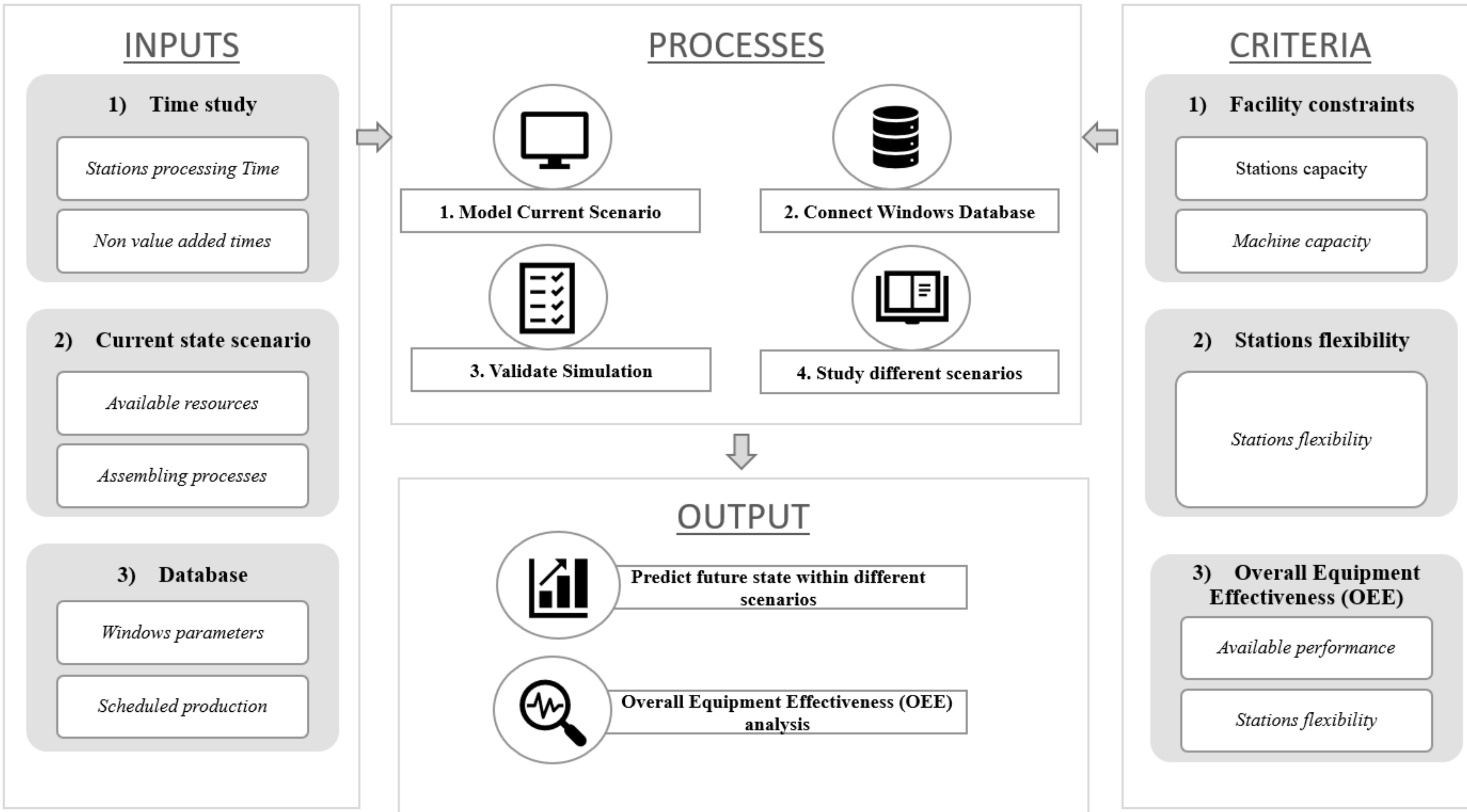

Figure 2- Research methodology

3.1 Existing system

Figure 3 contains a flowchart showing all the processes needed to build a window on the production line under study and a brief explanation of each station is later presented.

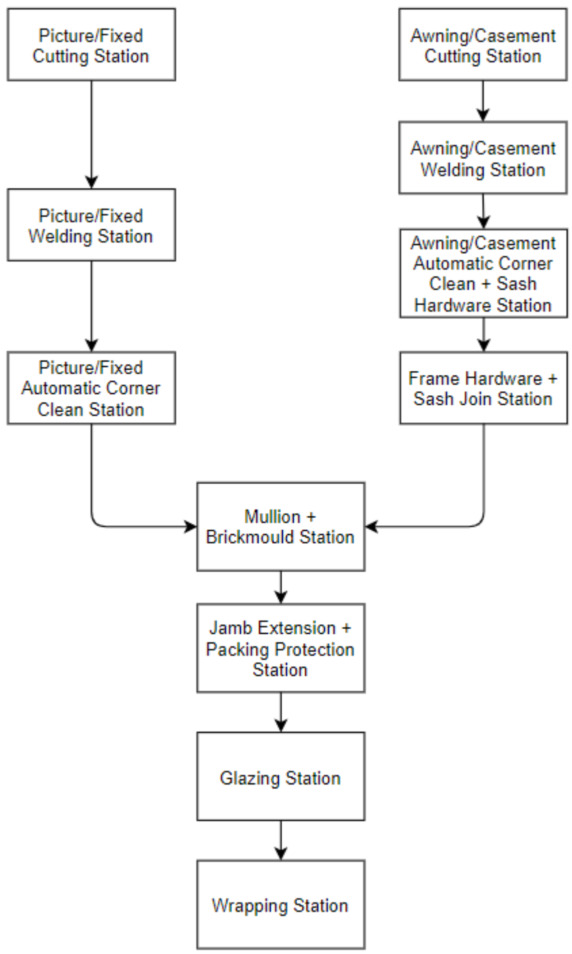

Figure 3- Processes flowchart

Each window, while being built, contains a "job order": a sticker with all information regarding that product's customization. The job order also contains the window type, which can be one of four: fixed, picture, casement or awning. An example of a job order can be seen in Figure 4.

This job order contains a two-box picture window. The graphic representation is the same for picture and fixed.

2100
25-Jun-2019 163
J
750 X 1000
E001160510 1
2100-F11-0000027855
750 X 1303 X 6 1/2"
NFRC
163

JAMB - PVC 4 3/8in 2202 WH
JAMB RIP -JXT1:N/A~
GLASS - SU Triple 34.4 688 x 238 HS2 InBoard: 3mm LowE180 OutBoard: 3mm Clear Middle: 3mm Clear SU Triple 34.4 688 x 938 HS2 InBoard: 3mm LowE180 OutBoard: 3mm Clear Middle: 3mm Clear

P00 - 2100 1Wx2H P\P 29 9/16x51 5/16 NoBM PVC
F11 - 2100 P 750 x 1000 White/White
F21 - 2100 P 750 x 300 White/White
P11SU1 - SU Triple 34.4 688 x 938 HS2
P21SU1 - SU Triple 34.4 688 x 238 HS2

Figure 4 - Job order

Picture and fixed windows are not operational and the difference between them is dependent on frame thickness and sealed unit size. Casement windows are operational, and their opening is similar to a door, always opening sideways. Awning windows are also operational, and their opening is upwards or downwards.

Figure 5 shows how casement and awning windows are represented on a job order.

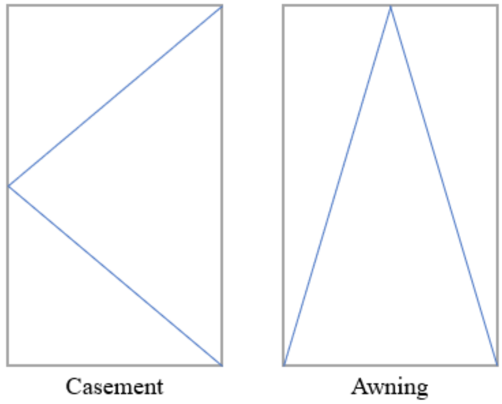

Figure 5- Casement and awning job order representation

3.1.1 Picture/fixed cutting station

As shown in Figure 6, this is the first station on the manufacturing line, where the PVC profiles are cut for picture and fixed (P/F) windows.

Figure 6 - Picture/fixed cutting station

3.1.2 Picture/fixed welding station

Profiles that were cut in the previous station are welded at all four corners using a steel plate that will heat up and join all of them together. This station can be seen in Figure 7. The loading operation is not automatic, requiring a worker to load and unload the welder.

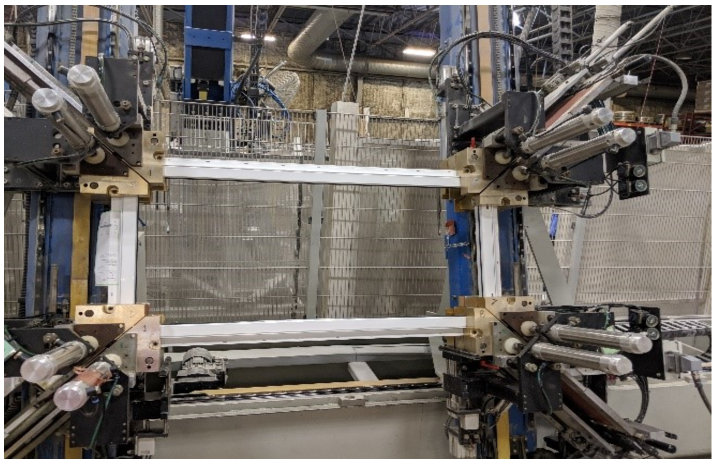

Figure 7- Picture/fixed welding station

3.1.3 Picture/fixed automatic corner clean station

At the automatic corner clean (ACC) station, a machine cleans the weld excess left by the previous station. Once again, load and unload operations are not automatic. Then, picture/fixed windows are taken directly to the mullion installation station. This station can be visualized in Figure 8.

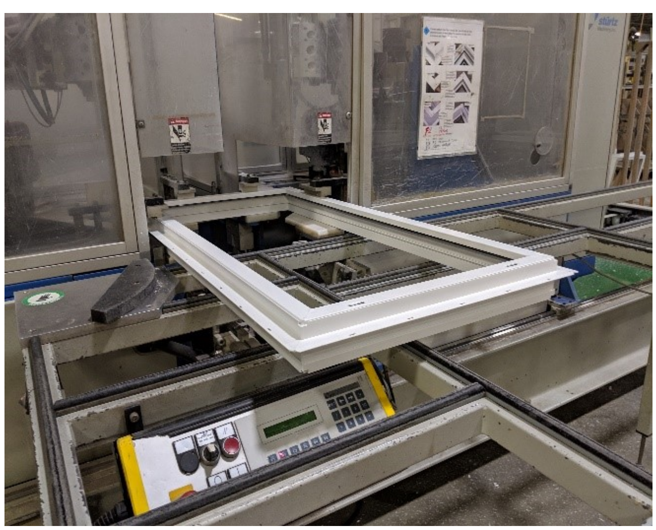

Figure 8 - Picture/fixed automatic corner clean station

3.1.4 Awning/casement cutting station

Awning and casement (A/C) are different variations of windows from the same production line. At this station, both sash and frame are cut at the same time by the same saw machine. This station is different from the picture/frame cutting, and both work independently and simultaneously, as there are two different saw machines.

3.1.5 Awning/casement welding station

A welding machine welds all four corners of both sash and frame. A/C and P/F are welded on different machines. Hence, they also work independently and simultaneously. After this station, sash and frame will be separated for hardware installation.

3.1.6 Awning/casement automatic corner clean and sash hardware station

At this station, one worker uses the automatic corner clean (ACC) machine and then installs the hardware for the sash before sending it to the next station. Only sashes from A/C windows will go through this station and the hardware for each is different, resulting in different processing times. Figure 9 shows a representation of a sash already with its hardware.

Figure 9 - Awning/casement automatic corner clean and sash hardware station

3.1.7 Frame hardware and sash join station

Only the frames that are for the A/C type of windows go through this station, and different hardware is installed depending on which type. After this, the sash (also with its respective hardware) is installed together with the frame. In this thesis, a set of sashes and a frame will now be referred as a "box". This station can be seen in Figure 10.

Figure 10 - Frame hardware and sash join station

3.1.8 Mullion and brickmould installation station

Often, the client requires two or more boxes in one final product (window), which means that the window might be composed of a picture or fixed along with a casement or awning box. The process of joining multiple boxes into a single product is called box-to-box installation. The brickmould is not mandatory and is only installed if requested by the client. This station can be visualized in Figure 11.

Figure 11 - Mullion and brickmould installation station

3.1.9 Jamb extension and protection installation station

Here, the jamb extension is installed, and processing time depends on the window perimeter. Also, some protection, which includes woodblocks and cardboard protection, is added to avoid damage during shipping. This station is represented in Figure 12.

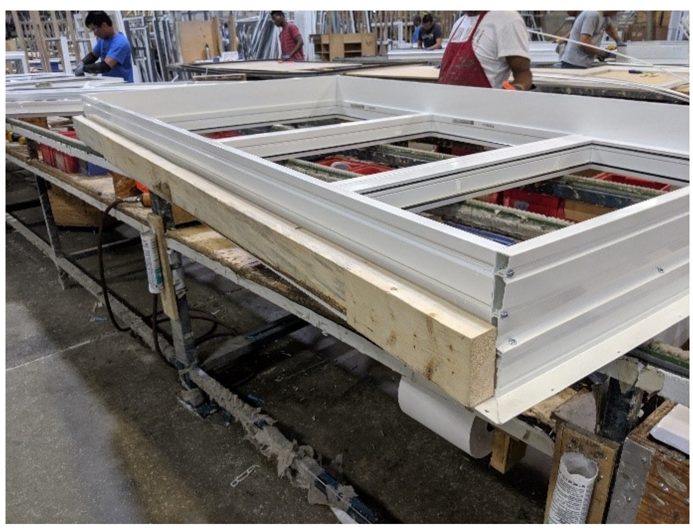

Figure 12- Jamb extension and protection installation station

3.1.10 Glazing station

As shown in Figure 13, the glass (glazing) is installed in the boxes, which are then prepared to be sent to the final station. Now the product can be referred to as a window.

Figure 13 - Glazing station

3.1.11 Wrapping station

The wrapping station is the last station before the windows are sent to the shipping area. The window is wrapped in plastic ready to be shipped to the customer, as seen in Figure 14.

Figure 14 - Wrapping station

3.2 Analyze the current scenario

Most manufacturing systems will not operate in a consistent manner: the number of workers may vary slightly depending on the day, and performance may vary, and breakdowns may happen unpredictably. There are many variables that need to be taken into consideration to achieve the closest outcome that matches reality. The following sections of this thesis describe important information regarding these variables.

3.2.1 Resources (Labour and Machine)

Table 1 shows the amount of resources needed for each station during a normal working day.

Table 1 - Number of available resources

Station	Labor Required	Machine Required	Notes
Picture/ Fixed Cutting	1 P/F Cutter	1 P/F Saw	-
Picture/Fixed Welding	1 P/F Welder	1 P/F Welder Machine	-
Picture/Fixed ACC	-	1 P/F ACC Machine	There is no fixed worker here.
Awning/Casement Cutting	1 A/C Cutter	1 A/C Saw	-
Awning/Casement Welding	1 A/C Welder	1 A/C Welder Machine	-
Awning/Casement ACC + Sash Hardware	1 Sash Hardware installer	1 A/C ACC	Only the ACC will require the machine
Frame Hardware + Sash Join	2 Frame Hardware installers	-	-
Mullion and Brickmould Installation	2 Mullion Installers	-	-
Jamb Extension + Protection Installation	2 Final Assemblers	-	-
Glazing	2 Glazers	-	-
Quality Check + Wrapping	1 Quality Checker	-	-
Total	**14**	**6**	

3.2.2 Assumptions during data collection

Due to the many constraints and variables of a manufacturing system, some assumptions are made to collect and clean the data:

1) The amount of rework required is uncertain given rework is related to quality of work and/or material condition, and the number of reworks changes every day. Hence, defect rates were analyzed throughout the facility for several different days and an estimate of the rework rate was calculated and added to the simulation model.

2) Various statistical probabilities were added to the simulation, such as rework rate, timings that vary depending on the window specifications and probabilities of various situations in which production is briefly delayed. The simulation will return different outcomes each time the software is used; therefore, the chosen number of runs for the simulation analysis is 100, which is enough to gain a good perspective on production behaviour and the fluctuation of results.

3) As previously mentioned, the production line will be missing one or more workers on some days, which influences the timings since there will be a reallocation of resources. To avoid this effect, timings were collected on normal production days, in which no reallocation was necessary.

4) Human labour is not consistent, and worker performance varies depending on the day. Therefore, timings were collected on separate days and outliers were discarded to reduce the likelihood of obtaining results that do not match reality.

3.2.3 Product customization

Product customization is often employed by companies to add variety to their products and offer different choices to clients. These customizations usually affect production performance.

For the production line that is being analyzed in this research, some of the stations require more time to finish their task due to customization. In the context of customization, the factors that can influence production are shown in Table 2.

Table 2- Customization options

Station	Customization Options	Notes
Picture/ Fixed Cutting	-	-
Picture/Fixed Welding	-	-
Picture/Fixed ACC	-	-
Awning/Casement Cutting	-	-
Awning/Casement Welding	-	-
Awning/Casement ACC and Sash Hardware	Window type	Casement and awning require different hardware.
Frame Hardware and Sash Join	Window type	Casement and awning require different hardware.
Mullion and Brickmould Installation	- Number of boxes - Brickmould type	More boxes require more mullions, adding more processing time to the product.
Jamb Extension and Protection Installation	- Window size	The larger the window, the more screws are needed to fix the jamb. Also, a larger window has a larger perimeter area on which protection must be installed.
Glazing	- Number of boxes	Each box will get one glazing unit; therefore, more boxes will increase processing time.
Wrapping	-	-

3.3 Collect real results

After analyzing all processes, resources, and customization possibilities with their impacts, and after defining some assumptions, the data is collected to feed the simulation program. During the time study, three timings are collected for each operation. In the stations where there is a large variation in the recorded timings due to customization, three timings for each possible variation are also collected. Following the aforementioned assumptions, a stopwatch is used, and some rules, as shown in Table 3, are defined to instruct the recording of times for each station to assure the timing device (stopwatch) is initiated and stopped at specific key points to improve the accuracy of collected data.

All collected timings can be found in APPENDIX A.

Table 3 - Time study starting and ending rules

Station	Timing Starts	Timing Ends
Picture/ Fixed Cutting	Fetch profile	Unload Saw
Picture/Fixed Welding	Load machine	Unload Machine
Picture/Fixed ACC	Load machine	Unload Machine
Awning/Casement Cutting	Fetch profile	Unload Saw
Awning/Casement Welding	Load machine	Unload Machine
Awning/Casement ACC	Load machine	Unload Machine
Sash Hardware	Fetch tools	Place Sash in the storage
Frame Hardware and Sash Join	Fetch tools	Place Frame in the storage
Mullion and Brickmould Installation	Fetch frame(s)	Place in the next station
Jamb Extension and Protection Installation	Fetch tools	Place in the next station
Glazing	Fetch tools	Place in the next station
Wrapping	Fetch window	Place in the storage

3.4 Building the simulation model

3.4.1 Creating the database

The company tracks all the job orders for a specific day in a spreadsheet. All parameters are listed on the job orders, including the sequencing in which the windows will enter the manufacturing system. The database was created using Microsoft Access and later connected using an existing tool with Simphony.NET. However, the simulation software needs to understand how to read each parameter, and for this purpose a translator is created to make this file reading manageable. An example of one fully translated database for a single day used in this research can be seen in APPENDIX B.

3.4.2 Implementing the variables

In this research, variables are the customization options that affect processing time for the product. Simphony.NET allows the user to use different types of variables: local and global.

Local variables carry information about each entity (in this case, each window), while global variables carry information that is not tied to a single entity, but to the simulation itself. Global variables are used to track specific information through the simulation process. For the window parameters, local variables were used, as shown in Table 4.

Table 4 - Local variables simulation inputs

Parameter	Description	Notes
LX (1)	Qty. casement/awning	Number of casement/awning boxes
LX (2)	Qty. picture/fixed	How many picture/fixed boxes
LX (3)	Height	In millimeters
LX (4)	Length	In millimeters
LX (5)	Perimeter	In millimeters
LX (6)	Number of boxes	Number of boxes in the window
LX (7)	Is there jamb?	1 = Yes 2 = No
LX (8)	Is there screen?	1 = Yes 2 = No
LX (9)	Qty awning	Number of awning boxes
LX (10)	Qty casement	Number of casement boxes
LX (11)	Is there brickmould?	1 = Yes 2 = No

Table 5 details all equations used in the simulation model:

Table 5 - Simulation equations

Task	Equation used	Notes
Install Hardware	(LX(9)*244) + (LX(10)*228)	Awning hardware installation = 244s Casement hardware installation = 228s
Tie Bar	If length < X, returns a specific duration	There are five different values for X, each returns a different duration
Box-to-box installation	144 * (LX(6) – 1)	If there are three boxes, there is the need of the joining process two times. Hence, the LX(6) – 1
Install Mullion Cover	0.017*LX(3)*(LX(6)-1)	The 0.017 is in seconds per millimetre. The mullion cover is installed between each box join.
Brickmould Installation	160 * LX(11)	Each brickmould requires 160s in average
Install Jamb Jamb Extension	0.049*LX(5)*LX(7)	The 0.049 is in seconds per millimetre.
Cardboard and wood protection	0.008*LX(5)*LX(7)	The 0.008 is in seconds per millimetre
Glass Installation	141 * LX(6)	Each glass averages 141 seconds for installation
Screen Installation	30 * LX(8)	Each screen averages 30 seconds for installation

To calculate production rates, global variables were used, since they are tied to the simulation itself and not to a specific entity (product). These global variables can be seen in Table 6.

Table 6 - Global Variables Simulation Inputs

Parameter	Description	Notes
GX (100)	Labour-force	Number of workers
GX (101)	Production	Number of windows built
GX (102)	Timestamp	Time at the end of the simulation
GX (103)	Production rate	Calculation of windows/man-hours

3.5 Collect Simulation Results

Understanding the results is as challenging as building the simulation program. Having all the data, such as resource utilization, lead times, and queue length, is not useful unless it is clear what they represent. For example, a station with a high utilization rate might not necessarily be the bottleneck, so the queue length also needs to be analyzed to see if that task needs to be further improvement. Furthermore, simply adding more resources (workers) to that station might not be the best decision, since subsequent stations could not keep up with the increased production rate, and more workers would result in higher labour costs, which would be a financial decision that needs to be analyzed to determine its feasibility.

3.6 Simulation Validation

After the simulation is finished and run, it needs to be validated to ensure the results are an accurate representation of reality (the current state). One of the simulation validation processes undertaken in this research was to compare the production rate calculated by the simulation model with the company's tracking system. This tracking system is fed every day by the manufacturing leaders with information such as number of windows built, how many workers were working on the line on that day, and any equipment breakdowns that may have affected production. More techniques were used to validate the simulation, and these are presented in the next section.

3.7 Simulating different scenarios

After validating the simulation model, some feasible scenarios were imagined in which production could be improved. Graphical analysis is performed to see how much one specific station can be improved without starving the next station or causing overproduction. The improvements under consideration range from small changes to the process to a reallocation of resources to smooth the production flow.

3.8 Overall Equipment Effectiveness (OEE)

An OEE analysis studies the availability, performance, and quality of the production line under study. Also, the current OEE of the targeted production line is calculated based on data collected on different days (to capture results fluctuation) and then compared with the best combination of proposed changes. The performance factor fluctuates depending on the day, and when the difference between the maximum and the minimum value is large that means that there is room for improvement, since production is inconsistent. This research aims to reduce this gap in order to achieve a more balanced production rate and to facilitate the identification of bottlenecks and how to eliminate them while boosting productivity. More information on about how to calculate each factor will be addressed in Chapter 5 of this thesis.

CHAPTER 4 – SIMULATION RESULTS AND SCENARIO ANALYSIS

In this chapter, the simulation model of the current scenario is presented along with its results, and after validation, some changes to the production line are proposed. At the end of this chapter, the best combination of proposed changes is determined.

The goal for this scenario productivity analysis is to find the bottleneck of the production line and determine the proper solutions to eliminate it. However, it should be noted that by performing changes in one station, another station may become a potential bottleneck. Therefore, this research takes into consideration this possibility and provides feasible solutions given the current manufacturing capacity while also not creating any new bottlenecks.

Also, not all suggestions that are proposed in this chapter will have a positive effect on the production line. Someone not familiar with manufacturing processes would assume that the removal of a station or the speeding up of the process would always result in an increase in productivity; however, this is not the reality. Some of the simulated scenarios will challenge this assumption by demonstrating why all the stations must be observed after any change to the process to avoid moving production issues to another place. Moreover, these suggestions are categorized into changes that do not require a large capital investment and changes that would require further cost-benefit analysis.

4.1 Simulation validation and outputs

The simulation software used for this research is Simphony.NET, which was developed by researchers at the University of Alberta. After performing the time study and recording all the operations for this specific production line, Simphony.NET is used to mimic the production flow and return the results required to determine the production rate. Also, to ensure variations were captured and to avoid significant discrepancies in the data, the simulation was set to 100 runs.

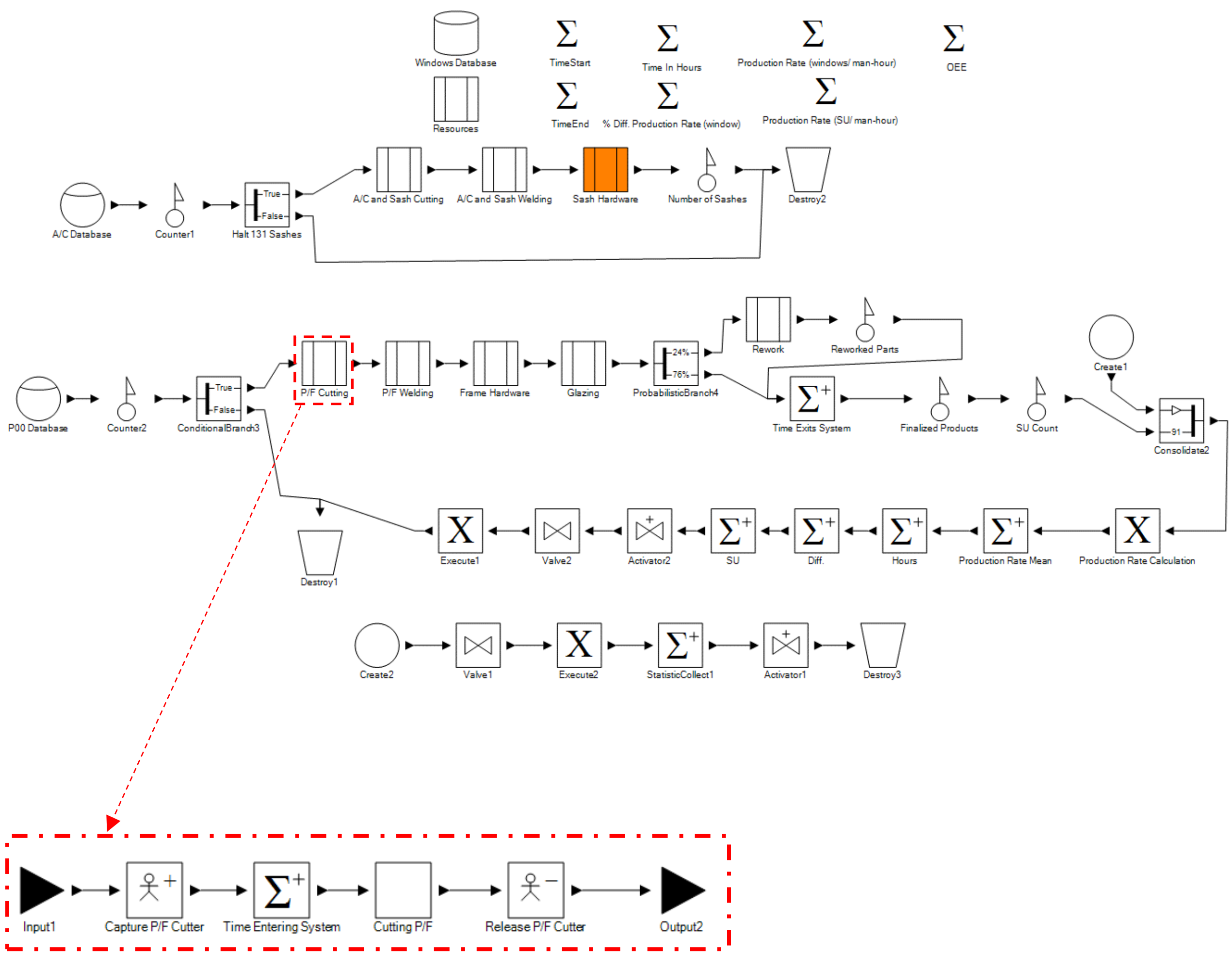

Figure 15 - Simulation screenshot

Each one of the elements represented on Figure 15 will have a different impact on the simulation model. A brief description of the elements used in the simulation model can be found in APPENDIX C.

The company uses a system to store information such as the number of workers and how many windows were finalized each day. Figure 16 shows an example of this data.

For comparison purposes, 35 different days were simulated, each one having their own customization options implemented and the results were compared to this historical data from the company. Also, some statistical calculations were implemented for data normality check, which can be seen in Sections 4.1.1, 4.1.2, 4.1.3 and 4.1.4.

By comparing just one day, the average output for the hourly production rate was 1.390 SU/labour-hour. SU is defined as "Sealed-units", which are each individual box of the window. The company's tracking system returns a production rate of 1.4613 SU/labour-hour, which is a difference of -4.79%. The output provided by the simulation model is an average of 100 runs, while the information provided by the company's historical data is a single value. For this reason, more days were selected for comparison purposes.

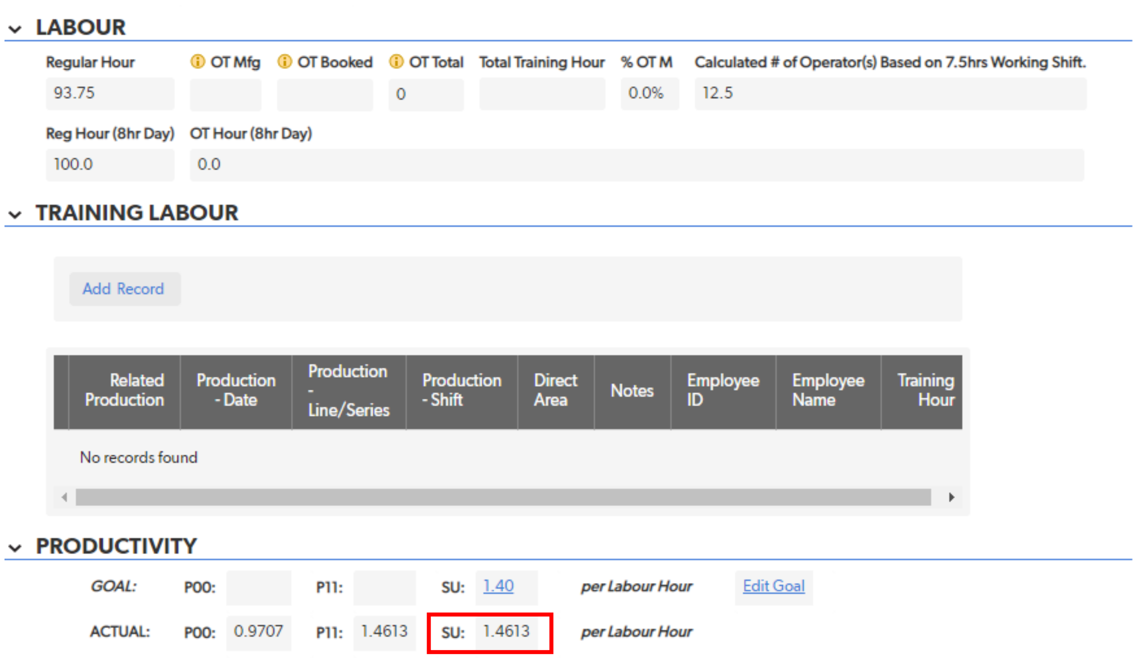

Figure 16 – Historical data company database

For each of the 35 days worth of production, the simulation was set to 100 runs. Which means that there were 3500 data points representing production rates. All points that resulted in over 10% of difference from the historical data were considered as outliers.

In this research, the production rate is calculated based on Equation 2 as shown.

$$Production\ Rate = \frac{Sealed\ Units}{(Number\ of\ workers * shift\ duration)} \tag{2}$$

Also, the simulation can be considered validated because several of the validation methods proposed by Sargent (2010) are employed, including:

- Historical validation: As seen in Figure 16, simulation results are relatively similar to the company's historical data. Comparing all 35 days, the production rate (in SU/labour-hour) provided by the company's system ranges from 0.95 to 1.55, while the output provided by the simulation model ranges from 1.25 to 1.42. For the 35 days, an average difference of 4.88% was observed.
- Face validity: The line supervisor, who has been responsible for this production line for years, was questioned as to whether the simulation model covered all tasks. The simulation model was presented with all stations, formulas to calculate processing times, available resources, and customization impacts. After analyzing the inputs, the supervisor affirmed that the simulation model is a good representation of what he observes in terms of production.
- Degenerate tasks: The simulation model is behaving as expected when parameters are altered. This will be explored in more detail in Section 4.2.

The averages of the resource utilization rates and waiting times can be found in Table 7.

Table 7 - Resource utilization and waiting times

Worker	Utilization	Waiting Times (s)
Picture/fixed cutter	34.80%	4,470.697
Picture/fixed welder (worker)	61.10%	1,660.184
Picture/fixed welder (machine)	44.50%	
ACC machine frame	22.70%	13.616
Awning/casement cutter	58.60%	7,884.998
Awning/casement welder (worker)	74.80%	1,095.236
Awning/casement welder (machine)	64.00%	
ACC awning/casement	37.50%	0
Awning/casement assembler	80.60%	804.132
Frame assembler 1	32.90%	15.128
Frame assembler 2	27.60%	68.260
Frame preparers	40.20%	63.200
Jamb extension assemblers	98.60%	5,257.192
Glazer	73.10%	128.489
Wrapper	39.20%	0.779

Based on the utilization rates and waiting times, it can be observed that "Jamb Extension Assemblers" are overloaded, since their utilization rate is very high and there is a large queue (waiting time) at the jamb extension station, which means that this is the main bottleneck of the production line under study.

As the bottleneck of the production line, the jamb extension station should be one of the first to receive attention when seeking production improvement. Using the same reasoning, both cutting stations could also be considered bottlenecks; however, this is not the case since this large queue is caused by all entities trying to use this station in the simulation model, i.e., all the windows are trying to enter the same station as soon as the simulation starts, creating the illusion of a large queue.

When comparing the results from the simulation with the historical data, there is also the need to determine whether they fit in the same distribution. Ideally, a normal distribution for both datasets is the best scenario, since most of the production rates would fit in a particular interval with a reduced number of outliers. To test the normality of both the historical and simulation datasets, three different statistical tests are used.

4.1.1 Kolmogorov Smirnov test

The Kolmogorov Smirnov (KS) test can be used to test the normality of the distribution and to compare whether historical and simulation data follows the same distribution. In this research, the data provided by the company's system and the output given by the simulation are tested for their normality. The α value chosen for this statistical analysis is 0.05; for a sample size of 35, the critical value of 0.2242 is used.

Table 8- Kolmogorov Smirnov Test

	Historical	**Simulation**
Count	35	35
Mean	1.419885714	1.400888571
St Dev	0.092752603	0.113220433
α	0.05	0.05
Critical Value	0.2242	0.2242
KS Test	0.124492213	0.132836018

As seen in Table 8, both KS test values are lower than the critical value. This is a good indicator that both sets of data (historical and simulation) are normally distributed. The KS test quantifies the distance between the empirical distribution function and the cumulative distribution.

A CDF (cumulative distribution function) determines the cumulative probability of a value X to be greater than or less than a specific value in the dataset. The CDF curve can also estimate which distribution the dataset would best fit. Figure 17 shows the cumulative distribution function comparing simulation with historical data.

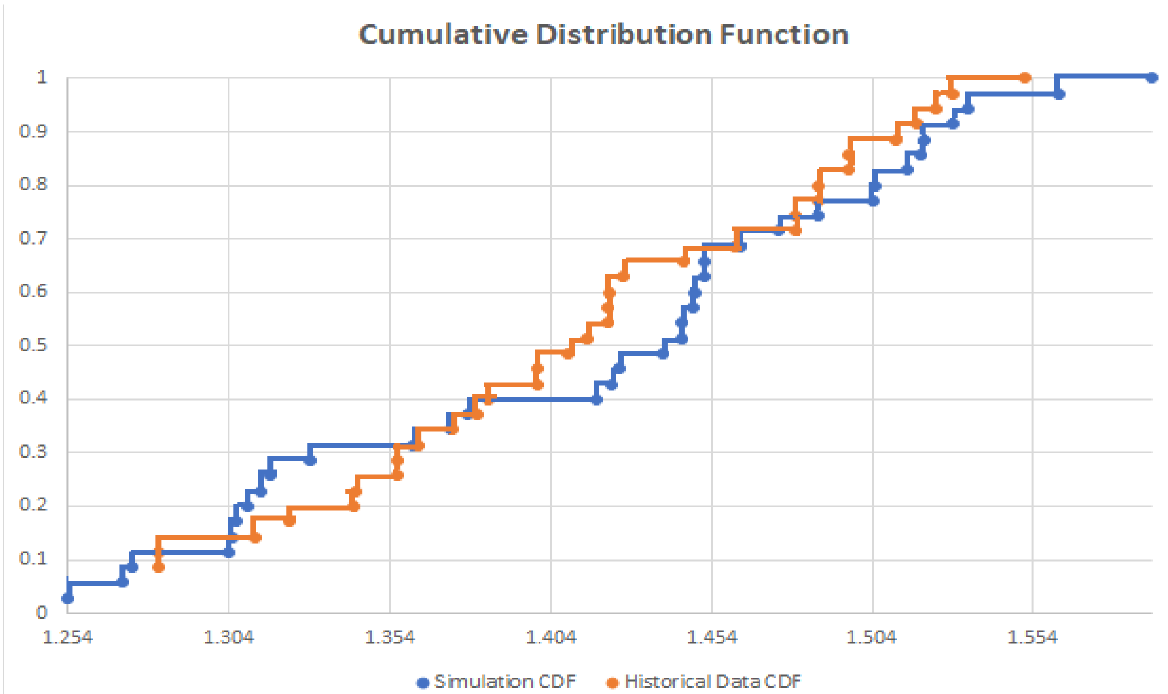

Figure 17 - Cumulative distribution function historical x simulation data

Also, by comparing both CDF plots and applying the KS test between the simulation and historical datasets, it is seen that the maximum absolute difference between the two cumulative distribution functions is 0.1724, which is less than the critical value 0.325.

4.1.2 Q-Q plot

A Q-Q plot is a graphical tool to help identify which theoretical distribution the dataset is most likely to fit.

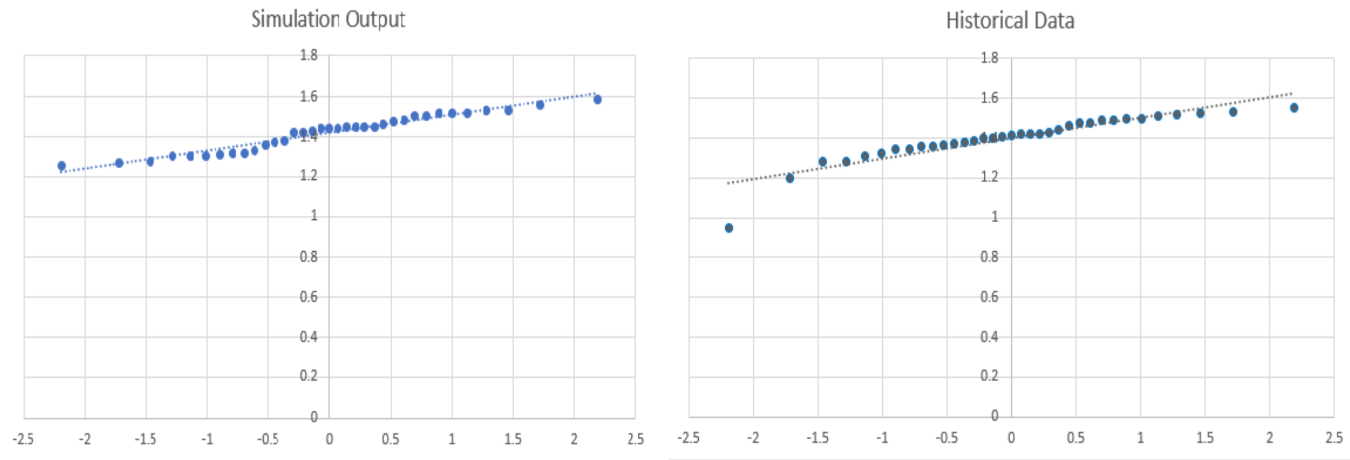

Figure 18- Q-Q plot for simulation and historical data

As seen in Figure 18, each point is one day of production. Both simulation and historical data points mostly follow the dotted 45° line, which is a strong indication that both datasets are normally distributed. The Q-Q plot of the historical vs simulated data is shown in Figure 19.

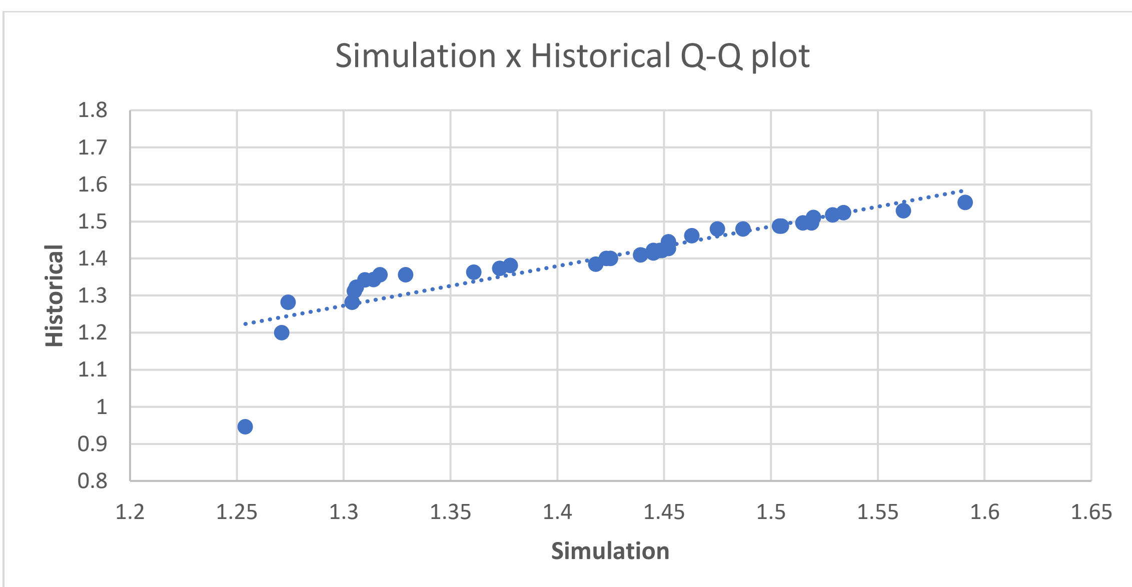

Figure 19- Q-Q plot for historical x simulation data

Most of the points follow the 45° trendline when being compared to each other, which is another indicator that points to the normality of the data.

4.1.3 T-Test

The T-test is important when trying to compare two datasets to determine whether they are statistically different or not. The results of this test can be seen in Table 9.

Table 9 - T-test results

	Historical	*Simulation*
Mean	1.400888571	1.419885714
Variance	0.012818866	0.008603045
Observations	35	35
Hypothesized Mean Difference	0	
df	65	
t Stat	-0.767879721	
P(T<=t) one-tail	0.222669656	
t Critical one-tail	1.668635976	
P(T<=t) two-tail	0.445339312	
t Critical two-tail	1.997137908	

Performing a two-tailed t-test, the value of t Stat is 0.7678, it is lower than the critical value t, which is 1.99, meaning that there is no statistically significant difference between the current observations and the simulation.

4.2 Testing different scenarios

In this section, new scenarios are simulated with the goal to increase productivity throughout the production line under study. If the proposed change is not feasible, the reason why the changes should not be implemented is explained.

4.2.1 Scenario 1: Eliminate jamb extension searching time

The jamb extension station is determined to be the main bottleneck of the production line, as it is the process with the longest processing time and with the largest fluctuations in processing times because the size of the window directly influences the work.

All jamb extensions (JE) are prepared in advance in a different place and stored near the jamb extension station. Often, the worker needs extra time to identify which jamb extension is needed for the product currently being worked on. Usually these products are sorted by sequence; however, in practice workers do not always respect the sequence, since by experience they will choose a window that will either feed the next station faster or give them more time to avoid having too many windows in queue for the next station.

Processing times at this station range from 140 to 500 seconds since the size of the window has a great impact on the work. There is a large amount of fluctuation in processing time per window, with spikes in productivity when processing smaller windows and decreasing productivity when processing larger ones.

A suggestion to reduce this processing time would be to sort these JE by size instead of sorting them by sequence. This way, identification would be easier and reduce the time required to search for the correct size, reducing the queue that is formed before this station as described in Section 4.1. The graph in Figure 20 shows production rate behaviour as the processing time for the jamb extension station varies.

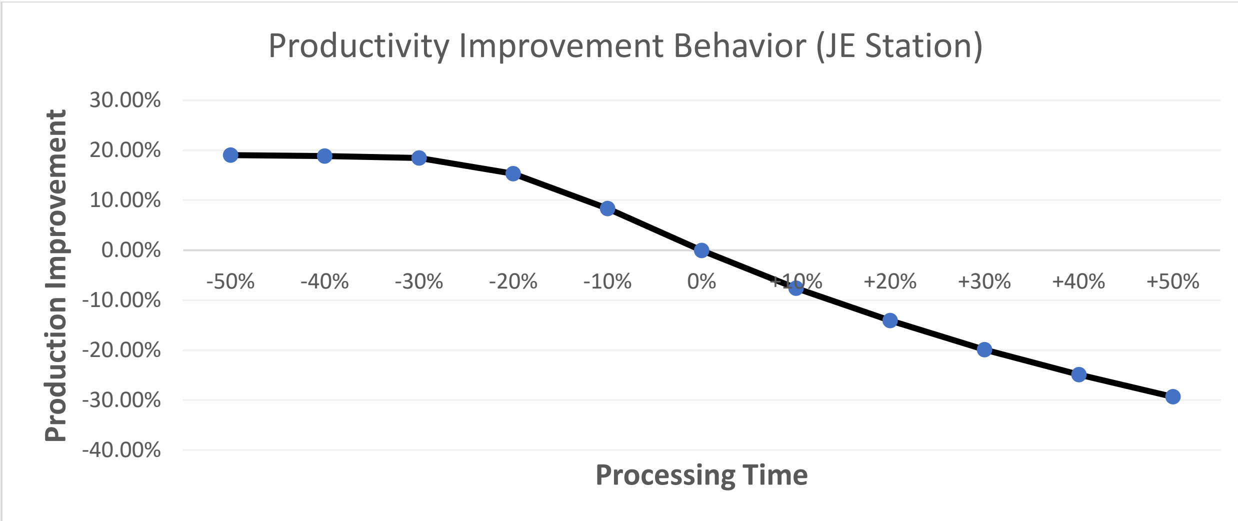

Figure 20 - Productivity Improvement Behavior (JE Station)

Increasing processing time is not the goal of the research, since it will increase queue length and decrease productivity. The cycle time at this station can be reduced by 5% if the change described above is implemented, which would improve production rate by 5%.

Also, as seen in Figure 20, further decreasing the processing time is not feasible. Decreasing the cycle time at this station may cause overloading for the next station, which will not result in improved overall efficiency since productivity is calculated based on the number of finished products. Therefore, investing more effort at this station is not recommended.

4.2.2 Scenario 2: Reducing glass searching time

As in the case of the jamb extension, workers also need to find the correct glass for the specific window they are working on. The panes of glass are also prepared in advance and stored near this station.

There is one main production line in the manufacturing facility under study where the glass is prepared for all stations. There are two types of glazing: double and triple glazing, and the customer decides which one they require. Double and triple glazed units are put in different carts (located near each other) and are also sorted by sequence. Also, the amount of stored glazing is greater in comparison to the jamb extensions, requiring additional time for the worker to identify the correct one for the product.

The same suggestion could be applied to this situation as was recommended in the case of the jamb extension station: While also sorting by glass type, the glazing could be sorted by size, increasing the ease with which the worker is able to identify the pane(s) of glass they are seeking.

The graph in Figure 21 shows production rate behaviour as the processing time for the glazing station shifts.

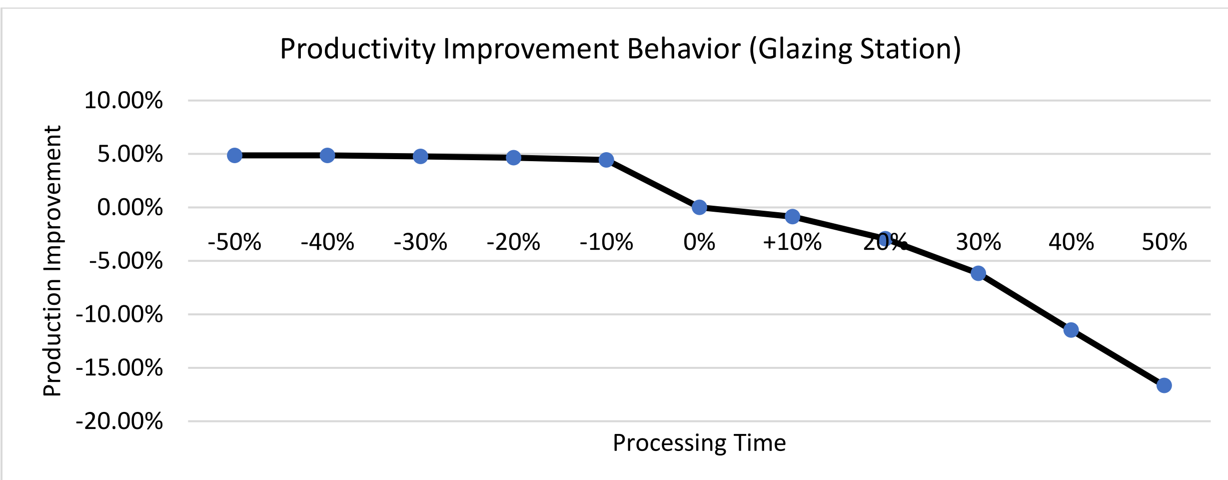

Figure 21- Productivity Improvement Behavior (Glazing Station)

The values shown in Figure 21 are calculated without including change proposed in scenario 1.

Timings on stations range between 185 for up to 600 seconds. However, this station does not have a high fluctuation of processing time, since of most of the products are single or double boxes, resulting in an average of 185 to 370 seconds. Processing time can be reduced up to 10% with the improvement suggestion, and this could increase productivity rate by 5%.

The next (and last station) is the wrapping. The processing time is faster than the glazing station, meaning that queue formation is rare and increasing productivity even more in the Glazing station would not result in an increase on the number of finished goods.

4.2.3 Scenario 3: Re-routing wrapping station

The wrapping station is the last station in the production line under study, which means it will dictate the final output. As the processing time at the wrapping station is faster than at the preceding station, the production rate is not affected by making improvements here. By re-routing this station to receive windows from more than one production line, the production rate improves by less than 1%. This recommendation does not also take into consideration scenarios 1 and 2. Figure 22 shows production improvement behaviour when reducing the processing time for the wrapping station.

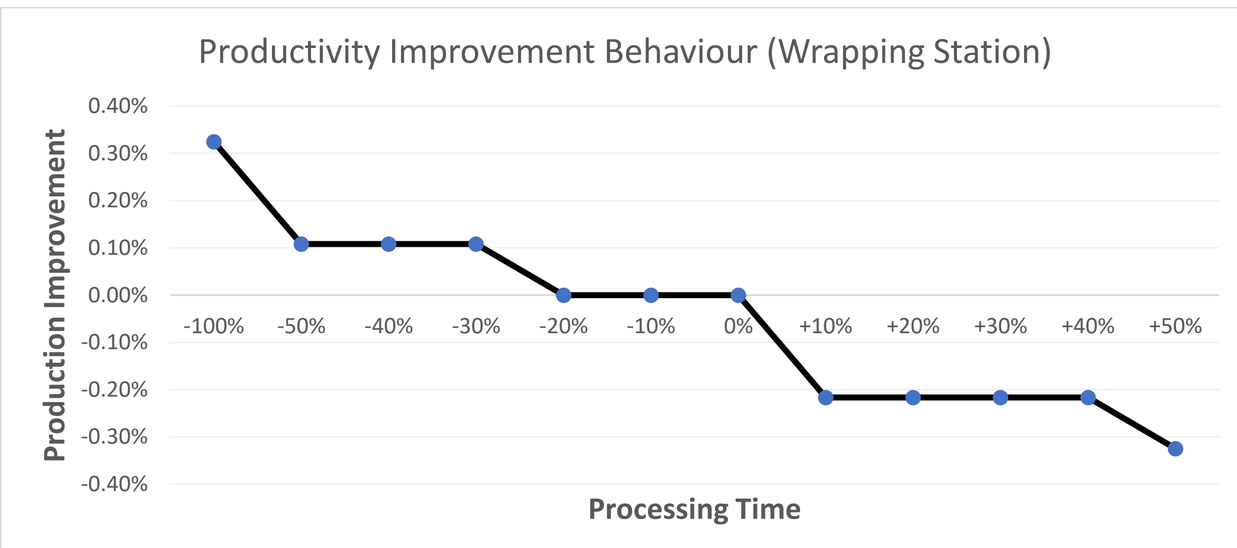

Figure 22- Productivity improvement behaviour (Wrapping Station)

However, re-routing this station or enabling this station to receive products from more than one production line will reduce costs (reducing the number of wrapping stations in the whole plant) that could be invested in a new machine or technology to improve performance for the other stations.

4.2.4 Scenario 4: Scenario 1 + Scenario 2 + Scenario 3

As seen in Scenario 2, productivity rates will not change significantly with the reduction in processing times at the glazing station. Since this station does not wait for products coming from the jamb extension station, significant changes are only observed by also reducing the JE processing time. Some options and their respective impact can be observed in Table 10. For these calculations, scenario 3 is also included.

Table 10 - Production Rate Difference Scenario 5

Option	Reduction in JE station processing time	Reduction in glass station processing time	Reduction in Wrapping	Production Rate	% Difference
1 (Current)	-	-	-	1.390	-
2	0	5%	100%	1.414	- 1.73%
3	5%	0%	100%	1.470	- 5.70%
4	**5%**	**5%**	**100%**	**1.480**	**- 6.39%**
5	10%	5%	100%	1.536	- 10.83%

From these options, the most feasible one would be scenario 4. As explained before, these 5% processing time reductions as indicated in the case of the JE station and the glazing station would be possible by reducing the amount of time that works are searching for the correct parts and material. Hence, productivity can be improved by up to 6.39% in a scenario in which those reductions are implemented together.

Moreover, due to current manufacturing limitations, further decreasing the processing time at the jamb extension station is not possible without implementing new technology; however, with new technology production could be increased to 10.83%.

4.2.5 Scenario 5: Resource addition or reallocation

Adding more workers to a production line is not one of the first options owners consider when performing productivity studies. There is a need to address the feasibility of such investment, for example: How many more windows can be built by adding these new workers? What would be their rates and how long would it take for the company to see a return on this investment?

Due to data sensitivity and confidentiality, and because workers at different stations receive pay at different rates, the feasibility in terms of the cost is not covered in this research; however, the increase in the production rate will be addressed.

For the resource addition approach (adding one or more workers), a different analysis method will be used. While adding more workers would result in an increase in the number of finished products, the high level of customization varies each day, which presents a challenge in terms of how to predict the increase to the production line capacity. Therefore, the simulation will run as the current state, but with the additional resources.

The imagined scenario would be adding two additional workers to the bottleneck identified on this production line: the jamb extension station. At this station workers usually perform this task in pairs, so adding two more workers would double the throughput at this station. This would increase production to 1.414 SU/labour-hour, a 2.5% increase.

If incrementing the change proposed at scenario 4, production can be improved to 1.588 SU/labour-hour, a 14.22% increase.

As discussed in Scenario 1, there comes a point at which the production line's improvement potential will start to diminish, since subsequent stations are not able to accommodate production at an increased rate.

Also, workers at the jamb extension station would experience a reduction on their workload 98% to 63% utilization as seen in Figure 23.

Resources

Element Name	Average Utilization
A/C and Sash Cutter	69.5%
A/C and Sash Welder (Human)	88.6%
A/C and Sash Welder (Machine)	75.8%
ACC Machine Frame	27.0%
ACC Machine Sash	44.4%
Frame Assembler 1	38.6%
Frame Assembler 2	32.7%
Frame Preparer	36.0%
Glazer	96.4%
JE Assemblers	63.0%
Picture/Fixed Cutter	41.3%
Picture/Fixed Welder (Human)	72.8%
Picture/Fixed Welder (Machine)	52.7%
Sash Assembler	95.3%
Wrapper	46.6%

Figure 23- Resource utilization with Scenario 5

4.3 Summary of results

For comparison purposes, Table 11 summarizes all the simulation results for the proposed scenarios. All the productivity factors are measured in SU/labour-hour.

Table 11 - Summary of results with all scenarios

Scenario	New production rate	% Difference
1	1.481	5.00%
2	1.473	4.44%
3	1.455	3.12%
4	**1.480**	**6.39%**
5	1.446	2.50%
	1.588	**14.22%**

Given the production line's constraints in terms of capacity, workers, and behaviour, the best option would be scenario 4 if the company decides to choose the most conservative approach (no investment in new resources).

If the company decides to add more labour to their manufacturing processes, scenario 5 would be more interesting, since the simulation shows that production can increase by 14.22%. However, the costs of training new resources such that they achieve desirable production rates is an additional cost that should be closely analyzed.

CHAPTER 5 – OEE ANALYSIS

OEE (overall equipment effectiveness) analysis is a performance tool that originated with the TPM (total production maintenance) approach developed by Nakajima (1988). This indicator evaluates a company's availability, performance, and work quality in a quantitative way, giving insights into the wastes of production and facilitating their mitigation.

Accuracy in the context of data collection is very important when employing an OEE analysis (Muchiri & Pintelon, 2008). DES can be used to support calculating the performance indicator and can also predict how it would change based on hypothetical scenarios.

OEE can be calculated by using the formula shown in Equation 1.

$$OEE = Av * Eff * Q$$

where:

Av is availability of the manufacturing line;

Eff is efficiency (or performance) from the manufacturing line; and

Q is quality of the product when finalized.

An OEE higher than 85% classifies the company as "world class". This can be achieved by having a smooth and balanced workflow, avoiding unnecessary time wastes, and producing products with no defects. However, very few companies achieve this goal. Most of them start doing this analysis with incorrect assumptions, which means the results don't have any real applicability.

In this chapter, the OEE is calculated for all the historical data collected from 35 days of production, and the results are interpreted in order to identify and mitigate the wastes.

5.1 Availability Factor

Availability is defined as the time during which workers are actively producing something. To simplify, it is the total time reduced by maintenance breaks, safety talks, and normally scheduled breaks. Equations 3 and 4 show how to calculate the availability factor.

$$\boldsymbol{Av} = \frac{\sum \mathrm{PT} - \sum \mathrm{DT} - \sum \mathrm{ST} - \sum \mathrm{B}}{\sum \mathrm{PT}} \tag{3}$$

$$\sum \mathrm{PT} = \mathrm{Nworkers} * \mathrm{Tshift} \tag{4}$$

where:

$\sum$ PT = sum of all processing time in hours from all workers in a single work day;

Nworkers = number of workers on that specific day;

Tshift = shift duration (in hours) in a single work day;

$\sum$ DT = sum of all downtimes that resulted in production disruption (e.g. machine breakdowns);

$\sum$ ST = sum of time (in hours) spent in weekly safety talks; and

$\sum$ B = sum of time (in hours) for breaks (coffee breaks, lunch)

Apart from the maintenance breaks, which are unpredictable, all other downtimes will always be the same and reducing them would affect the company’s work schedule. Table 12 describes the calculation for the availability factor for each one of the 35 studied days.

Table 12 - Availability Calculation

Day	SD	NW	LH	Breaks (hours)				MB	TPT	Availability
				Safety	Breaks	Lunch	NP Time			
1	8.5	11	93.5	1.83	5.5	5.5	12.83	0	80.67	86.27%
2	8.5	11	93.5	1.83	5.5	5.5	12.83	0	80.67	86.27%
3	8.5	11	93.5	1.83	5.5	5.5	12.83	0	80.67	86.27%
4	8.5	12	102	2.00	6	6	14.00	0	88.00	86.27%
5	8.5	10	85	1.67	5	5	11.67	0	73.33	86.27%
6	8.5	12	102	2.00	6	6	14.00	0	88.00	86.27%
7	8.5	12	102	2.00	6	6	14.00	0	88.00	86.27%
8	8.5	13	110.5	2.17	6.5	6.5	15.17	0	95.33	86.27%
9	8.5	9	76.5	1.50	4.5	4.5	10.50	0	66.00	86.27%
10	8.5	10	85	1.67	5	5	11.67	0	73.33	86.27%
11	8.5	10	85	1.67	5	5	11.67	0	73.33	86.27%
12	8.5	9	76.5	1.50	4.5	4.5	10.50	0	66.00	86.27%
13	8.5	12	102	2.00	6	6	14.00	0.75	87.25	85.54%
14	8.5	10	85	1.67	5	5	11.67	0	73.33	86.27%
15	8.5	13	110.5	2.17	6.5	6.5	15.17	0	95.33	86.27%
16	8.5	12	102	2.00	6	6	14.00	3	85.00	83.33%
17	8.5	13	110.5	2.17	6.5	6.5	15.17	0	95.33	86.27%
18	8.5	13	110.5	2.17	6.5	6.5	15.17	0	95.33	86.27%
19	8.5	14	119	2.33	7	7	16.33	0	102.67	86.27%
20	8.5	13	110.5	2.17	6.5	6.5	15.17	0	95.33	86.27%
21	8.5	13	110.5	2.17	6.5	6.5	15.17	0	95.33	86.27%
22	8.5	12	102	2.00	6	6	14.00	0	88.00	86.27%
23	8.5	13	110.5	2.17	6.5	6.5	15.17	0	95.33	86.27%
24	8.5	14	119	2.33	7	7	16.33	0.25	102.42	86.06%
25	8.5	13	110.5	2.17	6.5	6.5	15.17	0	95.33	86.27%
26	8.5	14	119	2.33	7	7	16.33	0	102.67	86.27%
27	8.5	15	127.5	2.50	7.5	7.5	17.50	0	110.00	86.27%
28	8.5	14	119	2.33	7	7	16.33	0	102.67	86.27%
29	8.5	13	110.5	2.17	6.5	6.5	15.17	0	95.33	86.27%
30	8.5	13	110.5	2.17	6.5	6.5	15.17	0.5	94.83	85.82%
31	8.5	14	119	2.33	7	7	16.33	0	102.67	86.27%
32	8.5	14	119	2.33	7	7	16.33	0	102.67	86.27%
33	8.5	13	110.5	2.17	6.5	6.5	15.17	0	95.33	86.27%
34	8.5	13	110.5	2.17	6.5	6.5	15.17	0	95.33	86.27%
35	8.5	14	119	2.33	7	7	16.33	0.25	102.42	86.06%
Avg.										**86%**

where:

SD = shift duration;

NW = number of active workers;

LH = labour-hours;

NP Time = non-productive time;

MB = maintenance break; and

TPT = total productive time.

During this research, it was mentioned that the shift duration (SD) is 7.5 hours. However, this number is the time the workers are producing (not including their safety breaks and lunch breaks). The total duration of the shift is 8.5 hours including 1 hour of break time.

The labour-hours (LH) were calculated by multiplying the number of active workers by the SD. The safety breaks and lunch breaks are fixed for each worker (since they are planned). The non-productive time (NP Time) is the sum of the most common non-value-added times observed during the time study, such as unnecessary movement of people and material transportation time.

Observing the results from these 35 days, and with an average of 13 active workers per shift, the availability factor averages 86.22%.

5.2 Performance

The performance factor calculates how far away a production line or station is from an ideal production or goal defined by the company. For the production line under study, on average, 13 workers are implicated in the assembling of the product. Processing times were collected whenever a worker at the station was familiar with the process to avoid discrepancies and results that do not reflect reality.

By definition, to calculate the performance factor, the company should know how much of their product can be produced within a day or shift. When this information is unavailable, reasonable assumptions must be discussed. When defining a goal, benchmark standards should not be used for comparison purposes since it will produce unrealistic results and lead to the idea that the company's standards are low. Leaders and manufacturing supervisors must understand the flexibility of their processes and the current capacity and propose a goal that their company wants to reach while respecting current limitations. After meetings with the leaders and manufacturing supervisors, the production goal was set at 120 windows each day.

In this thesis, the objective of Chapter 4 was to provide ideas on how the productivity could be improved, while this section is providing a goal that the company wants to achieve by implementing these changes in the future.

To calculate the performance factor for the OEE analysis, this production goal must be compared with the current state observed in the manufacturing facility. Equation 5 shows how to calculate the performance factor.

$$Pe = \frac{Ncurrent}{Ngoal} \tag{5}$$

where:

Ncurrent: number of windows built in a given day; and

Ngoal: number of windows defined for the performance goal.

Of the three indicators used to calculate the OEE factor, this is the one that may fluctuate the most since the number of workers and how productive they are will vary the results and may not accurately describe reality. Demand will also have an impact, since with a low workload, workers tend not to be as productive as they normally would be. To avoid calculating indicators that could be potential outliers, each station was carefully timed, and a few other assumptions were made (please refer to Section 3.2.2 for more information).

By using the assumption of 120 windows per day, the performance factor was calculated. For confidentiality and data sensitivity, the performance factor will not be directly shown in this research. However, it was observed that results average between 55% and 70%, which means that production can fluctuate. There is the need to reduce this fluctuation and make production more consistent from day to day, which can facilitate the understanding of the workflow and help to plan production ahead more efficiently. The proposed scenarios in Chapter 4 of this thesis can help to reduce this fluctuation.

5.3 Quality

Quality is a factor that cannot be easily predicted, since it depends on how the work is being performed and the quality of the material, which can have defects in a batch coming from the supplier. Simulations cannot exactly predict whether the product will be good quality at the end of production. However, an average of the number of defective products that reach the end of production every day can be calculated and accounted for in the simulation model. Tracking the possible root causes of the most recurrent defects might help reduce the amount of rework necessary; however, there is not a way to predict how the quality factor will fluctuate based on the proposed changes specified in this research. Working at a faster pace might result in damages to the product; therefore, another round of data collection would be necessary to adjust the OEE. In the context of this research, the quality factor will remain constant during this research. To calculate the quality factor, refer to Equation 7.

$$Qu = \frac{\sum T - \sum D}{\sum T} \tag{7}$$

where:

$\sum T$ = sum of total goods produced on that day (including defective and non-defective products); and

$\sum D$ = sum of total defective products observed at the end of production.

Please note that the window will fall into the defective count if the window requires any extra time after it passes through all the stations.

Most quality issues can be solved by being better organized while building the window, making sure there is no material missing before sending the product to the next station. Also, being more cautious while transporting the window from one location to another might reduce damaged materials issues.

As mentioned before, quality is not something that can be predicted. For this reason, an average number of defective products was collected in-loco (as the work was being executed). The company's historical data is not very reliable in terms of defects since there is no fixed person assigned to gather this information and only a few windows are checked each day for defects. Therefore, another suggestion would be to assign an existing worker to do the job of ensuring all windows pass the company's quality standards. This will be helpful since the creation of a database like this will help to identify the most recurrent reworks necessary and how to mitigate the rework.

A sample size calculator was used to identify how many products would need to be checked to have a level of confidence of 95% in the data. By collecting this information, the average of defects was 15%, resulting in an 85% quality factor.

5.4 OEE results interpretation with current and proposed scenarios

With all three OEE performance indicators calculated, their values can be analyzed to study how OEE will fluctuate and if the suggestions will have a desirable impact to justify the feasibility of a future investment.

Due to data sensitivity and confidentiality, the exact OEE value of the current state for all 35 days will not be detailed here. However, after removing outliers, the OEE values fall in the range between 45% and 60%. This performance indicator has a high fluctuation and changes needs to be addressed in order to balance productivity though different days for an easier identification of wastes and capacity.

Achieving 100% in the OEE is close to impossible. This theoretical scenario could only be achieved if the process is fully automated, with the same machine flawlessly performing all necessary tasks, without any downtime. In addition, world-class companies usually observe results of approximately 85% for the final OEE factor. This is another indicator that a lower value does not mean that the company is not skilled, rather it indicates that there are some time losses (as described in section 2.2.1) that could be mitigated to help the company improve the integration of lean studies.

For example, implementing changes that can reduce some of the transportation time or reallocating resources in such a way that workers can achieve their full potential can be tested in a simulation program. By eliminating some of these wastes, the number of processed goods increases, also increasing the performance and quality factors, raising the OEE score.

Of these three factors, the one that owners have the least control over is performance. A performance factor that averages between 45-60% means there is waste that can be reduced while assembling the product (e.g. transportation and queuing). To have better insights into exactly what type of waste and where the waste can be mitigated, each station should be studied individually and should receive its own performance factor. However, improving a specific station solely because it has a low OEE score is not recommended, because all stations should be considered when changing any process to avoid moving a bottleneck instead of eliminating it. Also, while increasing the speed (production rate) of the station can improve productivity tremendously, there are still potential issues such as more products being produced may result in more defective products, reducing the quality factor and the OEE score.

Simulation is a tool that can be used to support these decisions to specific stations. While a simulation model is able to automatically calculate fluctuations in OEE from day to day, it also provides information on the station's behaviour when implementing different future scenarios, such as the ones proposed in this research.

With the best proposed change outlined in Chapter 4, most OEE factors now range between 55-65%, which is a significant increase, but there is room for more improvements, such as investing in new technologies. The fluctuation of the OEE factor can be seen in Figure 24.

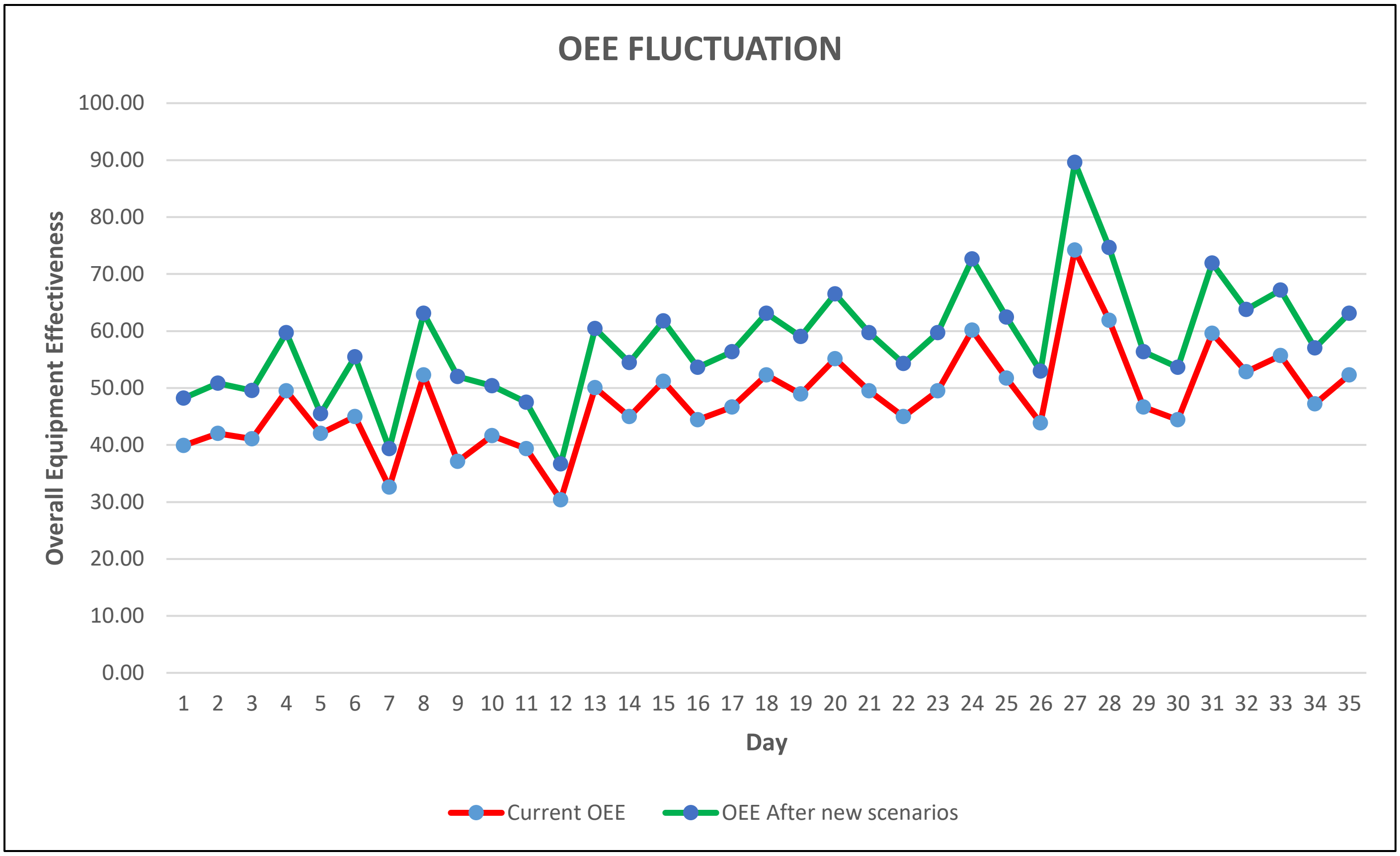

Figure 24- Fluctuation current OEE x new OEE

CHAPTER 6 – CONCLUSIONS AND FUTURE RECCOMENDATIONS

6.1 Research Summary

This research describes how simulation models can be used to understand the current state of manufacturing processes and to analyze hypothetical scenarios before their implementation. Moreover, simulation models are very useful for processes with large fluctuations in processing time. Companies still take a very conservative approach when evaluating an investment in new technologies with the goal to improve their production rates; however, most of these analyses are based on many assumptions. While simulation requires some understanding of the processes, it quantifies values and gives a better perspective as to how changes will affect the production rates.

Five possible hypothetical improvement scenarios are presented, and the simulation is used to determine their feasibility and overall impact on all stations of the production line under study. The simulation model proves that implementing changes to only one single station was not the best option, since mitigating one bottleneck will shift production overload to another station within the same production line. The targeted production line can realize a production increase in SU/labour-hour of up to 15% with the proposed scenarios. That said, all methods used in the course of this research can be replicated in the context of any production line, as long as there is sufficient reliable data to perform all analyses.

Simulation can also be used to support the calculating of performance indicators such as overall equipment effectiveness (OEE), since this indicator can identify the location of wastes and which type of wastes are occurring most frequently in a particular manufacturing process. Applying changes to attempt to improve (increase) this performance indicator can be validated with the use of simulation and further applied to different manufacturing industries.

6.2 Research Contributions

This research was conducted in order to achieve all the objectives presented in Chapter 1, including:

- identify manufacturing bottlenecks with the use of a simulation model;
- observe performance fluctuations in the context of the entire production line when applying the proposed changes to the simulation model of the production line under study;
- calculate the overall equipment effectiveness (OEE) of the production line under study; and
- provide evidence that discrete event simulation (DES) can be used to support the calculation of overall equipment effectiveness.

6.3 Research Limitations

The research was conducted with the following limitations:

- rework rates were manually collected and due to time constraints, the amount of data collected was minimal.
- worker performance will be different each day, but the simulation assumes that the processing time of the station is consistent for every product.
- the simulation assumes that windows are built in the same order as that defined in the database; however, workers do start assembling products according to that sequence, but they will, by experience, choose a different window in case they need to process products faster to avoid starving the next station; and
- in order to calculate the performance factor for the OEE analysis, assumptions were made (as stated in Section 3.2.2).

6.4 Recommendations for future study

This research demonstrates how DES (discrete event simulation) can assist businesses by providing an overview of the manufacturing behaviour given different scenarios and a comparison with the current scenario. Also, DES explains which areas you can attack with outputs provided by an OEE analysis.

There are still some areas of exploration, such as:

- quantifying the investment value for changes to the current scenario and based on manufacturing costs, calculating payback time;
- creating an algorithm within the simulation model that can improve line balancing, reduce high workloads, and mitigate non-value-added times by changing the sequence at which products enter the system; and
- analyzing each station of a production line separately using the OEE approach in order to identify which kind of waste is the most recurrent for a specific set of activities; then, use simulation to check scenarios of improving production.

This research can be replicated to similar industries. However, some limitations will arise. In manufacturing, usually there are stations on a sequential order working in the same product, which allows the calculation of the performance of the entire manufacturing line and the assessment of the OEE. In the construction field, different tasks should not be analyzed together, window installation and floor installation must be separately analyzed and have their own production rate and OEE score, since they are independent tasks and require different data for analysis.

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APPENDIX A

Table 13- Operations Time study

Operation	Unit	Time 1	Time 2	Time 3	Avg Time
Cut Picture/Fixed	*s*	97	94	99	96.67
Cut Casement/Awning	*s*	108	104	105	105.67
Weld Picture/Fixed	*s*	67	65	64	65.33
Weld Casement/Awning	*s*	108	102	104	104.67
Casement/Awning Manual Corner Clean	*s*	108	100	106	104.67
Picture/Fixed Automatic Corner Clean	*s*	101	102	101	101.33
Casement / Awning Automatic Corner Clean	*s*	101	102	101	101.33
Manual Corner Clean Picture / Fixed	*s*	100	115	108	107.67
Manual Corner Clean Sash	*s*	98	96	92	95.33
Casement Harware	*s*	260	242	227	243.00
Awning Hardware	*s*	228	225	231	228.00
Tie bar	**-**	Size dependant (varies from 53 to 86 seconds)			
Frame and Sash Join	*s*	82	86	87	85
Box-to-box join	*s*	149	140	145	144.67
Mullion Cover Installation	*mm/s*	0.015	0.018	0.017	0.017
Reno Brickmould	*s*	165.000	159.000	162.000	162.000
PVC Jamb Extension	*mm/s*	0.049	0.048	0.049	0.049
Packing (Wood + Cardboard)	*mm/s*	0.008	0.008	0.009	0.008
Glazing	*s*	141.000	139.000	143.000	141.000
Screen Installation	*s*	30.000	33.000	31.000	31.333
Wrapping	*s*	121.000	112.000	115.000	116.000

APPENDIX B

An example of a database used to connect to the simulation. The meaning of all these Local Variables can be checked on Table 4.

Table 14- Database example

LX(1)	LX(2)	LX(3)	LX(4)	LX(5)	LX(6)	LX(7)	LX(8)	LX(9)	LX(10)	LX(11)
1	0	1502	1502	6008	1	1	0	0	1	1
0	1	1505	505	4020	1	1	0	0	0	1
1	0	1502	1603	6210	1	1	0	0	1	1
0	1	1505	505	4020	1	1	0	0	0	1
0	1	1491	1183	5348	1	1	0	0	0	1
1	2	1491	1183	5348	3	1	0	1	0	1
1	2	1491	1183	5348	3	1	0	1	0	1
1	2	1006	1207	4426	3	1	0	1	0	1
1	1	1200	803	4006	2	1	0	0	1	1
1	0	1006	1407	4826	1	1	0	0	1	1
1	1	813	752	3130	2	1	0	0	1	0
1	0	1200	600	3600	1	1	0	0	1	0
0	1	1505	495	4000	1	1	0	0	0	0
1	0	1505	495	4000	1	1	0	0	1	0
1	0	1505	1432	5874	1	1	0	0	1	0
0	1	900	903	3606	1	1	0	0	0	0
0	2	1492	524	4032	2	1	0	0	0	1
0	1	1500	600	4200	1	1	0	0	0	0
0	1	1500	600	4200	1	1	0	0	0	0
0	1	1889	972	5722	1	1	0	0	0	0
1	1	1346	750	4192	2	1	1	1	0	0
1	0	1486	883	4738	1	1	0	0	1	0
1	0	1524	552	4152	1	1	0	0	1	1
0	1	1524	552	4152	1	1	0	0	0	1
0	1	1870	1918	7576	1	1	0	0	0	0
1	1	1346	750	4192	2	1	1	0	1	0
1	0	1899	667	5132	1	1	0	0	1	0
0	1	1200	750	3900	1	1	0	0	0	0
0	1	1870	1918	7576	1	1	0	0	0	0
1	1	1575	2489	8128	2	1	0	0	1	0
1	1	1575	2489	8128	2	1	0	0	1	0
1	1	1575	2489	8128	2	1	0	0	1	0
1	1	1575	2489	8128	2	1	0	0	1	0

1	1	1500	900	4800	2	1	0	0	1	0
0	1	1492	524	4032	1	1	0	0	0	1
1	0	1899	667	5132	1	1	0	0	1	0
1	0	1899	667	5132	1	1	0	0	1	0
1	0	750	600	2700	1	1	0	0	1	0
0	1	600	1500	4200	1	1	0	0	0	0
0	1	1200	600	3600	1	1	0	0	0	0
0	1	1702	279	3962	1	1	0	0	0	0
0	1	991	1600	5182	1	1	1	0	0	0
1	1	1500	2260	7520	2	1	0	0	1	0
0	3	1500	2260	7520	3	1	0	0	0	0
0	3	1200	750	3900	3	1	0	0	0	0
0	1	1500	2260	7520	1	1	0	0	0	0
0	3	1200	750	3900	3	1	0	0	0	0
0	1	1500	1500	6000	1	1	0	0	0	0
0	1	1200	750	3900	1	1	0	0	0	0
0	1	1200	750	3900	1	1	1	0	0	0
1	0	1200	1803	6006	1	1	1	0	1	0
1	1	1800	1200	6000	2	1	0	0	1	0
0	1	1800	1200	6000	1	1	0	0	0	0
0	1	1800	400	4400	1	1	0	0	0	0
0	1	1651	2710	8722	1	1	1	0	0	0
1	2	1800	900	5400	3	1	1	0	1	0
1	0	300	1357	3314	1	1	0	0	1	0
0	1	1200	1203	4806	1	1	1	0	0	0
1	1	1800	2100	7800	2	1	0	0	1	0
0	1	1800	900	5400	1	1	0	0	0	0
0	1	1800	900	5400	1	1	0	0	0	0
0	1	1200	750	3900	1	1	1	0	0	0
1	0	1651	750	4802	1	1	0	0	1	0
0	1	1651	2710	8722	1	1	1	0	0	0
1	2	1651	750	4802	3	1	0	0	1	0
0	1	1800	2100	7800	1	1	0	0	0	0
0	1	1800	1200	6000	1	1	0	0	0	0
0	1	1800	1200	6000	1	1	0	0	0	0
0	1	1200	1203	4806	1	1	0	0	0	0
1	1	900	1200	4200	2	1	0	0	1	0
0	1	1200	1203	4806	1	1	0	0	0	0
1	1	900	1403	4606	2	1	0	0	1	0
1	1	900	1203	4206	2	1	0	0	1	0
1	1	900	1403	4606	2	1	0	0	1	0

1	1	900	1203	4206	2	1	0	0	1	0
1	1	1200	1203	4806	2	1	0	0	1	0
1	1	900	1203	4206	2	1	0	0	1	0
1	1	1499	2845	8688	2	1	0	0	1	0
0	3	1219	610	3658	3	0	0	0	0	0
1	0	1502	1203	5410	1	0	0	0	1	1
0	1	1254	1254	5016	1	1	0	0	0	1
0	1	997	1203	4400	1	1	0	0	0	1
1	1	1800	1502	6604	2	1	0	0	1	1
0	1	1502	603	4210	1	1	0	0	0	1
1	0	1502	603	4210	1	1	0	0	1	1
1	0	997	1203	4400	1	1	0	0	1	1
1	1	1502	2401	7806	2	1	0	0	1	1
1	1	1502	603	4210	2	1	0	0	1	1
1	0	1800	603	4806	1	1	0	0	1	1
0	1	1800	2004	7608	1	1	0	0	0	1
1	1	1511	292	3606	2	1	0	0	1	1
0	1	1511	292	3606	1	1	0	0	0	1
0	1	1502	899	4802	1	1	0	0	0	1
0	1	997	997	3988	1	1	0	0	0	1
1	0	1800	603	4806	1	1	0	1	0	1
0	1	750	2406	6312	1	1	0	0	0	0
1	2	1249	1462	5422	3	0	0	0	1	1
0	1	1265	2408	7346	1	1	0	0	0	1
0	3	541	1456	3994	3	1	0	0	0	1
1	1	948	1164	4224	2	1	0	0	1	1
1	1	948	1164	4224	2	1	0	0	1	1
1	1	541	1456	3994	2	1	0	0	1	1
1	1	694	1751	4890	2	1	0	0	1	1
1	1	694	1751	4890	2	1	0	0	1	1
1	1	948	1164	4224	2	1	0	0	1	1
1	1	1848	3048	9792	2	1	0	0	1	1
2	1	1265	1599	5728	3	1	0	0	2	1
0	2	1005	1151	4312	2	1	0	0	0	1
1	0	700	700	2800	1	1	0	1	0	1
1	0	932	716	3296	1	1	0	1	0	1
1	0	1334	699	4066	1	1	0	0	1	0
1	1	781	565	2692	2	0	0	0	1	0
1	0	852	1761	5226	1	1	0	0	1	1
1	1	1334	699	4066	2	1	0	0	1	0
1	1	1030	929	3918	2	0	0	0	1	1

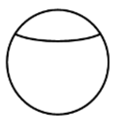
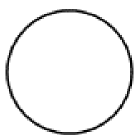
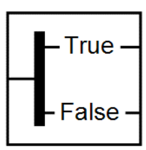
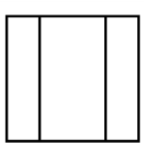
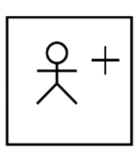
1	0	600	1500	4200	1	1	0	1	0	0
0	1	600	1500	4200	1	1	0	0	0	0
0	1	1456	802	4516	1	1	0	0	0	1
1	0	1575	2819	8788	1	1	0	0	1	0
0	3	1800	750	5100	3	1	0	0	0	0
0	1	1800	750	5100	1	1	0	0	0	0
0	1	1800	750	5100	1	1	1	0	0	0
1	0	1853	2846	9398	1	1	0	0	1	1
0	3	1475	1475	5900	3	1	0	0	0	0
0	1	1475	1475	5900	1	1	0	0	0	0
0	1	1475	1475	5900	1	1	0	0	0	0
0	1	1200	1203	4806	1	1	1	0	0	0
1	1	900	1200	4200	2	1	0	0	1	0
0	1	1041	1503	5088	1	1	1	0	0	0
2	0	1803	2405	8416	2	1	0	2	0	0
0	4	900	2403	6606	4	1	0	0	0	0
0	2	1200	1203	4806	2	1	1	0	0	0
1	1	1200	600	3600	2	1	1	0	1	0
1	0	1500	900	4800	1	1	1	0	1	0
1	0	1500	900	4800	1	1	1	0	1	0
1	0	1200	1503	5406	1	1	1	0	1	0
1	1	1200	1503	5406	2	1	1	0	1	0
1	1	1500	1505	6010	2	1	1	0	1	0
1	1	1500	1505	6010	2	1	1	0	1	0
1	1	1200	1503	5406	2	1	1	0	1	0
1	1	1800	1505	6610	2	1	1	0	1	0
1	1	1800	1505	6610	2	1	1	0	1	0
1	1	750	1503	4506	2	1	0	0	1	0
0	2	900	900	3600	2	1	0	0	0	1
0	1	1200	600	3600	1	1	1	0	0	0
1	0	1803	2405	8416	1	1	0	0	1	0
0	4	1000	1000	4000	4	1	1	0	0	0
1	0	1041	1503	5088	1	1	1	1	0	0
2	0	750	1503	4506	2	1	0	2	0	0
0	2	600	1503	4206	2	1	1	0	0	0
1	1	600	1503	4206	2	1	1	0	1	0
1	1	900	1400	4600	2	1	0	0	1	1
0	1	1000	750	3500	1	1	1	0	0	0
1	0	1200	750	3900	1	1	1	1	0	0
1	0	1200	750	3900	1	1	1	0	1	0
1	0	2103	1200	6606	1	1	1	0	1	0

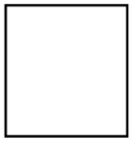
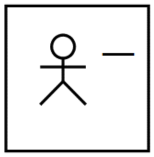
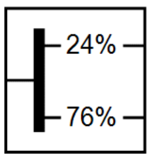
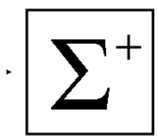
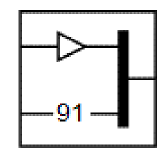
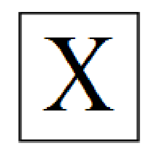
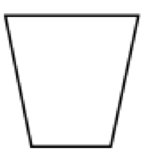
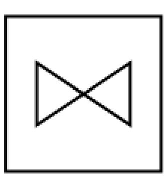
1	1	2103	1200	6606	2	1	1	1	0	0
1	1	1200	750	3900	2	1	1	1	0	0
1	0	1200	750	3900	1	1	0	0	1	0
0	1	1200	750	3900	1	1	1	0	0	0
1	0	900	900	3600	1	1	0	0	1	0
0	1	900	900	3600	1	1	0	0	0	0
0	1	900	1503	4806	1	1	1	0	0	0
2	0	1475	1475	5900	2	1	0	2	0	0
0	1	1475	1475	5900	1	1	0	0	0	0
0	1	1800	1800	7200	1	1	0	0	0	0
0	1	1800	1800	7200	1	1	0	0	0	0
0	1	1800	1800	7200	1	1	0	0	0	0
0	1	1800	1800	7200	1	1	0	0	0	0
0	1	1800	1800	7200	1	1	0	0	0	0

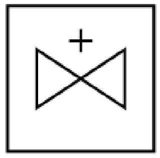
APPENDIX C

This appendix details what each element used in the simulation model represents, describing their name and their primary function inside the program.

Table 15 – Simulation Entities

No.	Element Symbol	Element Name	Action
1		Database Create	Linked to a Microsoft Access database file with information regarding product customization
2		Create	Creates the entity that will pass through the simulation.
3		Counter	Records how many products have passed through this element
4		Conditional	Often used to separate products with different attributes. Ex: Two products starts at the same station but branches in different ones
5		Composite	Mostly used for aesthetics in the program. Combines a work sequence and keeps user interface cleaner
6		Capture Resource	Captures a specific resource (worker) whenever available

7		Task	Represents a single task of the manufacturing line. Entity will be held by this element for the time determined by the user
8		Release Resource	Releases the resource specified at No. 6
9		Probabilistic	Divides entities based on a probability of an event to happen
10		Statistic Collection	Collects certain information defined by the user. For this simulation, it was used to calculate productivity rates using the Global variables introduced at the Methodology of this research.
11		Consolidate	Holds a certain number of entities (defined by the user) before releasing it back to the simulation
12		Execute	Can execute most commands from the simulation software using formulas. For this research, it was used to store some values into a global variable
13		Destroy	Destroys the entity when reaches this element
14		Valve	If the valve is set as closed at the beginning of the simulation, it will hold entities until it passes through a Valve activator

15		Open Valve	This is a Valve activator that will open the Valve (No. 14) whenever an entity goes through this element