Simulation Based Job Sequence Impacts on Window Manufacturing

by

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ABSTRACT

This thesis describes a framework to analyze the impacts of job sequencing on a window manufacturing company through implementation of various dispatching rules. In order to develop the framework, a study is carried out at a window manufacturing facility in order to gain comprehensive knowledge of the different processes employed on the production line. Discrete event simulation (DES) is employed to explore the effects of distinct job order sequencing scenarios on performance metrics, including total production time, productivity, and queueing area space variations. The implementation of a heuristic dispatching rule significantly improves total production time and a reduction of queueing area space. Additionally, this framework proves that the wrong job order sequencing can lead to a loss in productivity and a larger production line space.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

1.1 Research motivation

In the current environment of highly competitive business and globalization, the manufacturing industry is being forced to make changes to improve products, process design, and management. In the Canadian manufacturing sector, this is of most significance given that the sector represents 10% of Canada's total gross domestic product (GDP) and over 68% of all products exported according to the Government of Canada (2020).

In order to improve products, process design, and management, manufacturing companies need to rely on tools to observe the consequences of changes to the production line without the cost of implementing them on the real manufacturing line. One of these tools is simulation, where the production lines and each of the processes within them can be analyzed and modified as desired. This allows companies to simulate different scenarios and select the best options for changes to a production line.

In addition, manufacturing companies usually face challenges related to resources. Some of these challenges affecting manufacturing companies are defined by different job processing times, machines, and resource readiness, all of which are addressed in the sequencing task, which focuses on the allocation of limited resources to several tasks in order to achieve a performance objective. This task is often time consuming and if not implemented correctly can result in poor resource utilization, long production times, and unreliable due date commitments, resulting in a reduction of competitiveness, and an increase in production costs.

Extensive research has been carried out in terms of job sequencing impacts on several manufacturing industries, these studies are further mentioned in the literature review section of this thesis. However, research on the impacts of job order sequencing in window manufacturing has never been studied. This research is conducted to determine the impacts of different job sequencing scenarios on a window manufacturing line with the aid of a simulation model.

1.2 Research objectives

This research aims to develop a framework to analyze the impacts of various sequencing scenarios on a window manufacturing line and to propose different sequencing solutions that can achieve an improvement in production performance metrics. This framework is developed by conducting a work study, a time study, and by implementing a simulation model that mimics the current environment. The research objectives of the thesis are:

- to analyze and identify the sequencing scenarios with the development and implementation of a simulation model that may provide insight on possible improvement in terms of production performance metrics;
- to analyze the performance and the variability of total production time and productivity while testing different sequencing rules; and
- to identify the amount of variation in terms of the queueing area space requirement given the different scenarios that are based on the sequencing rules.

1.3 Thesis organization

This thesis is organized into six chapters:

- Chapter 1– The introduction contains the research motivation, research objectives and the thesis organization.
- Chapter 2 – The literature review covers manufacturing systems, off-site manufacturing, scheduling problems in manufacturing, and simulation. Furthermore, this chapter covers

previous work on the use of simulation to address scheduling problems in different industries.

- Chapter 3 – The methodology provides the framework and steps used to address the research problem, including work study, time study, simulation model development, and verification and validation of the model.
- Chapter 4 – As part of developing the process map, the product and the production line investigated in this research are described in detail, including product descriptions and types, and the work study and time study undertaken as part of this research.
- Chapter 5 – The process of developing of the simulation model is presented, as well as the verification and validation of the simulation model, and analysis of the implementation of sequencing rules using data from several production days.
- Chapter 6 - Conclusions and future research directions are presented, which include a discussion of takeaways from this research, the contributions of the research, the limitations of the research, and proposed further research opportunities.

2 LITERATURE REVIEW

2.1 Manufacturing systems

2.1.1 <u>Introduction</u>

In recent days, most people are familiar with the term manufacturing, since all the things used by humans in some way are affected by manufacturing. Therefore, it is possible to say that the history of manufacturing began with civilization. The word manufacture comes from the Latin and means made by hand. However, until the creation of the assembly line by Henry Ford, products were created by expert labourers and custom made to meet demands. Manufacturing can be defined as:

"[*T*]*he application of physical and chemical processes to modify the properties of a given start material in terms of its form, shape, size, mechanical characteristics, external appearance, etc., in order to fabricate a single part representing a product or multiple parts to be assembled to form a complex product. In order to perform a manufacturing process, it is necessary to utilize appropriated machines, tools, fixtures, energy, and manpower.*" (Segreto & Teti, 2014)

Manufacturing can also be seen as a system where raw materials are transformed into products (Bi et al., 2008). In addition, manufacturing systems (MFS) are broad systems involving people, machinery, and processes that collectively accomplish the operations of an enterprise. Furthermore, the support procedures used to manage the use of machines and workstations are part of MFS. From this point of view, these support procedures help to classify MFS from the perspective of how they target a changing market.

2.1.2 <u>Classification of manufacturing systems</u>

As previously stated, manufacturing systems can be categorized based on their approach to meeting the markets' features. MFS can be classified as dedicated manufacturing systems (DMS), flexible manufacturing systems (FMS), cellular manufacturing systems (CMS) and reconfigurable manufacturing systems (RMS) (Bortolini et al., 2018). DMS focuses on mass production and its objective is to cost effectively produce one specific product or part at high volumes. The characteristics of the product are to remain unchanged through the lifetime of the system; therefore, this type of MFS is costly and difficult to customize in practice (Mehrabi et al., 2002). FMS aims to accommodate changes in job orders and production schedules. This can be translated into the ability to produce a variety of products and to manage change in volume on the same system. This can be obtained through automated numerically controlled workstations. However, in most cases, the production rate is lower than DMS. Also, the equipment costs are higher; therefore, the product cost is higher. CMS, on the other hand, focuses on independent workstations that deliver products from the same family and under similar processing constraints. RMS targets a rapid change in structure to adjust production capacity and functionality of the same part family to quickly react to changes in market requirements (Bortolini et al., 2018).

In this research, a mixture of RMS and FMS is investigated because of the nature of the product under study, i.e., all the manufactured products need to be customized and mass production is no longer efficient. Therefore, one of the advantages of these two MFs, namely *mass customization*, can be utilized to accomplish the objectives of the enterprise in terms of productivity and costumer involvement.

2.1.3 Mass customization

In the discussion on mass customization, there exists a contradiction between customization and traditional manufacturing processes or mass production. Throughout history, manufacturing companies traditionally have chosen to produce either customized or mass standardized products. Now, mass customization offers an innovative way of producing products that is changing the way companies present themselves to the public, offering unique products in a mass produced, high volume and low cost manner (Duray, 2002).

Duray et al. (2000) point out a mass customization categorization that permits different approaches to implement mass customization capability. The authors also show that companies are employing different methods to produce such personalized products. The first is how much the customer is involved in the design process. The second is to check whether the term "mass" in mass customization is accurate, due to the volume a company can produce a unique personalized product (Duray et al., 2000)

Modularity is a key component and critical aspect when talking about mass customization; this key feature facilitates the clients' involvement in the personalization process while restricting how much range of choice the client has over the product. This allows the manufacturer to produce in a repetitive mater while reducing the variety of components added or changed to the standardized product (Duray et al., 2000).

2.2 Off-site construction manufacturing

Over the years, the construction industry has been critiqued for not being efficient by generating too much waste and for exceeding budgets and deadlines. Therefore, the construction industry has sought an industrialized construction technique to mitigate these inefficiencies, and one of these approaches is the implementation of off-site manufacturing (OSM) (Hu & Chong, 2019). The objective of OSM is to shift some of the activities from on-site construction to off-site in a controlled manufacturing environment while maintaining the mass customization for each of the subassemblies (Khalfan & Maqsood, 2014).

Off-site manufacturing has several similar terms used to describe OSM, such as off-site construction, off-site production, and off-site prefabrication (Hu & Chong, 2019). OSM can be classified as a process and a system. The first one defines OMS as a set of processes that implement prefabrication and preassembly to create units or modules so they can be transported to the site and be assembled to the final product. In this research the window manufacturing facility is classified as an OSM because the end product is transported at the end of fabrication to be installed on site (Rahimian et al., 2017).

2.3 Production scheduling

2.3.1 Scheduling problem

For more than 60 years, research on production scheduling has been constantly evolving, being the most popular area of research on operations management along with inventory control (Pannirselvam et al., 1999). Production scheduling mainly concerns the optimal allocation of limited resources for the manufacture of goods (Lawler et al., 1993), and aims to distribute and sequence the use of these resources where all production constraints are satisfied and the cost of production is reduced. Every time a common set of resources (labour, material, and equipment) is used to manufacture a variety of distinct products, a scheduling problem arises (Rodammer & White, 1988). According to Graves (1981), the scheduling problem has three major variables or dimensions in order to classify it. In Figure 1, the scheduling problem dimensions and possible types are presented.

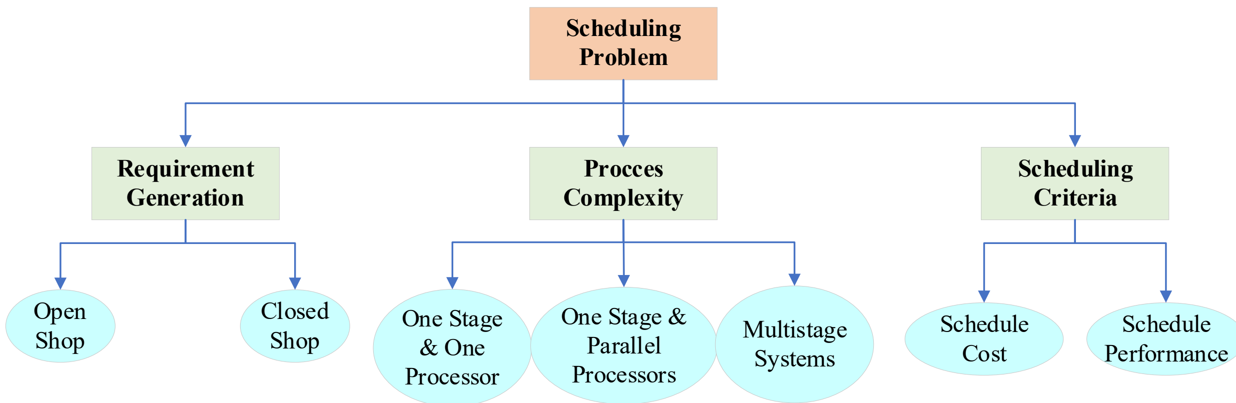

Figure 1 Classification of Scheduling Problem

The first dimension, requirement generation, is divided in two paths: orders are generated by customers or by inventory replenishment decisions. This dimension is often referred to as open shop versus closed shop, respectively. In a closed shop, all customer needs are provided from inventory in contrast in an open shop where all production orders are manufactured by customer request and no inventory is stocked. However, in most production settings, a completely open or closed shop is rare, but the main characteristic would be either open or closed (Graves, 1981).

The second dimension, process complexity, mainly focuses on the number of steps to be taken in each manufacturing activity. This dimension can be separated into one stage and multistage. For the one stage, the complexities are one stage/one processor and one stage/parallel processors. As for the multiple stages, where each activity requires it be done in different processors, it is divided into flow shop and job shop (Graves, 1981).

The third dimension, often called optimality criteria (Lawler et al., 1993) or scheduling criteria, concerns the evaluation of each schedule, based on cost or performance. Some of the most common types of performance measures are completion time, lateness, and tardiness (Graves, 1981).

For this research, it is necessary to define the problem in each of the dimensions. Firstly, the job orders in this system are created by customer request. Therefore, the production line under study can be categorized as a closed shop problem. Secondly, the number of processors in this problem is more than one. Thus, this facility can be described as a multistage system. Thirdly, the optimality criteria for the problem under study are multi-objective criteria.

2.3.2 Flow shop problem

One of the most common types of scheduling problems is the flow shop problem (FSP). This problem arrives from the second dimension given multiple tasks and processors. In addition, the FSP can be defined by a set of $N = 1,2,\ldots,n$ jobs that have to be processed on a set of $M=1,2,\ldots,m$ machines. The processing time of each job $j \in N$ on each machine $i \in$ M is known. Furthermore, this scheduling problem requires that all the job orders follow the same path from one machine to another. It is possible that not every job has an operation on each of the processors along the line but the movement between processors is in the same direction. A common example is an assembly line, where workers or workstations represent the processors. However, a strict case of flow shop problem is very rare because most lines would have to some extent the need to perform some rework.

The objective of an FPS is to find a processing sequence that through a criterion is optimized. Additionally, the number of possible solutions is the multiplication of all possible job permutations by all machines $(n!)^m$. Nonetheless, often in FPS literature it is simplified by having the same permutation of jobs for all machines. As a result, the number of possible solutions decreases to *n!*. The simpler version of the FPS is called permutation flow shop problem (PFSP) (Minella et al., 2008). In the present research, the manufacturing system under study is to be addressed as a permutation flow shop problem.

2.3.3 Permutation flow shop problem solutions

For many years researchers have investigated the PFSP, and different solution methods have been used to solve the problem. These approaches can be categorized as exact and approximation methods. The former covers the optimum solution, which in theory can be very appealing. However, exact solution methodologies can become inefficient as the problem grows given that many jobs are to be processed by many machines. Therefore, exact methods are practical for smaller flow shops (Yenisey & Yagmahan, 2014). As for the approximation methods, they can be used to address large size problems to produce good, but not necessarily optimal, solutions (Framinan et al., 2004). In the present research, the application of approximation methods is to be used to accomplish the objectives of the investigation.

2.4 Simulation

2.4.1 Introduction

Since its inception, simulation has been implemented in many sectors, such as manufacturing, public services, defense, construction, and healthcare. Simulation is one of the most popular techniques used in operations management research (Jahangirian et al., 2010). The use of computer simulation to develop simulation models and mimic production lines will be the focus of this research. Simulation is defined by the Encyclopedia Britannica (2014a) as:

“*the use of a computer to represent the dynamic responses of one system by the behaviour of another system modelled after it. A simulation uses a mathematical description, or model, of a real system in the form of a computer program. This model is composed of equations that duplicate the functional relationships within the real system. When the program is run, the resulting mathematical dynamics form an analog of the behaviour of the real system, with the results presented in the form of data*.”

2.4.2 Simulation in manufacturing

In the current business environment where all enterprises are required to be highly competitive in order to succeed, the manufacturing industry is not exempt from this situation. Thus, some of the challenges that the industry is facing are the needs for the constant development of new innovative products, the increasing trend of globalization, and the need to deliver mass customization. As a result of these challenges, businesses need to analyze complex and constantly evolving systems (Nee et al., 2012). Simulation is implemented with the aim of gaining insight into complex systems, and of completing the development and assessment of new operating polices before implementing them into the real system (Mourtzis et al., 2014).

2.4.3 Types of simulation

Simulations can be categorized based on three main factors: time of change, randomness, and data organization. (Mourtzis et al., 2014). The first one, time of change, is classified as either dynamic or static. If the simulation model is time dependant, it is considered dynamic. In contrast, when the simulation model is not affected by time, the term used is static simulation. With respect to randomness, the models can be either stochastic or deterministic. Stochastic models use some level of random process during execution, meaning that each time the simulation is run, the results are different as opposed to deterministic models where every result is the same on each run. Lastly, in terms of data organization, models are labeled as grid-based and mesh-free (Mourtzis et al., 2014).

The classification of dynamic models can be further categorized as discrete event simulation or continuous simulation. In continuous simulation models, the system results are tracked continuously during the course of the simulation in comparison to discrete event simulation (DES) models where outputs are recorded only at specific time points. In addition, DES is divided into two types: time-stepped and event-driven. The former consists of regular time intervals and alterations happen after a certain amount of time has occurred. In the latter, time intervals are intermittent, and updates are driven by scheduled events. For this research, DES is used since it mimics a real production flow because every operation is considered as an event and supplies are only altered when they pass through a workstation.

In discrete event simulation, the processes of a system are recorded points in time in a chronological order. All of these points represent a change in an aspect of the state of the system: these points in time are called events (Banks et al, 2009). The system's state can only be known when an event occurs, and each event triggers the subsequent event. In addition, the core elements of a DES, regardless of the tool used, are the clock to track time and note the timestamps of each event, the event list where all the possible events that can be scheduled are recorded, the statistics to track data of interest and give it as a result to the user, and the termination conditions that establish a rule or condition that finishes the loop (Nassehi, 2014).

2.4.4 Manufacturing applications of discrete event simulation

As manufacturing systems become more complex, the development of new production configurations and planning approaches need to take into account the review of many complex variables that are too hard for a human to process without the use of a computer system (Barlas & Heavey, 2016). In the present study, DES offers a strong tool to model these systems and compare the results of different scenarios. There are many simulation applications in manufacturing, but flow shop scheduling is the most relevant to this research. In a study by Jahangirian et al. (2010), a full review of the current practices for simulation is given.

2.4.5 Flow shop scheduling simulation

Discrete event simulation has been used to evaluate the performance of scheduling methods, sequencing rules, and spatial optimization. Zhuo et al. (2012) developed a simulation model to address block assembly scheduling by considering spatial optimization in a shipyard. In their study, Zhuo et al. (2012) presented results with significant impacts in terms of total production time depending on different types of sequencing rules, and in some cases these results presented a reduction of total production time by half. Moreover, this study showed a reduction of 20% space utilization for queueing areas. Additionally, Kuo et al. (2008) implement several dispatching rules in a multilayer ceramic capacitor (MLCC) production line where improvements were seen after implementing first-in, first-out (FIFO) and shortest processing time (SPT) dispatching rules obtaining reduction of 79% and 35% on production time, respectively. Another instance of DES implementation in manufacturing simulation was undertaken by Alfieri (2009) to study a multi-objective flow shop scheduling problem in a cardboard company where the daily production sequence was chosen by a tabu search based on a heuristic algorithm.

2.4.6 Simulation tools

In general, the essence of all simulation software applications is very similar. They are used for many reasons, including to improve the performance of production systems by verification of results before changes are implemented in the real system, to reduce the cost of assembly line planning, and to experiment with what-if scenarios to optimize resource allocation. Some of the widely known simulation software packages are AnyLogic, Simphony.NET, WITNESS, Plant Simulation, SIMSCRIPT, Automod, SIMUL8, and ARENA.

Simphony.NET is the software employed in this research, and this tool was developed by the University of Alberta (AbouRizk et al., 1999). Simphony.NET is an application developed for a Microsoft windows environment, and in this environment, modelling can be done two ways: using a general-purpose template, or as a special purpose simulation. The general-purpose template is a library of high-level elements that help the user develop all kinds of simulation models. The special purpose simulation is meant to represent specialized real-life problems, making the modelling task easier for users with little simulation background (AbouRizk et al, 2016).

2.4.7 Summary

In this research, a review of manufacturing systems, off-site manufacturing, scheduling problems in manufacturing and simulation has been carried out. In first instance, manufacturing is introduced and how manufacturing systems have evolved. In addition, the types of manufacturing systems are described with implementation of mass customization. Secondly, the construction industry takes some of the manufacturing techniques in the application of off-site manufacturing to minimize waste and improved efficiency by the implementation of some the on-site task in a controlled environment. Thirdly, production scheduling has been investigated constantly in recent years to optimize the allocation of limited resources within a manufacturing process, the identification and categorization of these problems are presented; the nature of how costumer needs are filled either by inventory or built for the client, the number of tasks, and the evaluation criteria are the principal variables in the definition of these problems. Lastly, simulation is introduced, and the different types of simulation are explained. DES, one of the types of simulations, has become one of the most used techniques in the evaluation of manufacturing process and the implementation of what if scenarios to improve production performance.

3 METHODOLOGY

3.1 Background

In the present research, a window and door manufacturer's production line was studied. The production of these window and door products is carried out on 10 different production lines. However, only one production line is under study because this production line is one of the largest, most complex, and busiest of all the production lines. In this chapter, the methodology used for this research will be presented.

3.2 Methodology overview

A method for using discrete event simulation is presented that has as its aim to understand and improve a production line by implementing different sequencing scenarios. In this chapter, the methodological approach, data collection, and research process are described. Figure 2 presents an overview of the proposed methodology to address the research objectives, which is divided in three parts: 1) data collection, 2) criteria, and 3) main process. In the following sections of this chapter, these three parts will be explained in more detail.

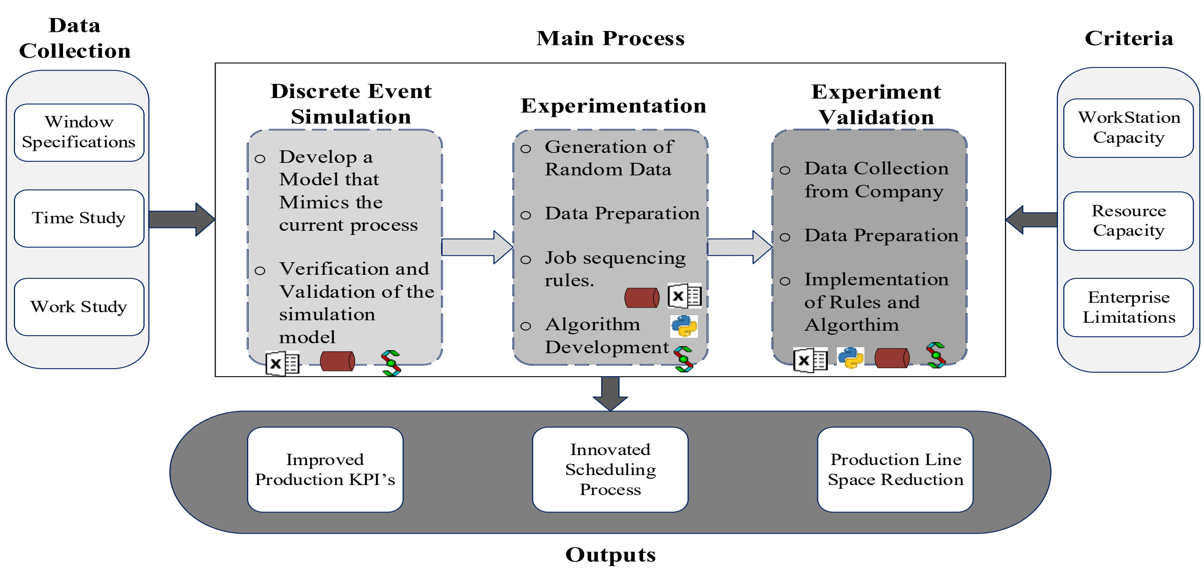

Figure 2 Research methodology

3.2.1 Data collection

3.2.1.1 Work study

Work study is a process of tracking all influencing factors involved in an operation to understand the operational elements and design a common way of performing the process. This process is often used in manufacturing systems to analyze the current state of the system. This procedure is described in section 4.1.2, where the operation was separated into individual tasks to be performed including machine tasks, variable tasks, and occasional tasks.

3.2.1.2 Time study

A time study is the technique of gathering the start to finish time of each task. In these individual tasks some time variances can be seen depending on the type of sealed unit, window configuration, size of the window, and type of components. This information is presented on section 4.2.

3.2.2 Criteria

The main process is constrained by criteria such as restricting factors, which include the workstation capacity, number of workers, equipment availability, and space.

3.2.3 Discrete event simulation

3.2.3.1 Building the simulation model

The present research implements DES to model the window production line because it mimics the actual manufacturing process given that materials are transformed only when they have passed through the workstation. In order to build the discrete event simulation, Simphony.NET is used. The process of building a simulation model involves first the abstraction and identification of the problems on the real system, in this case to test the effect of sequence changes on daily total production time. Secondly, a conceptual model is designed through the implementation of assumptions, inputs, and conditions. Lastly, the draft of the computer simulation model is carried out in the general template of Simphony.NET, implementing the information collected for the work study and the time study. In Appendix A, descriptions of the elements used from the general template are presented.

3.2.3.2 Simulation inputs

In this simulation model, elements are connected, and a flow of entities pass through these elements, and the entities represent job orders to be carried out in a day and information on the characteristics of each job order is held by each entity. In order for the simulation model to identify the entities to be produced each day, a database is created using Microsoft Access and later used by an element of Simphony.NET to load the daily production. However, in order for the simulation to mimic the real system, each element needs to behave according to the customization of the window. Therefore, there is a need to set local variables that allow the simulation model to read the characteristics of the product. A product anatomy can be seen in Figure 3. Furthermore, in Table 1, the information carried by the entities is presented.

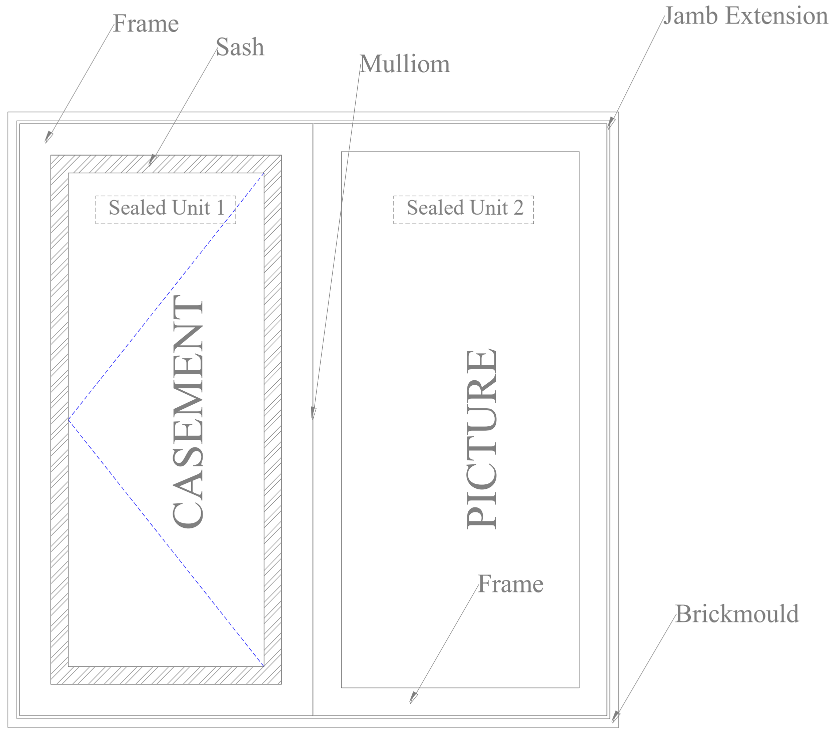

Figure 3 Window anatomy

Table 1 Local variables

Variable	Description	Notes
LX (1)	Height	Window Height in millimeters
LX (2)	Perimeter	Window Perimeter in millimeters
LX (3)	Sealed Units (SU)	Number of Sealed Units
LX (4)	Jamb Extension (JE)	Does window need Jamb? No=0;Yes=1
LX (5)	Brickmould (BM)	Does window need Brickmould? No=0;Yes=1
LX (6)	Screen	Does window need Screen? No=0;Yes=1
LX (7)	Mullion	Number of Mullions
LN (0)	JobOrder	Identification of each job order
LN (1)	Fixed (F)	Number of Fixed Sealed Units
LN (2)	Picture (P)	Number of Picture Sealed Units
LN (3)	Casement (C)	Number of Casement Sealed Units
LN (4)	Awning (A)	Number of Awning Sealed Units

3.2.3.3 Simulation validation and verification

Simulation models are abstractions of real systems, and they should be able to mimic most of the behaviours of a real system. However, simulation models do not always represent the system as intended. Therefore, it is necessary to perform validation and verification of these models.

In the present study, simulation is used to perform tests of different sequencing scenarios. Thus, the model must be validated and verified to ensure results are an accurate representation of the current state and that the results given by the simulation can be relied on to make decisions. For the verification stage, an approach suggested by AbouRizk et al. (2016) is undertaken and the following aspects are reviewed:

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

A historical validation method is used in the validation of the simulation model. The window manufacturing company uses a tracking system, where the number of windows produced and the number of labourers working are recorded for each day. With this information in hand, by simulating production for a particular day, the productivity calculated based on the data from the company's tracking system and the productivity calculated from the simulation are compared. This comparison measures the level of accuracy of the simulation.

3.2.4 <u>Experimentation</u>

3.2.4.1 Random data generation

Once the model is verified and validated, experimentation with respect to job order sequencing is carried out using random data in order to identify patterns in the performance metrics given the changes in work sequencing.

The task of generating the random data was done by following these steps:

- Historical data gathering (daily job orders)
- Calculate probability distributions for continuous components (e.g., height, width) and probabilities for discrete components (e.g., screen, brickmould, jamb extension)
- Generation of random samples (job orders)

To determine probabilities and probability distributions to be used in the generation of random job orders, data was collected from the company's daily orders. These data were summarized in an Excel file. Once the actual data was gathered, these data was categorized into two types: 1) discrete probabilities, and 2) continues distribution probabilities. In the first category, probabilities of a characteristic of a job order are taken to generate jamb extension, brickmould, screen, and number of sealed units. Regarding the second category, random deviates were generated for height and width of the windows. Once all the data is generated, a python algorithm is utilized to separate it into several days' worth of production data (i.e., job orders) and to formulate scenarios with dispatching rules.

3.2.4.2 Sequencing rules and heuristic algorithm

Sequencing rules are often referred as scheduling rules and dispatching rules. According to Panwalkar & Iskander (1977), there are several categories of these rules, such as priority, heuristic, and combinations of the two. Priority rules are built on information related to the job (e.g., processing time, number of operations). In contrast, heuristic rules involve nonmathematical aspects, such as scheduling a job in an idle time slot by visual inspection. In the present research, priority and heuristic rules are utilized to achieve the research objective.

In the present study, four priority rules are implemented in the randomly generated data to observe the performance in terms of production time, waiting times of parts in the queueing area, and space utilization of this queueing area. The priority rules used on this research, utilize the processing time and number of operations as the priorities for the rules. In addition, the rules are separated into shortest processing time (SPT) and longest processing time.

After experimentation on priority rules, a heuristic algorithm is created based on inspection of the daily orders, where the job orders are separated into small batches that are built of a mix of longest processing time, intermediate processing time, and shortest processing time. The implementation of this heuristic algorithm is further explained in section 5.4.2.2.

3.2.5 Experimentation validation

After experimentation with different priority rules and the heuristic algorithm is tested on the generated data that provides a broader range of scenarios, some performance indicators can be obtained and analyzed from these experiments. However, the generated data might not accurately represent the reality of the job orders that the manufacturing facility receives from day to day. Therefore, there is a need to validate the algorithm using daily production schedules from historical data collected from the window manufacturing company. Furthermore, this testing of the proposed scenarios using actual production data provides validation of the method used to randomly generate data.

4 DATA COLLECTION

In this chapter, the different types of data collected to carry out the methodology proposed in Chapter 3 are presented. The first type of data that was collected is a work study that is undertaken with the intent to recognize all the different processes occurring on the production line and to develop a familiarity with the manufactured products. The second type of data collection is the time study, described in Section 4.2. Once all the different manufacturing tasks were identified, information was collected regarding the start-to-finish time of each task.

4.1 Work study

4.1.1 <u>Window types and description</u>

The production line under study is referred to by the company as the “2100 Line”. On this production line, PVC windows are produced, and each window can be made of one or more units, which are referred to as “sealed units”. Furthermore, the sealed units (SU) produced on the line can be categorized into four types as represented in Figure 4. The categories are awning, casement, fixed, and picture. These SU can be further categorized into operational and non-operational.

- Awning: An operational SU that opens upwards with a hinge between the frame and the sash.
- Casement: An operational SU that opens sideways similar to a door opening, with a hinge between the frame and the sash.
- Fixed: Non-operational SU that in appearance is similar to Awning and Casement SU, because it has a sash that does not open.
- Picture: Non-operational SU, with no sash. Its appearance is slimmer than that of the fixed type because the SU does not have a sash.

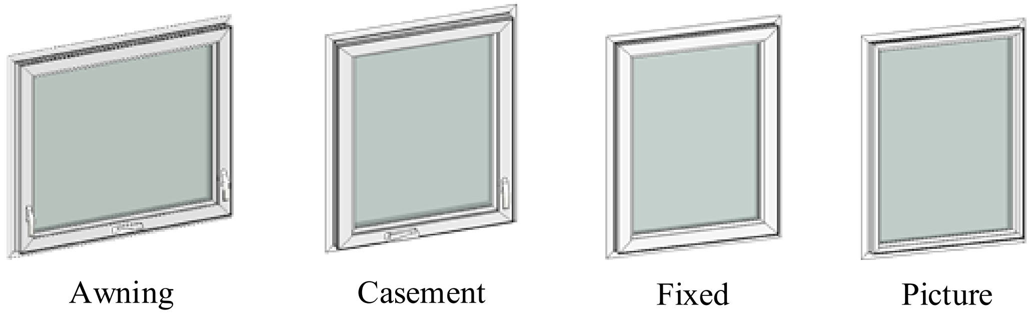

Figure 4 Types of sealed units

As previously stated, a window can be made of one or more sealed units. In Figure 5 some examples of window configurations are shown.

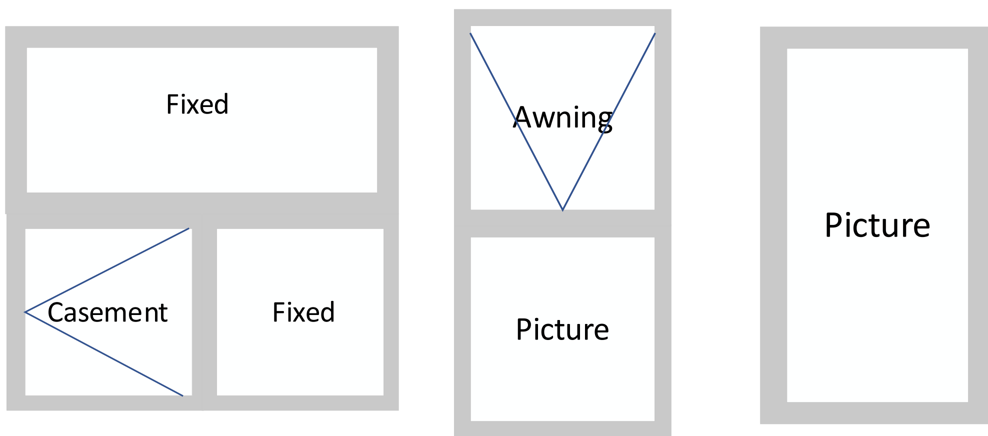

Figure 5 Window configurations

4.1.2 <u>Window manufacturing process</u>

The production line under study in this research is represented by the flowchart shown in Figure 6. The flowchart and the tasks listed in it will be further detailed later in this section.

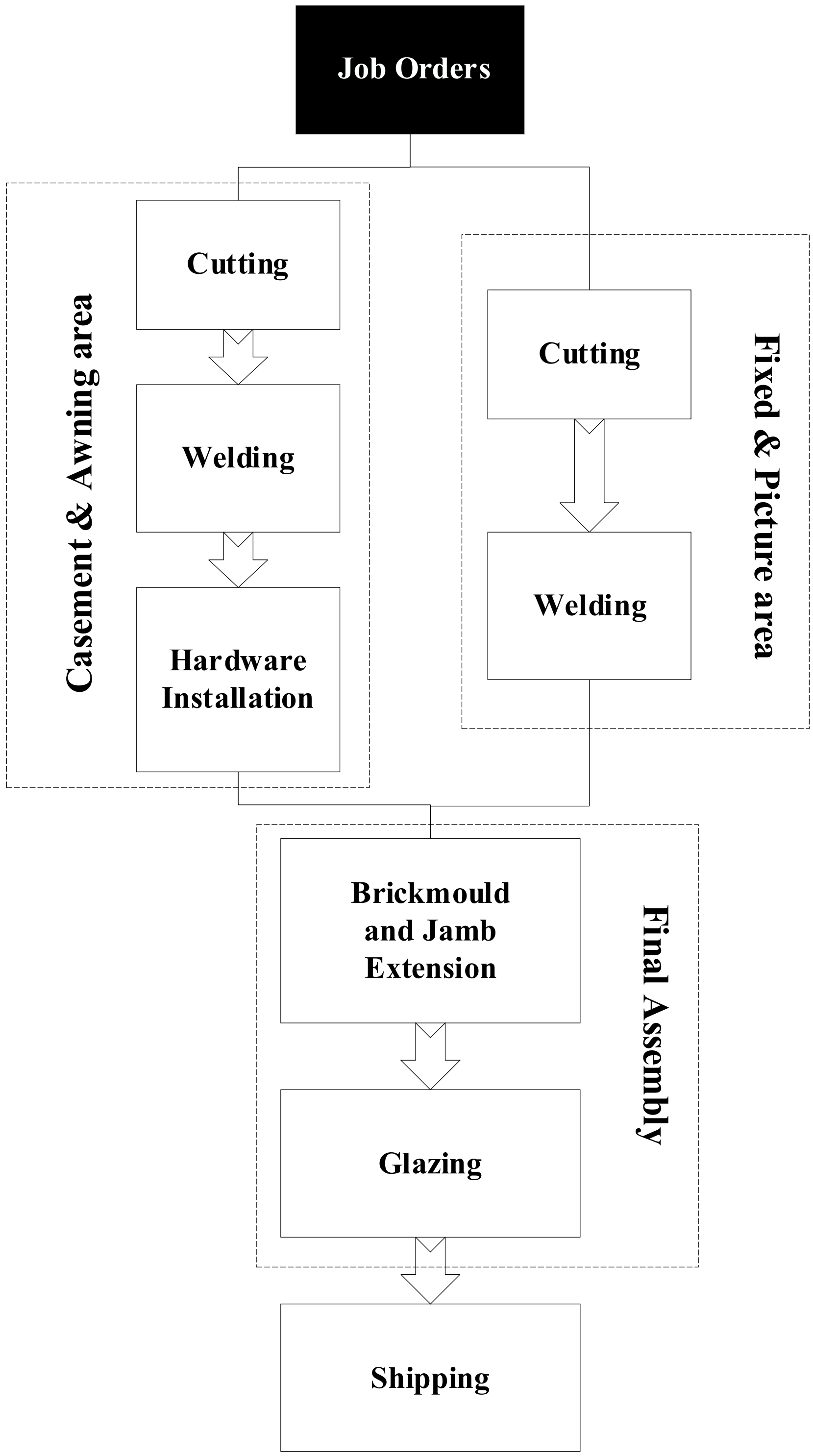

Figure 6 Production line flowchart

The 2100 Line works on a daily schedule of job orders to be produced, and these job orders are created when a customer purchases a window and it is scheduled according to capacity and deadlines. Once the sequence order is delivered to the floor, the production starts. After the production starts, each job order represents a window to be manufactured and the number of sealed units that are part of each window.

The production line is divided into two parallel lines where the operational sealed units are produced on one of the parallel lines, i.e., casement & awing area, and the non-operational sealed units are produced on the other, i.e., fixed and picture area. Once all the SU on the job order are completed, they advance to the next area, final assembly, where the sealed units are put together. After this process, the job order is ready for shipping. These areas will be explained in the next sections.

4.1.2.1 Casement and awning area

The casement and awning (C/A) area includes several stations:1) cutting station, 2) welding station, 3) automatic corner cleaning 4) manual corner cleaning, and 5) hardware installation.

1) In the cutting station, the PVC profiles are cut for the casement and awing sealed units. In Figure 7 the equipment used to cut the material is shown.

Figure 7 Cutting station

2) After the cutting station, the pieces move to the welding stations where the four sides of the frame are welded together. This process needs a worker to load the material onto the equipment, then the machine heats the plates to melt the corners in order to join the parts. In Figure 8, the equipment used in the task is shown.

Figure 8 Welding station

3) When the parts are welded together, they become the frame, and this frame has some imperfections on the welded joint. Therefore, there is a need to remove these imperfections using an automatic machine called the automatic corner cleaning (ACC) machine, as shown in Figure 9.

Figure 9 Automatic corner cleaning station (ACC)

4) Next, the frame goes to a hand corner cleaning task were a worker removes any residual welding material left by the automatic corner cleaning machine. This process can be observed in Figure 10.

Figure 10 Manual corner cleaning (MCC)

5) Lastly, hardware is installed to the frame and the sash. This hardware makes these types of sealed units operational. In addition, the hardware works as a joint between the sash and the frame. In Figure 11, a worker is shown installing the hardware, which allows the sash to open and close. After this process is completed, the parts are called a sealed unit.

Figure 11 Hardware installation

4.1.2.2 Fixed and picture area

In this area, fixed and picture (F/P) sealed units are manufactured. This is a parallel workstation to the awning and casement area, and the stations in this area include: 1) cutting station (see Figure 7); 2) welding station (see Figure 8); 3) automatic corner cleaning (ACC) (see Figure 9); and 4) manual corner cleaning (MCC) (see Figure 10). In the F/P area and the C/A area, all the tasks are the same except for the hardware installation.

4.1.2.3 Queueing Area

Once a sealed unit is completed on either of the parallel production lines, it is placed in a designated area to wait for final assembly. It is assumed that each sealed units contained in this area, holds the same space regardless of the size because they are placed in an upright position. Once all the sealed units required to complete a job order, they advance to the final assembly and removed from the queuing area. In this research, this area is referred as the queueing area, as shown in Figure 12.

Figure 12 Queueing area

4.1.2.4 Final assembly

As stated earlier, a window can be made of one or more sealed units; therefore, SU are joined together in the final assembly area if the window requires more than one sealed unit. Furthermore, at this workstation, the tasks include: 1) box-to-box joint; 2) brickmould installation; 3) jamb extension installation; 4) shipping blocks installation; 5) glazing; and 6) wrapping.

1) The first task at this workstation is the box-to-box joint, where the sealed units are merged, as shown in Figure 13. However, the box-to-box work is only done in the case where the window has more than one sealed unit.

Figure 13 Box-to-box task

2) After the first task in this area, the brickmould is installed when required by the customer.

Figure 14 Brickmould installation

3) Next is the jamb extension installation. This process is shown in Figure 15.

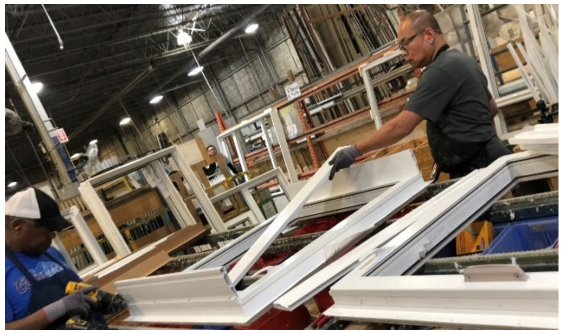

Figure 15 Jamb extension installation

4) After the jamb extension installation is terminated, protection for the purpose of shipping is installed on the window. Depending on the size of the window, the protection can be wood shipping blocks or cardboard blocks. Both processes can be seen in Figure 16.

Figure 16 Cardboard and wood shipping blocks installation

5) Lastly, the glass panels are installed (glazing) and the window is completed. Before the window is shipped to the customer, it is wrapped in plastic. These last activities are shown in Figure 17.

Figure 17 Glazing and wrapping.

4.2 Time study

The second part of the data collection process is the time study. Once the operation is broken down into tasks, the time study is performed for each workstation described in Section 4.1.2. This information is presented in Table 2.

Table 2 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 Hardware	***s***	260	242	227	243.00
Awning Hardware	***s***	228	225	231	228.00
Tie bar	**-**	**Size dependent (varies from 53 to 86 seconds) ***			
Frame and Sash Joint	***s***	82	86	87	86.50
Box-to-box Joint	***s***	149	140	145	144.67
Mullion Cover Installation	***s/mm***	0.015	0.018	0.017	0.02
Reno Brickmould	***s***	165	159	162	162.00
PVC Jamb Extension	***s/mm***	0.049	0.048	0.049	0.05
Packing (Wood + Cardboard)	***s/mm***	0.008	0.008	0.009	0.01
Glazing	***s***	141	139	143	141.00
Screen Installation	***s***	30	33	31	31.33
Wrapping	***s***	121	112	115	116.00

5 SIMULATION MODEL DEVELOPMENT AND ANALYSIS

In this chapter, the methodology presented in Chapter 3 pertaining to simulation, validation, and experimentation is implemented in the context of the window production line. Firstly, the development of the simulation model is presented. Secondly, the validation and verification of the simulation model is described. Thirdly, the results of the experimentation with the sequencing rules and the algorithm with randomly generated data are presented. Lastly, the experimentation validation is performed with historical data provided by the window manufacturing company using the same rules and algorithm tested on the randomly generated data.

5.1 Case study

The case study in this research is done in a window manufacturing company. As previously mentioned, this company has several production lines, but the production line under study is one of the most complex and busiest lines, referred to as the 2100 line. An overview of the processes was presented in Section 4.1.2. In Figure 18, the layout of the production line is shown. In addition, this illustration represents where the production begins and where it ends with the shipping.

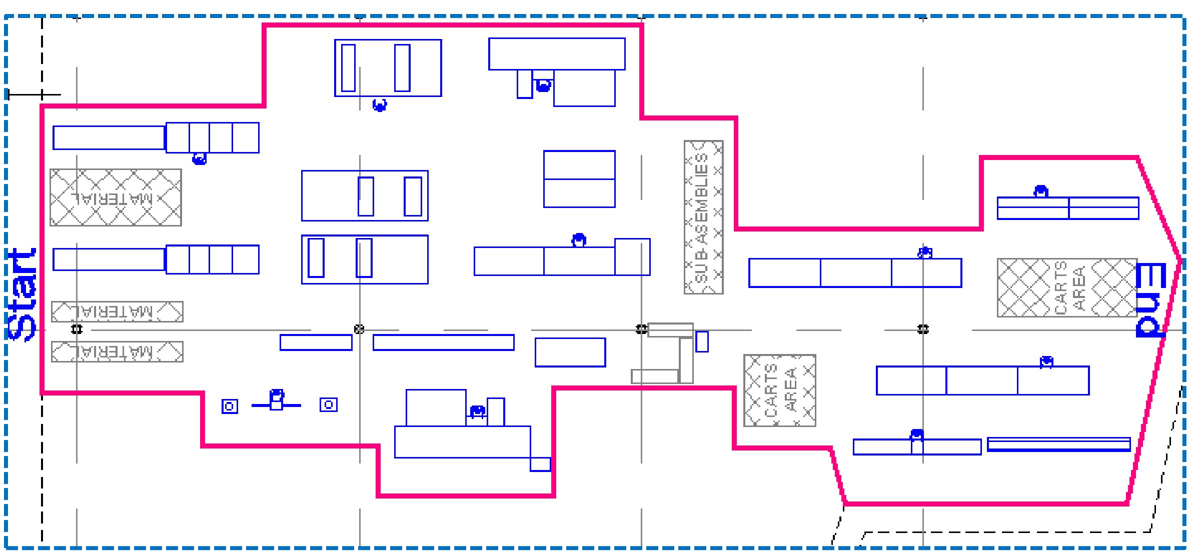

Figure 18 Production layout of 2100 line

5.2 Simulation model development.

The simulation model was designed using the sequential operations presented in Figure 6. The model elements can be seen in Figure 19. The model consists of seven composite elements: 1) resources, 2) generate orders, 3) fixed, 4) picture, 5) casement, 6) awning, and 7) final assembling.

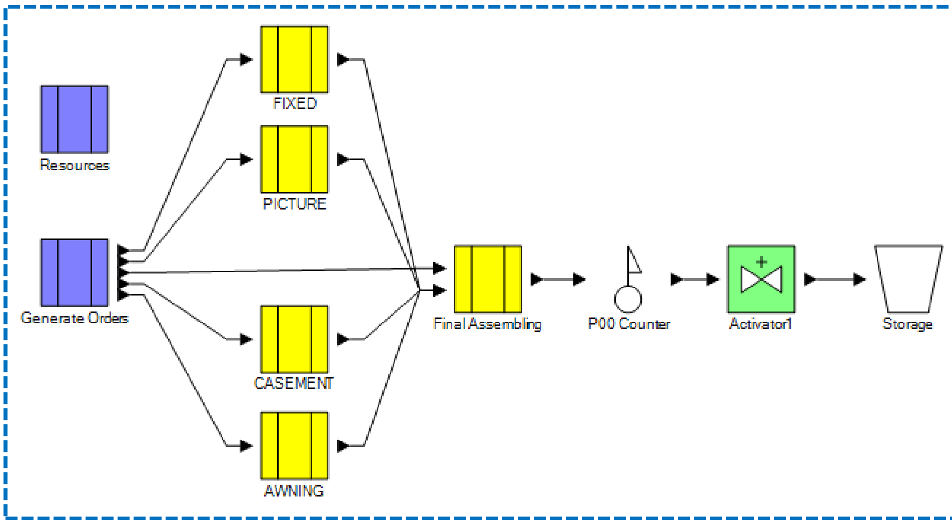

Figure 19 Simulation model layout

The resources composite element contains information on type and number of all resources used for the simulation model. In Figure 20, the resources used in the simulation model can be seen. In addition, in Appendix B, information on each resource is presented.

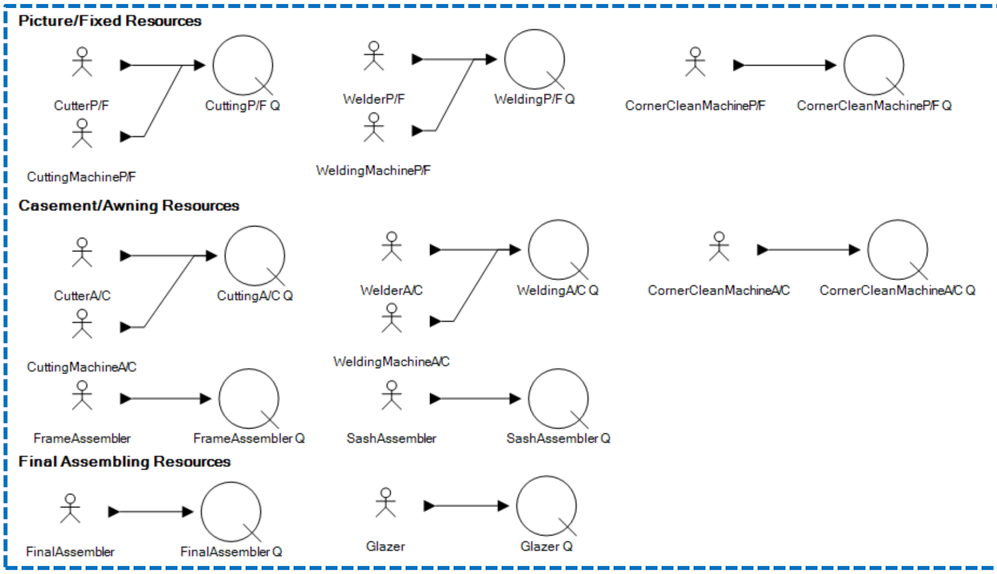

Figure 20 Resource composite

Inside the generate orders composite, several programing activities are carried out. Firstly, the database containing the job orders to be produced is read and entities are created for every window. In addition, each entity carries information pertaining to each window as described in Table 1. Secondly, each entity is divided into the number of sealed units to be manufactured. Lastly, sealed units are sent to their corresponding manufacturing line. This process is illustrated in Figure 21.

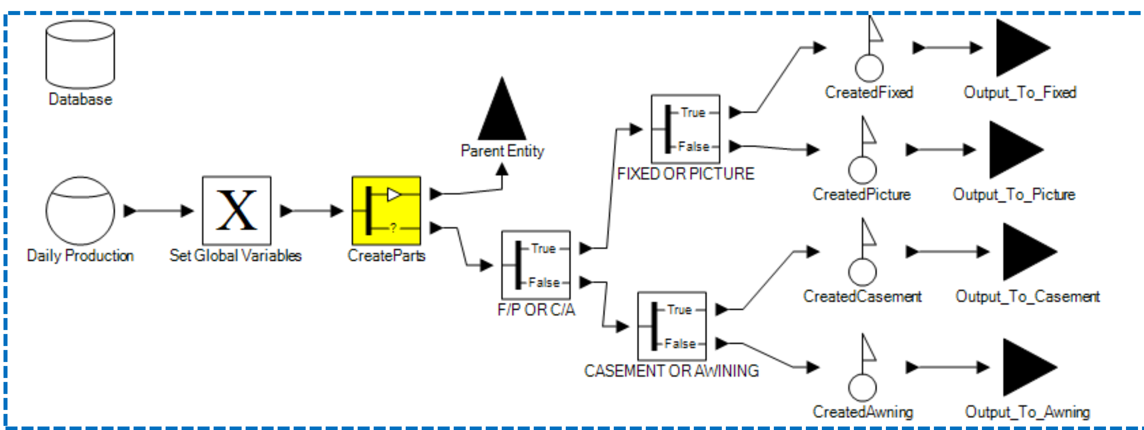

Figure 21 Generate orders composite

The fixed and picture composites contain the operations and resources described in Section 4.1.2.2. A task is complete only once an entity is generated in this area, and each entity carries its attributes that contribute to variations in processing time.

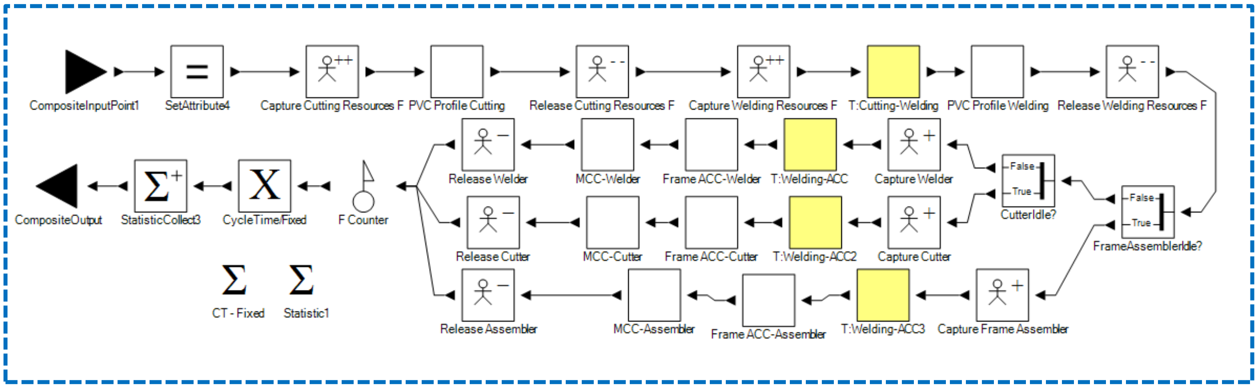

Figure 22 Fixed and picture composites

Furthermore, the operations of the casement and awning area mentioned in Section 4.1.2.1 are represented within the awning and casement composite. In this composite, the tasks are modelled and the time to process them are calculated depending on the variables of each sealed unit. Figure 23 shows the operations carried out in the awning and casement composite.

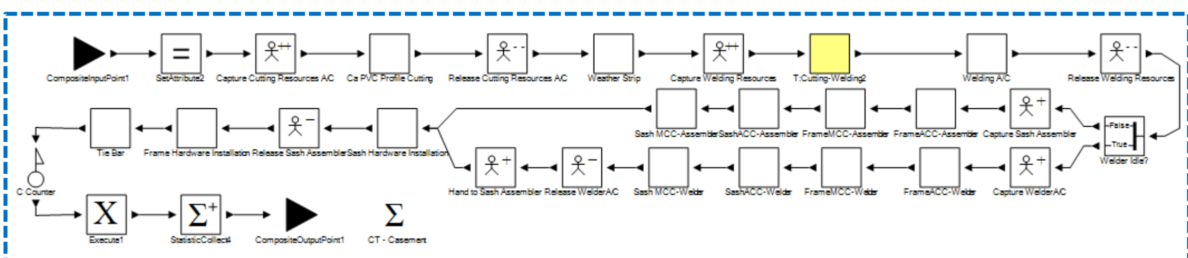

Figure 23 Awning and casement composite

The last composite of the simulation model corresponds to the final assembly mentioned in Section 4.1.2.4. In this composite, a new element of Simphony.NET is implemented where each of the waiting parts are consolidated with their counterparts, which is a process that mimics the reality where each sealed unit must be joined with other sealed units of the same job order. These tasks are shown in Figure 24.

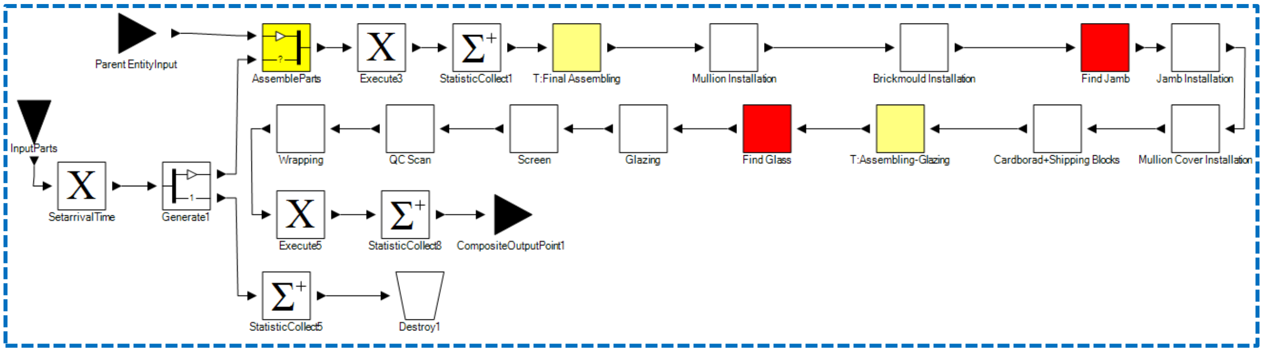

Figure 24 Final assembly composite

5.3 Simulation validation and verification

The verification process consisted of the examination and restoring of all syntax errors, data errors, experimental errors, and bugs in the model. In the next stage, the validation was carried out in accordance with some of validation techniques described by Sargent (2010). These techniques include traces, historical data validation, and extreme conditions tests.

5.3.1 <u>Traces</u>

The conceptual model validity can be determined by tracing entities. The purpose of this technique is to track entities through sub-models to determine if the logic utilized is correct. In this research, traces are utilized to determine whether the parts of each window are created and sent to the appropriate station (fixed, picture, awning, and casement), and to verify the number of entities and how they behave when they arrive to the final assembly composite. In Table 3, the daily production of March 19, 2020 is presented. Furthermore, Figure 25 shows the traces for the number of parts to be manufactured and assembled by the simulation model. By comparing Table 3 and Figure 25, it is determined that the simulation model creates the parts as expected because the parts created by the simulation model are the same as the number on the database for March 19 2020.

Table 3 March 19, 2020 daily production data

Date	Sealed Units	Windows	Fixed	Picture	Casement	Awning
19- March	251	162	22	119	81	29

Counters

Element Name	Final Count
1 CreatedFixed	22.000
2 CreatedPicture	119.000
3 CreatedCasement	81.000
4 CreatedAwning	29.000
P00 Counter	162.000

Figure 25 Screenshot of simulated production

Moreover, the traces are utilized to validate whether the simulation mimics the system when windows pass to the final assembly area as soon as all the parts of the widow are completed, and the resources are available. In Table 4, a list of 10 windows to be produced is presented and Figure 26 shows the tracing of how the windows enter the final assembly.

Table 4 Production data for tracing validation

ID	Screen	F	P	C	A	Mullion	Height	Width	Perimeter	Startseq	SU	JE	No Fin	BM
1	0	1	0	1	0	1	705	1454	4318	1	2	1	0	0
2	0	1	0	1	0	1	705	1454	4318	2	2	1	0	0
3	0	0	1	0	0	0	450	1200	3300	3	1	1	0	0
4	0	0	1	0	0	0	1500	1500	6000	4	1	1	0	0
5	0	0	1	0	1	1	1289	927	4432	5	2	1	1	1
6	0	0	0	0	1	0	813	762	3150	6	1	1	0	0
7	0	0	1	0	0	0	1800	900	5400	7	1	1	0	0
8	1	0	0	1	0	0	1500	750	4500	8	1	1	0	0
9	0	0	0	0	1	0	864	851	3430	9	1	1	0	0

10	1	0	0	1	0	0	1200	900	4200	10	1	1	0	0

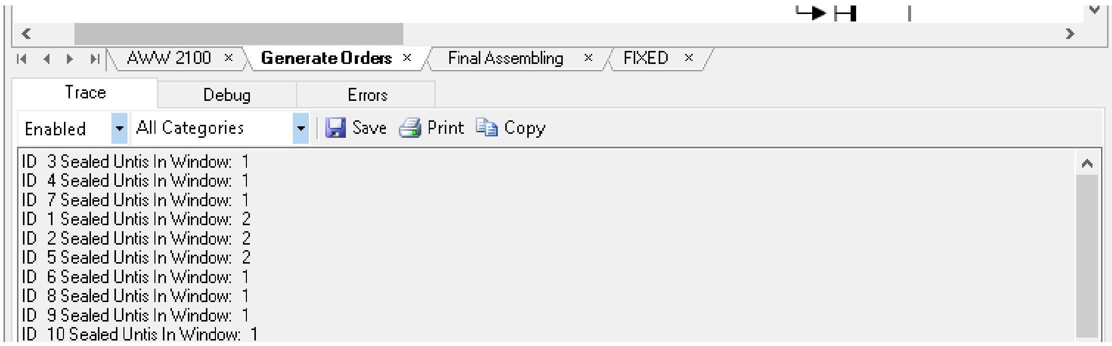

Figure 26 Screenshot of Final Assembly Production

In Figure 26, the windows with higher number of sealed units enter later in to the final assembly, which mimics what happens in the real system where windows with higher processing time of sub-parts have to wait until all seal units are finished and ready to go and be assembled at the final assembly workstation.

5.3.2 <u>Comparison to other models</u>

This type of validation compares outputs of the simulation model with previously validated models. In this study the results obtained from the simulation are compared with outputs obtained by the model developed by Paniquar de Souto (2020). The output to be compared is the productivity rate given by both models. According to Paniquar de Souto (2020), the range of productivity given by the simulation model is 1.25 to 1.42 sealed units per man hour. In Table 5, it can be observed that all the productivity rates given by the simulation model under study fall below that range obtained from Paniquar de Souto (2020) model.

5.3.3 <u>Historical data validation</u>

The historical data validation compares historical productivity and total production time of the actual production line with the same metrics for the simulated production line. The daily production data from March 16 to March 19 of 2020 were used to perform the validation. The window manufacturing company keeps track of the daily production count and the resources utilized to manufacture those windows; this information is compared with the simulation results. The validation results can be seen in Table 5. Productivity is defined in this study as the number of sealed units produced per man hour and is calculated as per Equation (1). It can be observed from Table 5 that the average difference in productivity between the two models is less than 5%, and the difference in productivity for each day was not more than 10%.

$$Productivity = \frac{Sealed\ Units\ Produced}{Total\ Production\ Time * Labourers}\ (\frac{SU}{ManHour}) \quad (1)$$

Table 5 Validation results

Date	Labourers	Sealed Units	Actual Productivity (SU/ManHr)	Simulated Productivity (SU/ManHr)	Actual Time (Hr)	Simulated Time (Hr)	Difference
19-Mar	13	137	1.405	1.397	7.5	7.543	1%
18-Mar	12	118	1.311	1.331	7.5	7.388	-1%
17-Mar	13	144	1.477	1.407	7.5	7.873	5%
16-Mar	12	130	1.444	1.341	7.5	8.08	8%
Avg							**3%**

The simulation model can be considered as having been validated because for all the validation techniques employed in the present research, the simulation model's output produced expected results and with a reasonable amount of accuracy.

5.4 Experimentation

5.4.1 Random data generation

In this section, the experimentation with the simulation model using randomly generated data is presented. The first step in this process is to gather actual job orders from the company's database. Relevant information from the dataset is shown in Table 6.

Table 6 Actual dataset

Dataset Attributes	Quantity
Job Orders (Windows)	1072
Sealed Units	1601
Fixed	201
Picture	708
Casement	552
Awning	140
Jamb Extension	992
Brickmould	281
Screen	670

Based on the information provided in the dataset, probability distributions were computed for continuous variables such as height and width. Moreover, probabilities were calculated for discrete components such as screen, brick mould, jamb extension, and number of fixed, picture, casement, and awning sealed units per window. In Table 7, the probabilities for each of the attributes are presented. Attributes with no and yes probabilities are represented by 0 and 1, respectively. In addition, the range of number of each type of sealed unit can be drawn from 0 to 3.

Table 7 Discrete attributes probabilities

Dataset Attributes	0	1	2	3
Fixed	75%	23%	1.72%	0.28%
Picture	45.24%	45.90%	7.00%	1.86%
Casement	49.91%	48.69%	1.4%	0%
Awning	75.60%	21.75%	0.65%	0%
Jamb Extension	7%	93%	-	-
Brickmould	74%	26%	-	-
Screen	77%	23%	-	-

In Table 8, the probability distributions for the height and width of each of the randomly generated windows can be seen. These probability distributions were fitted using Simphony.NET fitting software. Furthermore, in Figure 27, the likelihood of both attributes is shown as well as the theoretical distribution.

Table 8 Continuous attributes probability distributions

Dataset Attributes	Distribution	Parameter 1	Parameter 2
Height (mm)	Uniform	Minimum	Maximum
		567	1838
Width (mm)	Pearson5	Shape	Scale
		3.83	3493.88

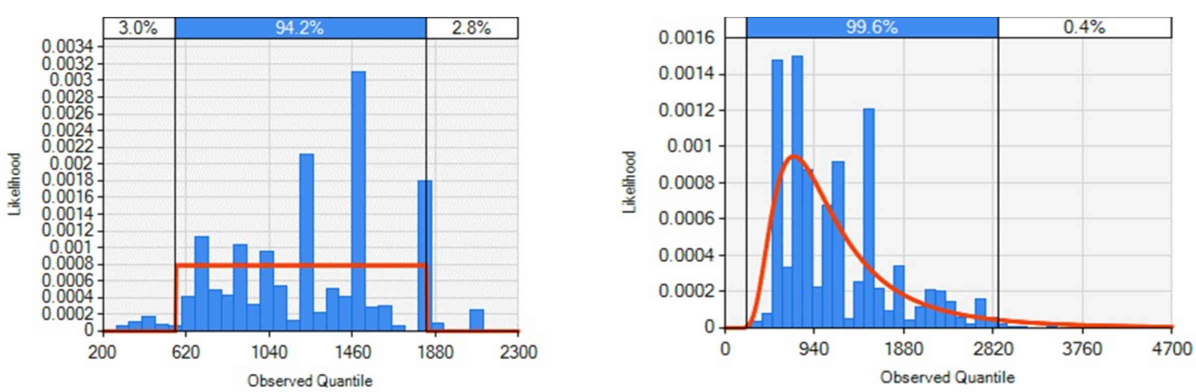

Figure 27 Height and width likelihoods

After all the probabilities were calculated, enough job orders are created to simulate 40 days of window production, and the total number of generated job orders is 6,000. However, 758 job orders are discarded because they have zero sealed units to be produced. In Table 9 and Table 10, quantities for the whole dataset and for each day of production are presented, respectively.

Table 9 Randomly generated dataset attributes

Dataset Attributes	Quantity
Job Orders (Windows)	5242
Sealed Units	9255
Fixed	1377
Picture	3590
Casement	3044
Awning	140
Jamb Extension	4901
Brickmould	1375
Screen	1212
SU/Job Order	1.765
Avg Job Orders/Day	131.05
Avg SU/Day	231.75
Std Deviation SU/Day	10.31

Table 10 Randomly generated job orders

Day	Windows	SU	Screen	F	P	C	A	JE	BM
1	139	249	33	28	117	73	31	130	33
2	138	248	33	39	102	71	36	132	26
3	128	232	33	29	90	82	31	123	40
4	129	216	36	35	74	77	30	122	35
5	125	226	26	28	88	80	30	122	29

6	138	242	31	32	96	81	33	128	45
7	125	219	32	36	74	72	37	112	38
8	123	213	26	23	89	75	26	117	34
9	124	218	26	28	86	74	30	117	35
10	137	237	31	39	90	70	38	125	33
11	139	238	38	34	95	71	38	130	43
12	132	210	23	25	79	77	29	125	37
13	134	242	34	42	95	77	28	121	36
14	128	233	29	39	90	79	25	118	35
15	134	235	26	41	80	87	27	128	30
16	135	238	25	39	100	74	25	125	28
17	127	236	31	38	80	87	31	119	37
18	127	219	35	36	83	75	25	122	37
19	135	241	32	40	88	74	39	131	34
20	132	234	35	36	92	78	28	122	34
21	127	238	25	33	99	75	31	119	29
22	130	228	37	41	86	66	35	123	31
23	121	223	36	28	99	65	31	115	28
24	131	227	21	33	76	82	36	122	30
25	130	235	35	38	90	76	31	125	42
26	134	218	36	33	86	73	26	122	31
27	129	235	33	43	93	68	31	121	43
28	132	246	24	32	113	80	21	127	27
29	130	239	23	32	90	81	36	118	36
30	135	231	33	37	86	75	33	125	41
31	127	220	39	43	87	70	20	119	36
32	131	241	30	43	89	72	37	126	41
33	129	233	23	27	108	73	25	117	28
34	137	241	27	28	90	87	36	129	30
35	127	221	31	27	83	82	29	115	29
36	132	229	30	36	92	70	31	122	25
37	126	215	25	29	68	81	37	110	35
38	140	244	26	42	95	81	26	130	33
39	130	223	22	33	75	75	40	121	42
40	135	242	41	32	97	78	35	126	39

5.4.2 Implementation of sequencing rules and algorithm

In this section, priority rules are implemented using the dataset discussed in the last section. These rules are applied to the daily production sequence to monitor the performance of the production line. Furthermore, a sequencing algorithm based on heuristic rules is presented and implemented on the dataset.

5.4.2.1 Sequencing rules

Sequencing rules are implemented on daily production based on the number and type of sealed units. Most of the time, the type of sealed unit and number of them is more significant in terms of processing time. Therefore, the rules implemented to observe the implications of sequence on performance are developed based on the criteria mentioned above. These rules are presented below and are also represented graphically. First, Figure 28 shows a graphical representation of a dataset of windows to be produced.

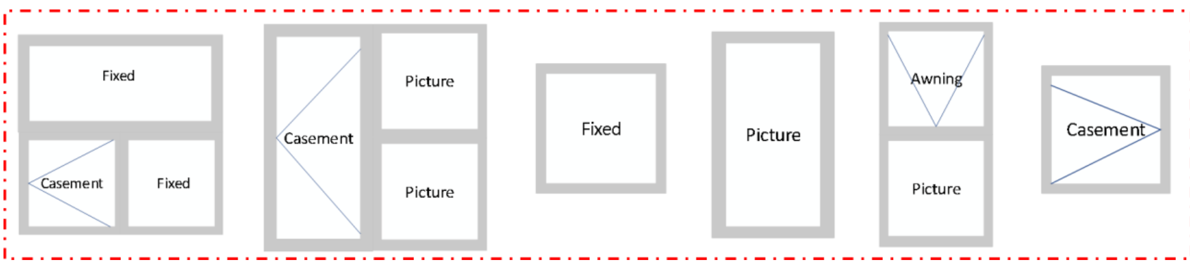

Figure 28 Example Dataset

Rule 1: Largest number of fixed SU, next largest number of picture SU, then smallest number of casement SU, and finally smallest number of awning SU. Figure 29 shows an example of Rule 1 as applied to the example dataset.

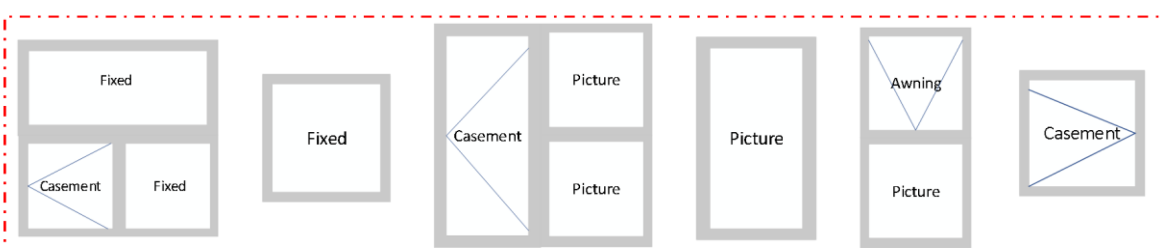

Figure 29 Rule 1 Example

Rule 2: Largest number of casement SU, next smallest number of picture SU, then largest number of awning SU, and finally largest number of fixed SU. In Figure 30, a representation of Rule 2 is presented as applied to the example dataset.

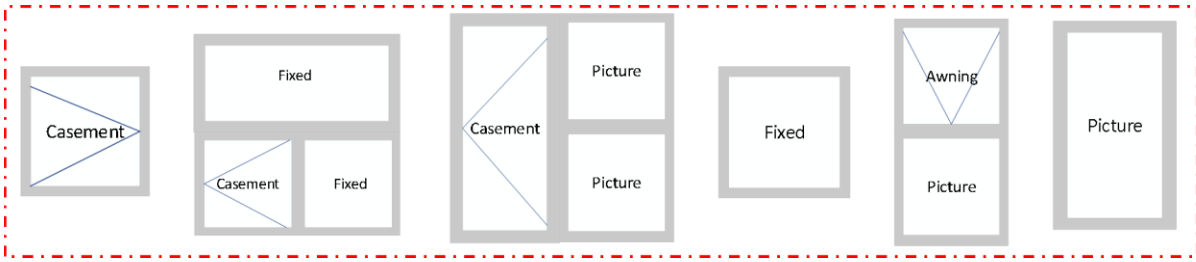

Figure 30 Rule 2 Example

Rule 3: Largest number of fixed SU, next smallest number of picture SU, then largest number of awning SU, and finally smallest number of casement SU. In Figure 31, a representation of Rule 3 is presented as applied to the example dataset.

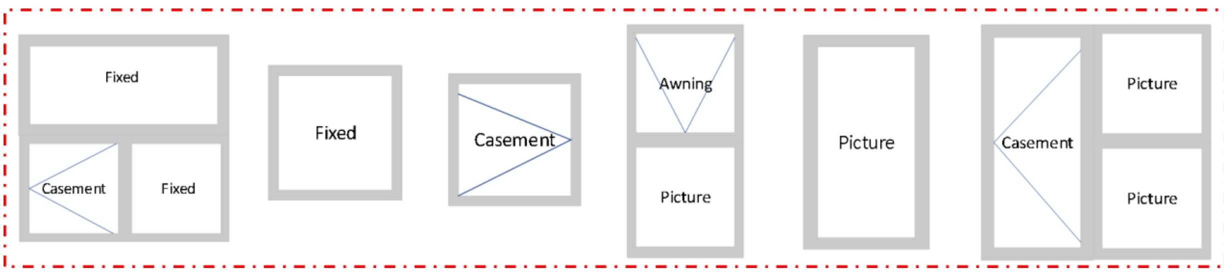

Figure 31 Rule 3 Example

Rule 4: Largest number of picture SU, next smallest number of fixed SU, then largest number of casement SU, and finally largest number of awning SU. Rule 4 is shown in Figure 32.

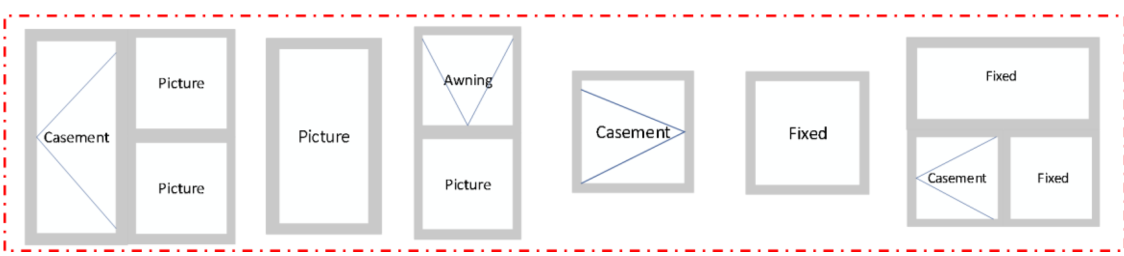

Figure 32 Rule 4 Example

5.4.2.2 Algorithm

After testing the different sequencing rules, an algorithm based on heuristics is developed. This algorithm inspects the daily job orders and parameters are calculated. These parameters are consequently utilized to separate the job orders for the day into small batches that consist of a mix of processing times and parallel manufacture. The algorithm is carried out in six steps, which are presented below.

Step 1: Identification of daily parameters

- Number of windows to be produced (TW)
- Number of windows with three or more sealed units (MW)
- Number of windows with two sealed units (DW)
- Number of single casement and awning (SCA)
- Number of single fixed and picture (SFP)

Step 2: Calculate number of batches (B)

$$B = \frac{TW}{MW}$$

Step 3: Compute number of DW per batch (DW_B)

$$DW_B = \frac{DW}{B}$$

Step 4: Compute number of SFP per batch

$$SFP_B = \frac{SFP}{B}$$

Step 5: Select number of SCA per batch

$$SCA_B \leq 1$$

Step 6: Batches are created by selecting:

- One MW
- DW_B
- SFP_B
- SCA_B

This algorithm is applied to the graphical dataset shown in Figure 28. The representation of this process can be seen in Figure 33.

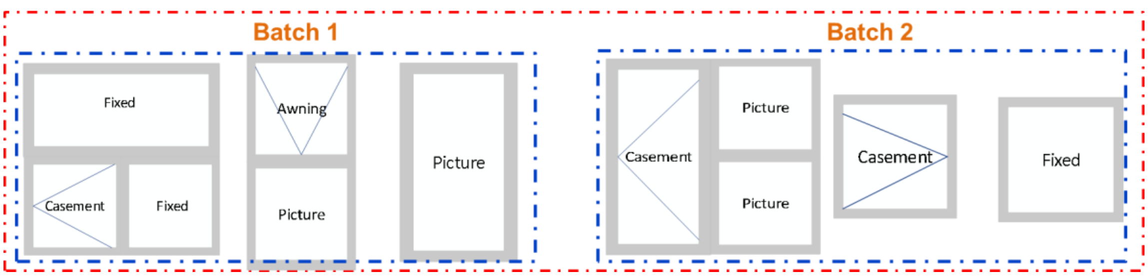

Figure 33 Batch algorithm

This algorithm was developed under the logic that the produced windows can be separated into three categories: long processing time (LPT), intermediate processing time (IPT), and short processing time (SPT). In reviewing the pool of windows to be produced for the day, the set of rules selects small batches integrating a mix of processing times and parallel activities to reduce waiting times, and idle times of resources.

5.4.2.3 Analysis of simulation results

Once the model is validated, the data is generated and the job order sequences are proposed. The next step is to utilize them as input in the simulation model. Several performance metrics are observed including the total production time, and the number of queue parts waiting for final assembly. The simulation is run using each of the 40 days of generated data.

The first performance metric to be analyzed is the total production time (TPT). In Figure 34, boxplots with TPT information can be seen. In this graph, the TPT of all 40 days are organized by rules and sequencing algorithm, and there is significant variation in average TPT from one sequencing rule to another; this variation on average accounts for 8%. In addition, Table 11 presents the statistics with respect to total production time over the 40 days' worth of simulated data. This table has four columns: max change, min change, average change, and standard deviation of change. The first column, max change represents the maximum change of TPT in a single day of production. Next, min change shows the minimum change of TPT of one day of production, and the last two columns represent the average and standard deviation of all the changes in TPT for all 40 days.

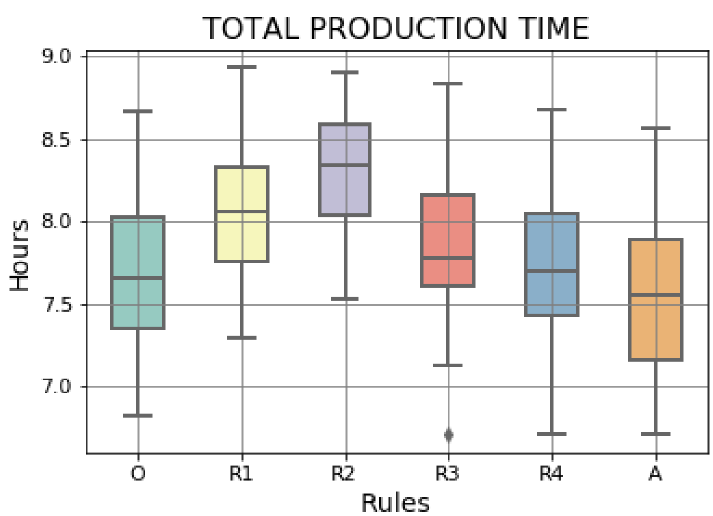

Figure 34 Total production time by dispatching rule boxplot

It can be seen from Table 11 that the variation of change on TPT ranges from 2% to 22%, meaning that the wrong sequence can lead to a 22% loss in productivity. In addition,

Table 12 shows the impact on TPT each day. From this table, it can be determined there is a relationship between the number of F/P sealed units and the impact on total production time due to order sequencing. Furthermore, these results show that a higher number of F/P SU leads to a higher impact on TPT.

Table 11 Total Production Time Statistics

	Max Change	Min Change	Average Change	Standard Deviation
TPT	22%	2%	9%	6%

Table 12 Total Production Time change by Day

Day	Windows	SU	Fix	Pic	Cas	Aw	TPT Impact
1	139	249	28	117	73	31	18%
2	138	248	39	102	71	36	13%
3	128	232	29	90	82	31	3%
4	129	216	35	74	77	30	2%
5	125	226	28	88	80	30	3%
6	138	242	32	96	81	33	7%
7	125	219	36	74	72	37	3%
8	123	213	23	89	75	26	6%
9	124	218	28	86	74	30	4%
10	137	237	39	90	70	38	7%
11	139	238	34	95	71	38	12%
12	132	210	25	79	77	29	2%
13	134	242	42	95	77	28	12%
14	128	233	39	90	79	25	11%
15	134	235	41	80	87	27	5%
16	135	238	39	100	74	25	19%
17	127	236	38	80	87	31	3%
18	127	219	36	83	75	25	9%
19	135	241	40	88	74	39	6%
20	132	234	36	92	78	28	11%
21	127	238	33	99	75	31	17%
22	130	228	41	86	66	35	11%
23	121	223	28	99	65	31	17%
24	131	227	33	76	82	36	2%
25	130	235	38	90	76	31	10%
26	134	218	33	86	73	26	7%

27	129	235	43	93	68	31	20%
28	132	246	32	113	80	21	22%
29	130	239	32	90	81	36	2%
30	135	231	37	86	75	33	6%
31	127	220	43	87	70	20	17%
32	131	241	43	89	72	37	10%
33	129	233	27	108	73	25	16%
34	137	241	28	90	87	36	4%
35	127	221	27	83	82	29	4%
36	132	229	36	92	70	31	11%
37	126	215	29	68	81	37	4%
38	140	244	42	95	81	26	13%
39	130	223	33	75	75	40	2%
40	135	242	32	97	78	35	10%

In addition to the results presented above, in Table 13, the minimum production time (MTPT) and the rule that provided the MPTP can be seen. From this table, the algorithm based on heuristic rules resulted in the best performance on 92% of the days.

Table 13 Minimum Total Production Time by Rule

Day	Production Time	Rule	Day	Production Time	Rule
1	7.44	A	**21**	7.60	O
2	7.63	A	**22**	7.17	A
3	7.93	A	**23**	6.87	A
4	7.51	A	**24**	8.28	A
5	7.75	A	**25**	7.51	A
6	8.04	A	**26**	6.99	A
7	7.66	A	**27**	7.01	A
8	7.11	A	**28**	7.16	A
9	7.30	A	**29**	8.20	A
10	7.63	A	**30**	7.61	A
11	7.70	A	**31**	6.71	R4
12	7.49	A	**32**	7.69	A
13	7.39	A	**33**	6.99	A
14	7.33	A	**34**	8.56	A
15	7.97	A	**35**	7.77	A
16	7.12	A	**36**	7.16	A
17	8.27	R1	**37**	8.23	A
18	7.12	A	**38**	7.51	A

19	7.93	A	**39**	8.07	A
20	7.45	A	**40**	7.88	A

The second performance indicator to be analyzed is the number of sealed units waiting for final assembly. In Figure 35, six boxplots are presented to show the maximum number of parts waiting each day on the queueing area(i.e., queue length) organized by sequencing rule. It can be observed that the number of parts waiting for final assembly varies significantly from one rule to another. The worst case, Rule R2, presents on average a maximum of 60 sealed units waiting for final assembly, whereas the best case scenario, heuristic algorithm (A), shows an average of 15 sealed units waiting. This represents a 400% difference in waiting area space from the best case to the worst case.

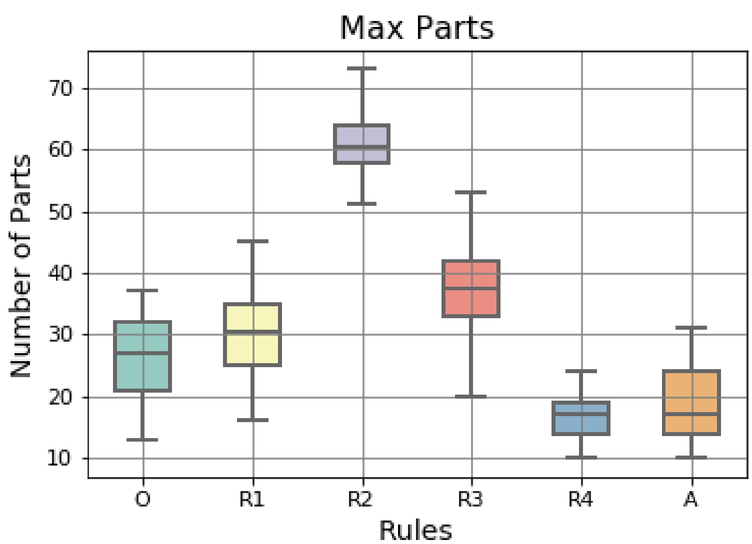

Figure 35 Queue length boxplot by rule

5.5 Experimentation validation

Once experimentation of sequencing rules is tested on randomly generated data, the trends of performance indicators need to be validated. Thus, an implementation of this experiment is applied to daily production schedules from historical data, where were collected from the window manufacturing company.

5.5.1 Input data

Data including daily production orders are gathered from historical data of the window manufacturing company. This dataset consists of 1,342 sealed units that represent 902 windows produced over a period of six days. Table 14 presents the dataset attributes, quantities for each type of sealed unit, and dataset statistics.

Table 14 Attributes and statistics from historical dataset

Dataset Attributes	Quantity
Job Orders (Windows)	902
Sealed Units	1342
Fixed	184
Picture	564
Casement	472
Awning	122
Jamb Extension	827
Brickmould	231
Screen	212
SU/Job Order	1.49
Avg Job Orders/Day	150.33
Avg SU/Day	233.67

Quantities for each day of production are presented in Table 15.

Table 15 Historical data statistics by day

Day	Windows	SU	Screen	F	P	C	A	JE	BM
1	140	190	7	37	48	94	8	140	8
2	115	214	16	23	96	86	11	81	24
3	149	241	48	65	83	74	19	93	16
4	150	228	52	19	108	86	15	101	36
5	186	223	26	17	115	51	40	180	113

6	162	251	61	22	119	81	29	136	34

5.5.2 <u>Implementation of sequencing rules and algorithm on historical data</u>

In this section, the sequencing rules and the algorithm are implemented using the historical data to analyze the impacts of the sequencing rules on production. The observed performance metrics are total production time and maximum number of sealed units waiting for final assembly. In Figure 36, the TPT is plotted for each day to identify the variations in TPT that result from changing the sequencing rule. The amount of variation in TPT can be as much as 26% from the worst case scenario to best case scenario.

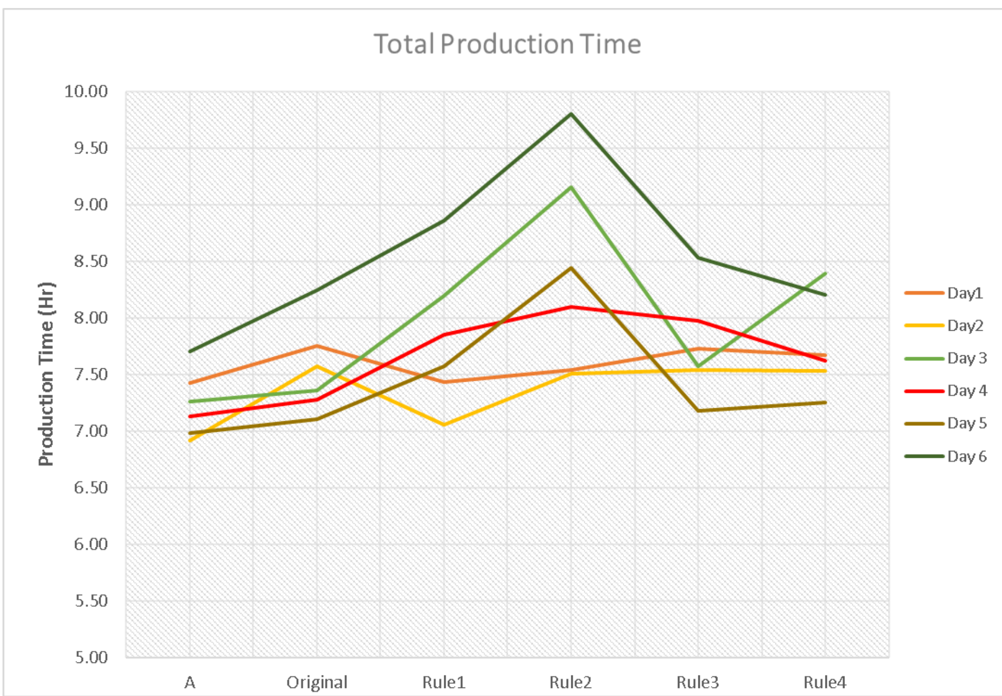

Figure 36 Total production time by rule

In Figure 37, the sum of the six TPT by sequencing rule is shown. The sequencing algorithm gives the most optimized TPT at 43 hours of total production time. Furthermore, Rule 2 provides the longest TPT at 51 hours.

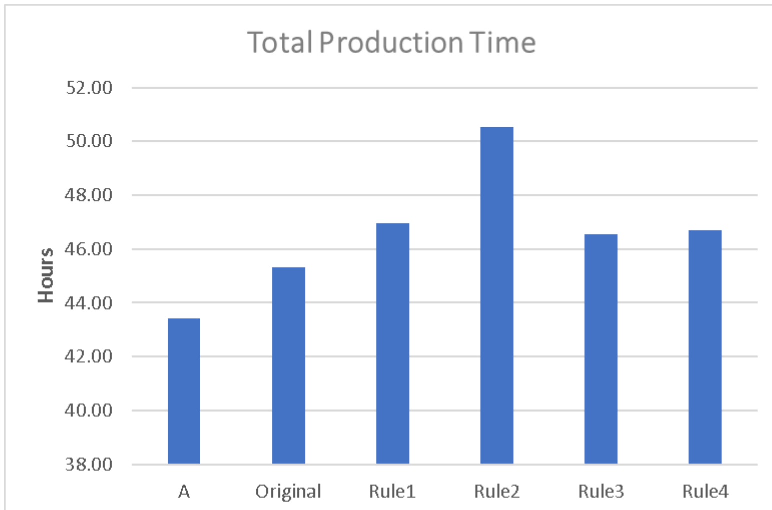

Figure 37 Sum of TPT by rule

The second metric, i.e., the maximum number of sealed units waiting for final assembly (MWFA), is represented by the graph shown in Figure 38. These graphs show the MWFA for each day and the performance for each rule. There is a variation of 6 times the space needed form the space needed on the algorithm and Rule 2.

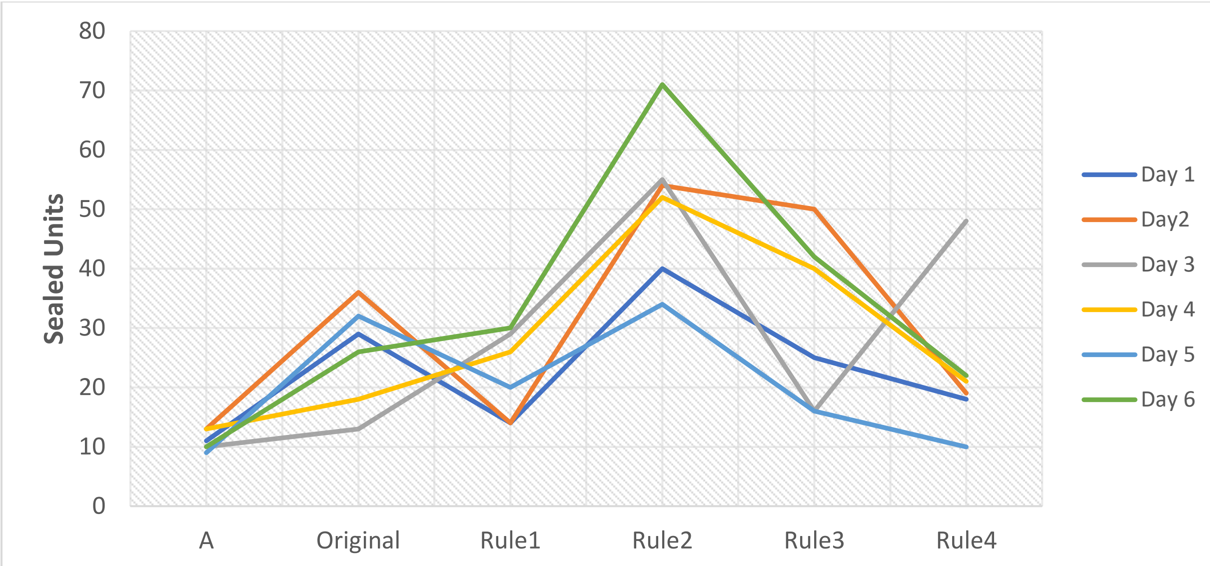

Figure 38 Maximum number SU waiting for final assembly by dispatching rule

In Table 17, a summary of results of the experimentation validation can be seen. In terms of the average over the six days, the impact on TPT of sequencing is 17% and the variation in space requirements is 370%. In addition, a result with a higher productivity and lowest total production time is considered as the best case.

Table 16 Summary of results of experimentation validation

Day	Labours	Completed Sealed Untis	Productivity (Sealed Units/ Man Hour)		Total Production Time(Hours)		Diference in total Production Time	Waiting Area for Parts (Sealed Units)		Waiting Area Space Variation
			Best Case Scenario	Worst Case Scenario	Best Case Scenario	Worst Case Scenario		Best Case Scenario	Worst Case Scenario	
1	21	190	1.22	1.17	7.42	7.75	4%	11	40	264%
2	21	251	1.47	1.35	6.92	7.57	9%	13	54	315%
3	21	223	1.58	1.25	7.26	9.15	26%	10	55	450%
4	21	228	1.52	1.34	7.13	8.10	14%	13	52	300%
5	23	241	1.39	1.15	6.99	8.44	21%	9	34	278%
6	21	214	1.55	1.22	7.70	9.80	27%	10	71	610%
AVG							17%			370%

5.6 Summary and discussion of results

In order to implement the methodology of this research, a work study and time study were carried out to understand the processes and operations on the window production line. With the information and data collected through these studies, a simulation model was developed to mimic the operations of the production line. The simulation model was verified and validated with comparisons with historical data, traces, and comparison to similar models. Historical validation showed, on average, a difference of less than 5% in productivity between the simulated results and actual data.

Once the model was validated and verified, several dispatching rules based on processing times and a heuristic algorithm were used to in an experiment to determine their effects on the production line. In order to carry out the experimentation, randomly generated data were created containing 9,255 sealed units that represent 5,242 windows and 40 days' worth of production. During this experimentation, it was found that, on average, the total production time varied by 9% and in some cases up to 22%. In addition, this experimentation showed a variation in queueing area space of almost 400%.

The experimentation on randomly generated data resulted in significant variations of the performance metrics. However, in order to have a broader perspective of the impacts of sequencing in window manufacturing, the same scenarios in terms of dispatching rules were implemented using historical data. This dataset consists of 1,342 sealed units that represent 902 windows produced over a period of six days. From this experimentation, the variation of total production time performance showed a bigger difference on average between the best to worst scenario with a variation of TPT of 17%, on average. As per the queueing area performance showed similar results on variation of space. The variation on the queueing areas was on average 370% between the best-case and the worst-case scenario.

In both experiments, using randomly generated data and using historical data, the heuristic algorithm (as described in Section 5.4.2.2) resulted in a reduced TPT and in a reduction of space for final assembly queueing area. In the first experiment using randomly generated data, the algorithm produced the shortest total production time and the smallest waiting area space requirement 92% of the time. Moreover, the performance of the heuristic algorithm showed better results in 100% of the cases.

6 CONCLUSION

6.1 Research summary

This thesis presents a framework to analyze the impacts of different job order sequencing scenarios on the performance of a window manufacturing line using a simulation model. The first step was to break down the operation into individual tasks and to carry out a time study to determine the duration of each individual task. The next step is to build a simulation model based on the information collected from the work study and the time study, and to validate the simulation with several validation techniques, including historical validation, tracing validation, and comparison to other models. The job sequencing experimentation was carried out using two types of data: randomly generated and historical data.

Various sequencing scenarios, namely four priority rules and one heuristic algorithm, were implemented to determine the impacts in terms of TPT and queueing area utilization. Furthermore, the priority rules show that total production time can vary significantly from one rule to another, and the overall performance of one rule over the others was not shown, while the implementation of a heuristic approach optimized TPT and space in the queueing area in almost all the cases. The production line under study can present variations in TPT up to 22% in the case of the randomly generated data, and up to 26% in historical data. By employing this framework, it was determined that the proposed heuristic approach to job order sequencing can improve productivity by 17% on average on the generated data and historical data.

6.2 Research contributions

This research was carried out to analyze the impacts of job sequencing on a window manufacturing line and the research, therefore, makes the following contributions:

- The sequence of window job orders can have a significant impact on total production time if different sequencing scenarios are implemented. Variations in total production time are in the range of 4% to 27%.
- The implementation of heuristic dispatching rules can improve the performance metrics of the production line without affecting the number of resources utilized or the process layout.
- The space on queueing areas can be reduced by 70% if a sequencing optimization is applied to the daily schedule.

6.3 Research limitations

This research is subject to several limitations, including:

- The processing time of the operations were fixed times and functions based on characteristics of the windows, not distributions, which is based on the assumption that the productivity of all workers is the same at all times.
- The scheduling of rework activities is not considered in the simulation model.

6.4 Future research

In the present research, the use of discrete event simulation provided insight into how sequencing patterns can affect production performance on manufacturing lines. Some areas of future research include the following:

- Implementation of more complex algorithms or algorithms based on machine learning to further optimize production and increase sequencing for longer periods, such as weekly and monthly.
- Implementation of sequencing optimization on all the remaining production lines in a facility to improve overall performance metrics.

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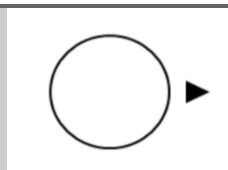
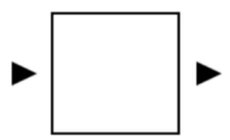
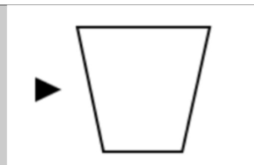
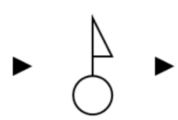
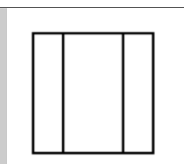
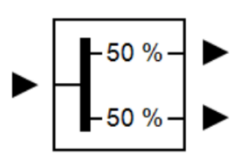
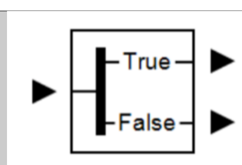
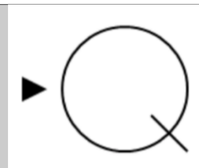
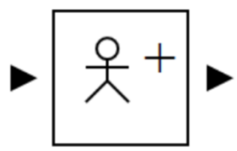
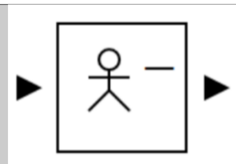
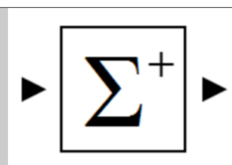
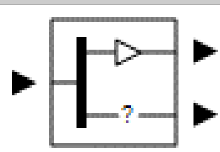
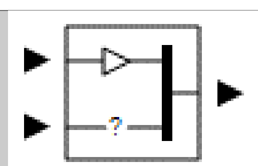
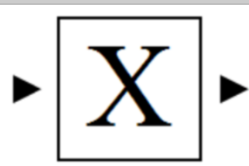
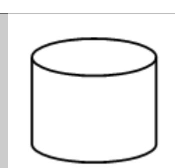
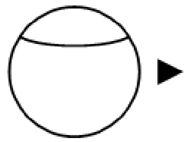
APPENDIX A

Element Name	Symbol	Description
Create		Creates and introduces entities to the simulation model
Task		Represents a process or task, entities pass through it and are contained until a determined time has past
Destroy		Eliminates an entity from the simulation model once it reaches the element
Counter		Tracks the number of entities passing through and statistics related to interarrival time, production rate
Composite		Contains elements for sub-models and it is used to keep the model neater
Probabilistic Branch		Sends entities into different paths based on the probability
Conditional Branch		Sends entities into different paths based on a true or false condition
Resource		Defines a resource

File		Provide a location where the entities wait for a resource
Capture		Captures a resource or more once an entity passes through it
Release		Release a resource or more once an entity passes through it
Statistics	Σ	Defines a custom statistic,
Statistic Collect		Gives information on a certain variable every time an entity passes through it
Generate		Creates one or more copies, depending on an entity variable of the entity passing through
Consolidate		Assembles all the entities cloned by the generate element, once all of them arrive to the element
Execute		Executes user-written code when an entity passing through
Database		Connects to a database

Database Create		Introduces entities into the simulation model with the characteristics inserted on the database

APPENDIX B

Resource Name	Workstation Area	Type
Cutter P/F	Fixed And Picture Area	Labour
Cutting Machine P/F	Fixed And Picture Area	Equipment
Welder	Fixed And Picture Area	Labour
Welding Machine	Fixed And Picture Area	Equipment
Corner Cleaning Machine	Fixed And Picture Area	Equipment
Cutter P/F	Casement and Awning Area	Labour
Cutting Machine P/F	Casement and Awning Area	Equipment
Welder	Casement and Awning Area	Labour
Welding Machine	Casement and Awning Area	Equipment
Sash Assembler	Casement and Awning Area	Labour
Frame Assembler	Casement and Awning Area	Labour
Corner Cleaning Machine	Casement and Awning Area	Equipment
Final Assembler	Final Assembly	Labour
Glazer	Final Assembly	Labour