# System State Analysis Using Value Stream Mapping, Discrete Event Simulation, and Fuzzy Logic

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Construction Engineering and Management

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# Abstract

Offsite construction (OSC) is a construction method commonly used for its benefits in improving quality, saving costs, and decreasing delivery time. Research on OSC production covers a wide range of applications, methodologies, and approaches, as attempts to optimize different aspects of any production system. However, a gap exists in the myopic approach of optimizing a production system, whereby studies focus on certain metrics that highlight a part of the system that overshadows another. This leads to suboptimal results and in some cases might lead to negative impacts on the production system. This research presents a framework to study and optimize OSC production systems on micro and macro levels. The framework is based on lean concepts and lean thinking. A case study of an OSC facility for making cabinets is used to apply and validate the framework. The research includes the application of value stream mapping (VSM) as a conceptual model to understand the current state of the system. Discrete-event simulation (DES) is used to study performance metrics on a micro level, including production lead time (PLT), production rate, station utilization, and levels of work in progress (WIP). Along with the analysis conducted to study the relationship between the different metrics evaluated, a new metric, total processing time / production lead time (TPT/PLT), is introduced as a single indicator of the overall state of the production system. TPT/PLT is analysed using fuzzy logic, since production system state is a linguistic variable. Lastly, lean interventions aimed to improve production are suggested and studied using the presented techniques to evaluate their impact on the production system, particularly with respect to certain metrics and holistically with respect to the system state. The results demonstrate that these interventions improve certain aspects of the production system; however, some lead to negative or neutral impact on the overall system state.

This highlights the importance of a having a holistic approach when optimizing production systems with the consideration of the whole and not only the parts.

## Acknowledgments

I would like to start by expressing my sincere respect and gratitude to my supervisor Dr. Farook Hamzeh for his mentorship throughout these two years, both inside and outside the classroom. You inspired me to believe in bold ideas and do what I love in the best way possible. Your valuable advice and continuous support and motivation guided me to embark on this journey and reach this milestone. It is a great honour to be your student. Thank you for everything you taught me.

I am also grateful for Ray, Steven, and Kelly for providing the information and knowledge I needed to conduct this study. They offered help whenever needed and openly shared their immense knowledge in cabinet manufacturing. Thank you for the continuous assistance.

Lastly, to my family and friends, whom I feel indebted for their abundant love and support. To my best friends Ahed, Amal, and Yara, thank you for believing in me and uplifting me whenever I feel down. A special thanks to my mother Sanaa and my brother Amin – I owe you everything.

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## List of Abbreviations

| Abbreviation | Full term |
|---|---|
| BIM | building information modelling |
| CV | coefficient of variation |
| DES | discrete-event simulation |
| DSR | design science research |
| DSS | decision-support system |
| EB | edgebander |
| LP | lean production |
| OSC | offsite construction |
| PERT | program evaluation and review technique |
| PLT | production lead time |
| SM | simulation model |
| TPT | total processing time |
| TVM | transformation-flow-value |
| VSM | value stream mapping |
| WIP | work in progress |

# Chapter 1 – Introduction

## 1.1 Background and Problem Statement

Goodier and Gibb (2007) defined offsite construction (OSC) as assembling and manufacturing building components before shipping and installing them onsite; while Smith and Quale (2017) added to the definition to include designing and planning of the components built offsite. This gave depth and range to what OSC research covers, which provides opportunity for scholars and practitioners to improve and innovate in this field. OSC has been demonstrated to be an effective construction method, especially with respect to improved quality and productivity of construction projects (Abdelhamid et al., 2008; Alvanchi et al., 2012; Gibb & Isack, 2003; Razkenari et al., 2020). Construction elements and deliverables in an OSC site are executed in a better equipped and controlled setting, which in turn gives companies a better opportunity to control operations and activities happening in their facility. The industry has embraced offsite methods and techniques, utilizing them in all aspects of construction execution ranging from structural (concrete, steel, and composite elements), mechanical, electrical, plumbing, finishing, and so on. Regardless of what component is being built offsite, scholars and practitioners are studying integration mechanisms of building information modelling (BIM), lean, sustainability, and other concepts and techniques with OSC (Jin et al., 2008). This indicates a continuous effort to improve offsite operations and production facilities which reflects on performance of construction projects and delivery efficiency (Lu, 2009; Pan et al., 2007).

The attempt to maximize value of a production system and minimize its waste is inspired by lean production (LP) (Womack et al., 2007) and falls under production system design (Ballard et al., 2001). Koskela et al. (2002) laid the groundwork for the application of lean theory in the construction industry. The transformation-flow-value (TFV) theory in viewing construction activities and operations revolutionized how production planning and control is practiced. Activities are not only treated in terms of a sequence transforming inputs to outputs (predecessors and successors), but they are also viewed from a flow standpoint where waste is eliminated in terms of waiting time, rework, work in progress (WIP), and variability. Moreover, the concept of value is also put into perspective. Activities or trades are considered internal customers; meaning that they receive work that is considered valuable from their predecessors.

Also, they deliver what their successor considers to be valuable and not what they assume is valuable. Lean theory and practices were first introduced by Toyota in the 1950s and became well-known in the automotive and manufacturing industry; however, an inadequate amount of attention is paid to the incorporation of lean and agile principles and simulation in OSC (Mostafa et al., 2016). This gives the opportunity to study the different types of application and implementation of such concepts in OSC.

Regardless of what aspect is being executed offsite or even onsite, teams always aim to control and decrease variability in their work. Variability can manifest in several forms, such as variability in production rate, task/station durations, schedule, and inventory, just to name a few. Variability is the enemy of production; it hinders performance, obscures objectives, and increases uncertainty (Deif, 2012; Goldratt & Cox, 2012; Hopp & Spearman, 2008; Thomas et al., 2002).

Tommelein et al. (1997) illustrated in a parade game the ripple effect of workflow variability in trades' activities on their succeeding trades. The game shows that variations in flow causes the project to be delayed, throughput to decrease, and waste to increase. Variability may cause resource starvation, meaning trades cannot start their work because of delays from pre-requisite activities, or it may cause high levels of WIP between activities. This concept is universal for production systems, whether a production line or a sequence of activities in a construction project. The problem of workflow variability and waste in the offsite context is also discussed in the literature. Blismas and Wakefield (2009a; 2009b) elaborated on OSC production problems such as high levels of WIP and long lead times, which are the main indicators of high workflow variability and waste. Variability has several root causes and sources that ripple in a complex fashion affecting the value stream of a production system. As the implications of variability in OSC are very well studied, the approach adopted for tackling them and optimizing a production system is still inadequate to reflect the true state of the system. Studies have a myopic approach, where they focus on limited areas of improvement, reflected by metrics, without considering the holistic state of the production system studied. The effort put into optimizing parts of a production system in turn leads to sub-optimal results (Koskela et al., 2002).

This research falls under production system design in OSC. The research is inspired by lean theory in production and includes the application of several lean tools and techniques based on lean thinking, along with simulation and fuzzy analysis, to assess and improve the state of the OSC production system investigated. The novelty of this study lies in its objectives: it attempts to provide a holistic perspective on the state of a production system based on several metrics and their relationships, combination of tools and techniques, and a unique model developed for production system assessment. The model is initially used to assess the current state of a production system, then used to study the impact of several lean interventions aimed to improve the production system state. The case study investigates an offsite cabinet manufacturing facility that supplies cabinets to construction sites for installation.

## 1.2 Research Questions

To tackle the aforementioned research problem, two research questions are stated:

1. How can a state of an offsite production system be assessed in a holistic manner?
2. How can lean concepts and tools be utilized to improve offsite production system as a whole rather than its parts?

## 1.3 Expected Contributions

### 1.3.1 Academic contributions

- Developing a framework to evaluate and improve the state of offsite production systems using fuzzy analysis, simulation (Monte Carlo and discrete-event simulation), and value stream mapping (VSM).
- Implementing a door-to-door holistic lean approach for system state assessment taking into consideration value and flow perspectives in production and not only production rate (transformational).

### 1.3.2 Industrial contributions

- Providing valuable knowledge about station performance and production performance including cycle times and production rates, detailed motion studies, local production problems, and material counts.
- Developing a practical decision-support system (DSS) that can be used by the management team to assess waste generation and system state of their production system.

- Providing qualitative and quantitative analysis on the current state of the production system and suggesting lean interventions that were demonstrated to improve production and efficiency.

## 1.4 Research Methodology

Design science research (DSR) is adopted as a research methodology for this study. The purpose of using DSR is to establish scientific solutions for practical problems (Holmstrom et al., 2009); this methodology links theory to practice (Rocha et al., 2012). DSR is used in many research domains such as information systems (Hevner, 2007; Hevner et al., 2004; March & Smith, 1995; Vaishnavi, 2007) and operation management (Van Aken et al., 2016). It also suits construction management research, since it facilitates the ideation and execution of practical solutions addressing real-world problems and is based on scientific reasoning (Rocha et al., 2012).

Conducting a DSR methodology consists of three essential steps: (1) identifying the problem, (2) designing a solution or artefact, and (3) evaluating the solution.

### 1.4.1 Problem identification

With the attempt to reduce and eliminate variability in production systems, researchers tend to use a myopic lens in their approach; for example, the link of variability decrease to one objective function such as throughput. This approach has led to sub-optimal results, since many important measures and factors of a production system are overshadowed. The problem of variability in production is very well addressed in the literature and in practice, in which its effects and repercussions are studied and analyzed thoroughly. However, very little research has addressed variability with a holistic approach taking into consideration the state of the production system and not only parts of it.

### 1.4.2 Developing an artefact

Designing the artefact includes the methods, tools, and models developed to tackle the problem (Hevner et al., 2004). In this study, the solution developed to address a problem is grounded in lean theory in production. This approach is based on a lean perspective of what is considered wasteful and what is considered valuable in a production system. Moreover, the solution aims to understand the impact of reducing variability on the state of a production system as a whole rather than the parts.

Figure 1 illustrates the research framework adopted in this study to achieve the research objectives stated. The first phase includes assessing the current state of the production system. The first step is collecting data available using different collection methods, such as ethnographic study, interviews, time and motion studies, shop floor observations and part counting, video surveillance, and exploration of company's database. This step is paramount in understanding the process at a high level of detail, which allows choosing an appropriate level of abstraction to achieve the study's objectives. The second step is creating a value stream map of the production line. This step includes preliminary state evaluation in terms of inventory between stations, station cycle time, station uptime, and changeover time. Along with the production workflow and station sequencing, these metrics should be validated to ensure that the value stream represents reality. The third step is building a simulation model to better evaluate the production line in terms of WIP between stations, station utilization, production lead time (PLT), and throughput.

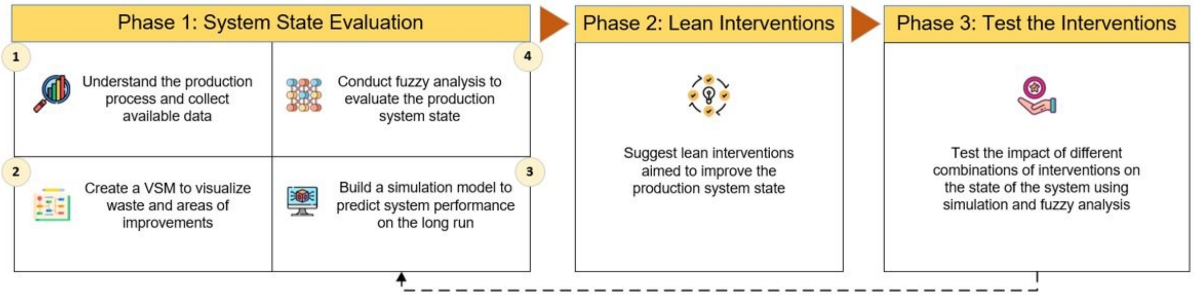


**Figure 1:** Research framework

The model is verified and validated using several techniques such as face validity, event validity, and internal validity. After that, the results are analyzed and used in the fourth step, which is fuzzy analysis. Fuzzy analysis is used to account for subjectivity in assessing the production system state. From the results of the simulation model, data is extracted to be used in a fuzzy environment where terms describing the production state and membership functions are defined. After assessing the production system, several lean interventions that aim to improve the production state are suggested in phase 2, based on the problems detected in phase one. In phase 3, lean interventions are modelled and analyzed using simulation and fuzzy analysis, the results of re-assessing the production system after these interventions are compared with the current state. The effect of these interventions would reflect the system as a whole rather than specific stations or metrics. This helps give a wider picture about the effects of these interventions on variability and also on several key metrics evaluated.

### 1.4.3 Evaluation

The evaluation of the framework is performed using data from a real-world OSC facility that manufactures cabinets for construction projects. The evaluation includes the implementation of all phases of the framework and a feedback cycle from the company's management to better refine the framework to achieve research and industrial goals. The feedback cycle was in the form of periodic presentations to the company to better achieve the research and industrial goals.

## 1.5 Organization of Thesis

This thesis includes eight chapters structured as follows: Chapter 2 presents a literature review on LP, VSM, simulation, and fuzzy logic in construction. Chapter 3 introduces the case study investigated in this study. Chapter 4 explains how the value stream map was created for the shop floor to gain insights on how much waste exists in the system. Chapter 5 elaborates on how the discrete-event simulation (DES) model was built, verified, and validated. The chapter also presents the results obtained from the model. Chapter 6 introduces a novel metric, TPT/PLT, and explains how it is used in a fuzzy environment. Chapter 7 states all the interventions suggested and discusses their simulation results in the simulation model (SM) and the fuzzy model. Lastly, chapter 8 concludes with a summary and overall conclusion, along with stating the model limitations and recommendations for future research.

# Chapter 2 – Literature Review

## 2.1 Introduction

Research on OSC covers a wide range of topics. This thesis focuses on production system design in OSC settings. It includes the application of DES, VSM, and fuzzy logic to optimize an OSC production line. Thus, this chapter presents an extensive literature review on the application of the aforementioned techniques in the construction industry, OSC in particular. Since this research is based on lean thinking and includes lean tools and techniques, studies on LP in OSC are also covered in this chapter. The literature review showcases a wide range of gaps filled throughout the years of research done on OSC. However, none of the studies cover the combination of all the tools and techniques presented in this thesis. Moreover, a gap in the optimization approach has been found from the research done. The lack includes the myopic approach most studies adopt to optimize parts of a production system without considering the holistic state of it. This chapter gives an overview of the application of these techniques in the OSC industry.

## 2.2 Lean Production (LP)

LP is a paradigm shift that has altered the way production is approached (Meyer & Waddell, 2007). It has been increasingly adopted as companies are recognizing the positive impacts and benefits of LP (Jasti & Kodali, 2015; Marodin & Saurin, 2013). Imtiaz and Ibrahim (2007) found a positive correlation between LP and operational performance demonstrating the positive impact of LP on production systems. Abreu-Ledón et al. (2018) conducted a meta-analytic study to define the link between business performance and LP. They found that LP positively impacts business performance on an aggregate level. Originating from the automotive industry, LP expanded to other manufacturing sectors, reaching service operations and processes (Holweg, 2007). Construction is not an exception, for neither onsite nor offsite operations. Inspired by LP, Koskela (1992) introduced lean theory to the construction industry as a new production philosophy. Koskela et al. (2002) explained how the TFV theory, proposed by Koskela (2000), serves as a basis for lean construction and project delivery. Looking to offsite construction, LP has been widely adopted for its impact on production systems. Marte Gómez et al. (2021) found an increasing trend in adopting lean construction, BIM, and offsite processes in the UK construction industry. They found that the impact of implementing BIM and lean construction in offsite construction facilities lead to waste, time, and cost reduction. Moreover, when implemented fittingly, these approaches increase workflow efficiency and quality. Yu et al. (2013) showcased an implementation case study of LP in a modular construction company. Tools and techniques such as VSM, 5S (sort, set in order, shine, standardize, and sustain), takt time planning, and other methods reduced labour cost and hours, overtime, and takt time. Moreover, labour efficiency and number of orders increased as a result of a six-month effort to implement lean principles and techniques. Goh and Goh (2019) also presented a LP transformation case study in a modular construction site in Singapore. Their study included the application of data encryption standard (DES) along with lean techniques such as VSM, total quality management (TQM), E-Kanban, and just-in-time/JIT. Cycle times, process times, and WIP levels were significantly reduced; moreover, resource utilization rates, process efficiency, and labour productivity were improved. Spisakova and Kozlovska (2019) investigated the benefits of applying LP principles to a Slovak offsite construction company. They found that a proper implementation can lead to up to 50% reduction in labour hours, machinery and equipment cost, workspace, and production mistakes.

Lean philosophy underlies the apparent success of LP implementation. Inspired by the 4P model developed by Liker (2004), Meiling et al. (2012) highlighted the importance of people, processes, and philosophy for adopting LP and continuous improvement in offsite construction. The approach in this study focusses not only on process improvement, but it also takes into account cultural and social factors that are principals in lean transformation and sustainable LP.

### 2.3 Value Stream Mapping (VSM)

VSM is a lean technique used to visualize production and design flow of a production process. Rother and Shook (2003) explained fundamental concepts behind using the tool, highlighting the importance of optimizing the whole rather than individual processes. Lasa et al. (2008) evaluated VSM as a tool and found that it is effective in production system design. They highlighted key success factors such as the use of appropriate information systems, adequate training resources, and proper management of implementation steps. Braglia et al. (2006) stated that VSM is essential when implementing LP. They highlighted several advantages of using VSM, such as visualization of material and information flow, information display related to production time and inventory levels, and linking production process to the whole supply chain. VSM is widely used in the manufacturing (McDonald et al., 2002; Rahani & Al-Ashraf, 2012; Vinodh et al., 2010) and construction (Espinoza et al., 2021; Germano et al., 2017; Pasqualini & Zawislak, 2005) industries to assess and improve production. In the context of offsite construction**,** Zhang et al. (2020) proposed a process-oriented framework using VSM and production line breakdown structure. Their framework was assessed on a modular construction production line and demonstrated to improve production by decreasing lead time by 20% and saving 15% of total-work hours. El Sakka et al. (2016) used VSM as a lean tool to investigate a modular construction fabrication process. Their study included the development of a current state map to visualize the current process, and it proposed improvements using lean principles summarized in a future state map. The recommended future state map showed a reduction of 50.6% in lead time and was expected to improve safety and cost efficiency when implemented. Heravi and Firoozi (2017) investigated the application of VSM on a prefabricated steel frame production line. The tool was used to identify waste and the root causes, through examination of the current state map. Lean improvements were proposed using a future state map and modelled using a discrete-event simulation (DES) model; lead time and production costs were decreased by 34% and 16%, respectively. Masood et al. (2017) used VSM on an offsite manufacturing supply chain for structural framing for cold-formed steel houses. They utilized VSM to assess the current state and point out potential improvement opportunities. Björnfot et al. (2011) applied VSM to visualize the flow of three different production lines in three different offsite construction companies: patio door manufacturing, interior wall manufacturing, and kitchen cabinet assembly. They highlighted the importance of cultural changes necessary to ensure proper application of VSM and adoption of lean. In short, VSM can be utilized in different contexts and serves as an effective tool to tackle waste in production. It helps in visualizing production and information flow, which in turn helps in identifying opportunities for improvement and waste elimination.

### 2.4 Simulation

Construction simulation is a powerful tool to design and analyze construction processes and understand the behaviour of construction systems (AbouRizk, 2010). Simulation has been widely used to analyze and improve onsite (Birgissson, 2009; Smith, 1998; Smith et al., 1995) and offsite (Hamdan et al., 2015; Barkokebas et al., 2020; Altaf et al., 2014) construction operations.

Sacks et al. (2007) utilized DES to demonstrate significant potential in improving cashflow, production rate, and delivery time using lean principles and techniques in a highrise building project. Tommelein (1997) used DES to model lean construction concepts such as push versus pull, waste, uncertainty, and flow in offsite and onsite construction processes. Alvanchi et al. (2012) used Simphony.NET to simulate an offsite steel construction process and capture conflicts between the fabrication and erection phases of a bridge construction project. Their utilization of DES facilitated analysis of several fabrication plans and the detection of a potential 10% reduction in total project time. Mostafa and Chileshe (2015) used DES to simulate an offsite house manufacturing supply chain from order receival to house delivery. The DES models helped increase the effectiveness of the entire process by validating improvements in site preparation duration, manufacturing duration, and total delivery duration. Wang et al. (2018) used DES to optimize an offsite construction delivery schedule, which resulted in 90% of deliveries being on time and saving an average of 40 minutes in daily activities. Velarde et al. (2009) used DES to study the impact of lean techniques and tools aiming to improve a housing offsite construction facility. Their results showed potential improvement of up to 40% in production and reduction in labour operational costs. Hamdan et al. (2015) proposed a framework that incorporates BIM with DES to model and improve inventory in an offsite construction facility. Their model promises improvements in inventory planning, sizing, and costing. Martinez et al. (2020) used DES to study different wood framing support system designs for machinery in an offsite construction facility. In their work, DES helped study the cost, constructability, and performance based on different design parameters, and the model helped develop a design that is 10% more productive and costs 40% less than the current systems. They modelled a pipe-stool design and installation process and concrete batching and placing process to demonstrate the power of DES in improving and making processes leaner. Afifi et al. (2020) utilized DES and continuous simulation to model lean improvements in a single-door assembly line for an offsite construction facility. Their model was used to assess the current assembly line and study the impact of suggested improvements. Their proposed amendments promise significant improvements in overall productivity and worker utilization. Mohsen et al. (2021) investigated a cabinet offsite manufacturing facility using DES to understand and improve the production rate and station utilization of the production line. Thus simulation, when applied effectively and correctly, provides a dynamic tool that helps companies to analyze and study the impact of changes and improvements proactively before investing money. In the present study, DES is used to analyze the current production system of an offsite construction facility and examine the impacts lean improvements on the production state.

## 2.5 Fuzzy Logic

Fuzzy logic systems have a wide range of application in the construction industry, especially in construction management and engineering; they serve as powerful tools that aid decision-making (Fayek & Lourenzutti, 2018; Plebankiewicz et al. 2021). Fuzzy logic has been used in analyzing construction CPM schedules (Chanas & Zielinski, 2001; Chen & Hsueh, 2008, Kumar & Kaur, 2010), risk management and evaluation (Zheng & Ng, 2005; Zolfaghari & Mousavi, 2018), and prediction of cost overruns (Dikmen et al., 2007; Knight & Fayek, 2002; Pham et al., 2020). Zhang et al. (2003) applied fuzzy logic to DES in tackling uncertainty in construction resource quantities and activity durations. Their fuzzy simulation system helped demonstrate that flexible resource demand has positive impact on productivity. Abbasnia et al. (2008) used fuzzy logic to solve time-cost trade-off problems in construction.

Fuzzy logic is also utilized in the OSC field. Arashpour et al. (2018) used fuzzy TOPSIS to develop a framework for processing integration optimization in OSC to balance the utilization of multi-skilled resources. Looby et al. (2021) used fuzzy logic to perceive uncertainty related to offsite prefabrication applications in the UK construction industry. The perception of uncertainty was based on uptake, impression, and strategy; their research implied that culture and negative impressions form the main barriers to the uptake of offsite prefabrication in the UK construction industry. Li et al. (2013) used fuzzy-AHP to rank risk factors related to modular construction, along with simulation, to assess the cost and duration impact of these factors on projects. Shams Bidhendi et al. (2019) used fuzzy-based ANP to define weighting for different metrics in a modular construction company. Their adopted methodology helped clarify the overall leanness score of the production facility. Fuzzy logic has proven to be a powerful and compatible technique when integrated with other tools and methodologies. This research uses fuzzy logic along with simulation and lean tools to better assess the overall state of OSC production systems.

## 2.6 Conclusions

This chapter presented a literature review on the topics included in this study. Since this research is based on lean thinking and uses several tools and techniques, such as VSM, simulation, and fuzzy logic, this chapter covers the aforementioned topics. The chapter started with studies on the importance of LP and its application in the OSC industry. Moreover, it covered studies on VSM showcasing the power of this lean tool in production system design and its power to help in understanding what is wasteful and what is valuable in any production system. Furthermore, studies on simulation and the application of DES in OSC along with other techniques also were presented to demonstrate the usefulness of the tool in production optimization. Lastly, the chapter elaborates on the application of fuzzy logic in the construction industry. From the literature review, a gap was found in the OSC industry, since there is no research that tries to cover the research questions stated in this study. Moreover, none of them combine all three tools in any application. Chapter 3 introduces the case study investigated in which all the mentioned tools and techniques were applied.

# Chapter 3 – Case Study

## 3.1 Introduction

The OSC facility taken as a case study for the framework implementation is an Edmonton-based cabinet manufacturing company that supplies cabinets to construction projects. It is recognized as one of the largest millwork providers in Western Canada; offering cabinet products, custom cabinets, kitchen renovations, cabinet doors, and more. The company is heavily involved with construction projects and builders as clients to produce, assemble, and install cabinets as part of the finishing phase of their projects. The cabinet crew on-site plays a critical role in the project, since any delay in assembly may lead to delays in project delivery schedules and succeeding finishing trades. This chapter explains in detail the work structure of the company, the manufacturing processes for producing a cabinet, and the data sources used to conduct the study.

The information flow from design to manufacturing is represented in Figure 2. These milestones describe the workflow structure from design to manufacturing. The study focuses on production control and manufacturing processes. Everything that takes place before and after these two milestones is outside of the scope of this study.

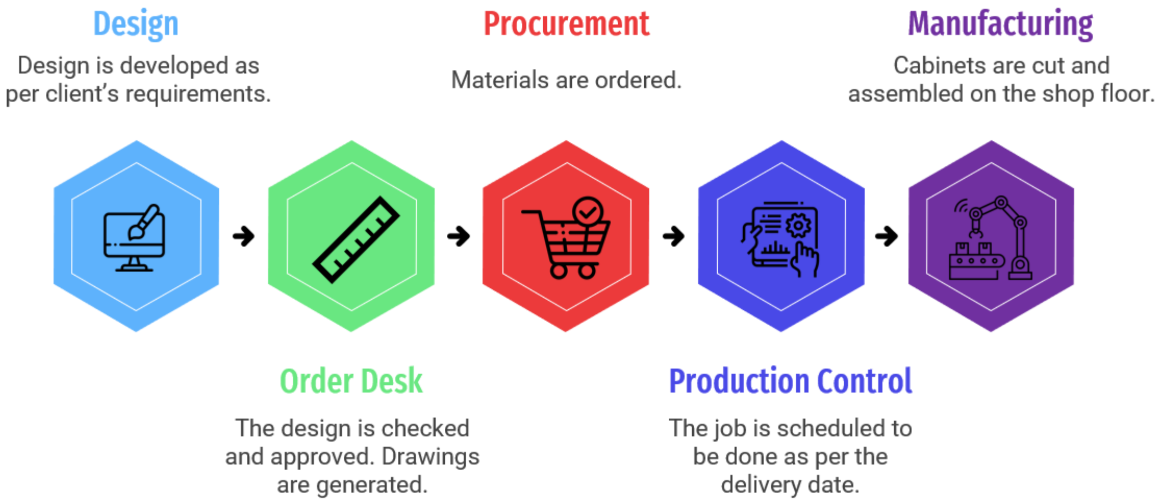


**Figure 2:** Company's information flow

A *job* is a confirmed order by a client that has a specific design, specifications, and number of cabinets. After a job is designed, engineered, and procured, it is assigned to a specific workflow that describes the sequence of stations that the cabinets will follow on the shop floor. This is because jobs may differ in terms of cabinet finishing (painted or not), doors and fronts (in-house made or buy-out doors), and staging (job processed over 1–2 stages). These workflows are predetermined and embedded in the production system to make scheduling and production control easier. So, for every job that falls under any of the workflows, the sequence of the stations needed to do that job is already known and will be scheduled by the production control department. From data of 455 jobs, the workflows were aggregated to check the distribution of the jobs with respect to their workflows.

Two workflows are assumed to be of major importance. The first is IH_NoFin_1S, meaning the doors are cut and made in-house with no painting of any fronts or cabinet parts, and all is done in one stage occupying 51% of production. The second is BO_NoFin_1S, meaning the doors are outsourced, no painting of any fronts or cabinet parts is done, and everything is done in one stage occupying 30% of production. These two workflows follow very similar sequence of stations, and they both form 81% of production as shown in Figure 3. For this reason, the value stream map and the SM will both be based on these two workflows.

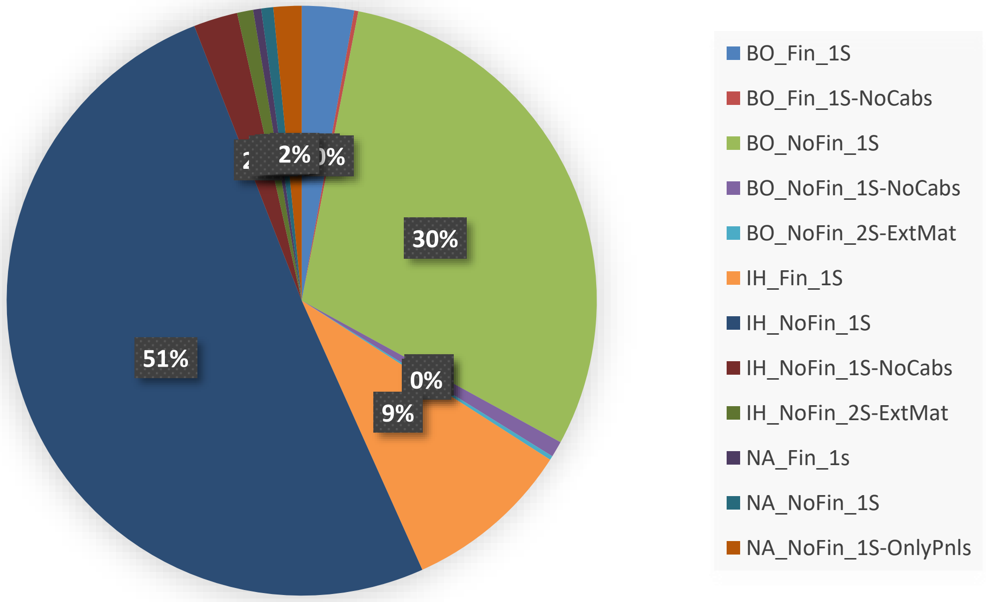


**Figure 3:** Percentage of job workflows

## 3.2 Process Description

The flowchart in Figure 4 describes the sequence of stations a cabinet goes through for the IH_NoFin_1S and BO_NoFin_1S workflows. As shown, there is a sequence of tasks that occur to assemble a cabinet. First, the router pulls a specific sheet type from the sheet stockpile based on the job being processed, and then cuts the sheet into cabinet parts. The operator cleans, labels, and puts the cabinet parts in the router cart. The label has a job number, a cabinet number, and notes the sides of the part that will be edge taped. Figure 5 shows the router cart with sorted cabinet parts. Figure 6 shows an example of a label put on every cabinet part generated from the saw.

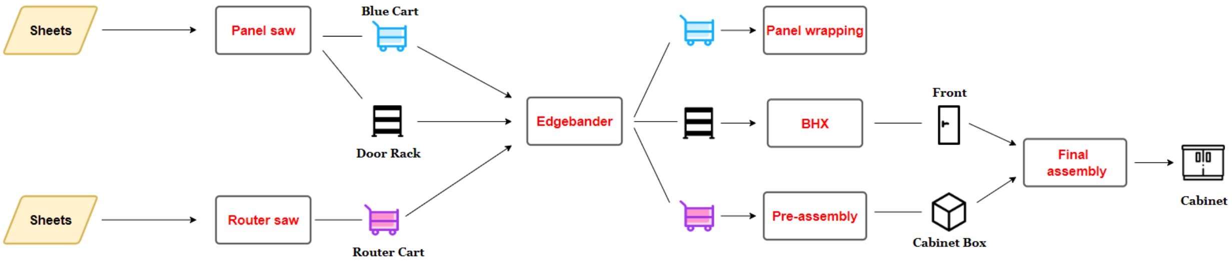


**Figure 4:** Assembly flowchart for IH_NoFin_1S and BO_NoFin_1S workflow

**Figure 5:** Router cart with cabinet parts

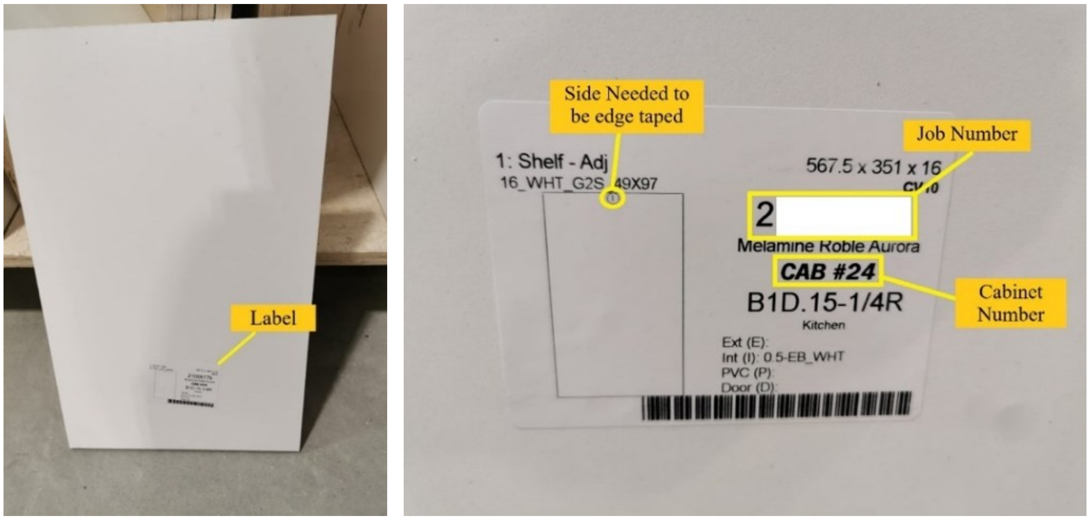


**Figure 6:** Labeled cabinet part

Simultaneously, the panel saw also pulls sheets from the sheet stockpile and cuts them into panels and fronts. The panels are put into the blue cart and the fronts into the door rack as shown in Figures 7 and 8, respectively.

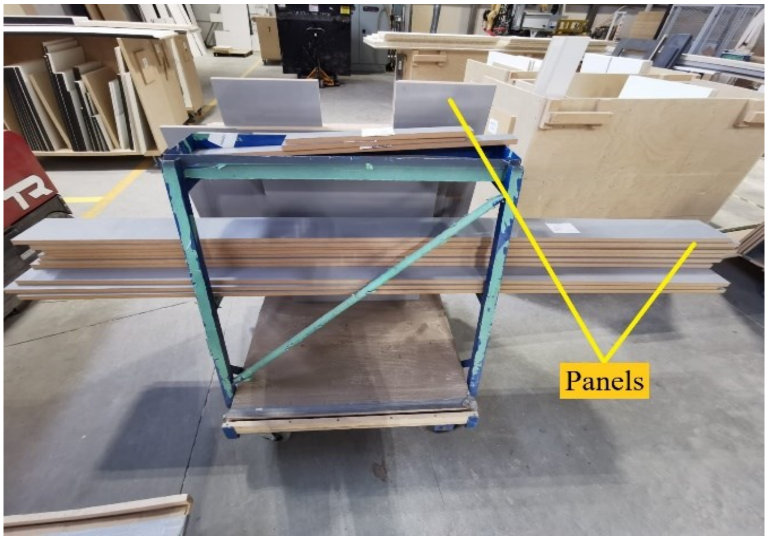


**Figure 7:** Blue cart

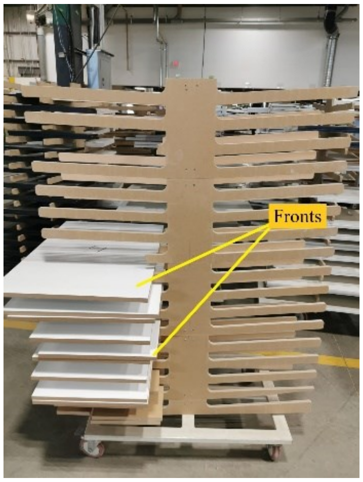


**Figure 8:** Door rack

The router carts, blue carts, and door racks are all pushed to the edgebander (EB) for the parts to be edge taped. The EB operator recieves a cart, checks what kind of tape the parts need, sets up the tape and the EB, and then tapes the edges of every part that needs edge taping. Next, the operator returns the part to the cart it was received from. Figure 9 shows the EB station with different kinds of carts waiting to be edge taped.

**Figure 9:** EB with router carts and door racks waiting to be processed

After taping all parts, the operator sends the blue cart to the panel wrapping station, the router cart to the pre-assembly station for joining cabinet parts, and the door rack to the BHX for drilling the fronts. BHX is a machine that drills door fronts and panel as per the design specifications.

The router cart goes to pre-assembly, where an operator installs the hardware needed based on the cabinet drawings, as shown in Figure 10. Then, the operator sorts the parts on the line based on their designated cabinet number, as shown in Figure 11. Lastly, an operator receives the parts from the pre-assembly line and joins all the parts together, as shown in Figure 12.

**Figure 10:** Hardware installation in the pre-assembly station

**Figure 11:** Pre-assembly line occupied with cabinets waiting to be built

**Figure 12:** Cabinet building in the pre-assembly stage after hardware installation

After pressing all parts together on the press machine as shown in Figure 13, the cabinet goes to the final assembly line.

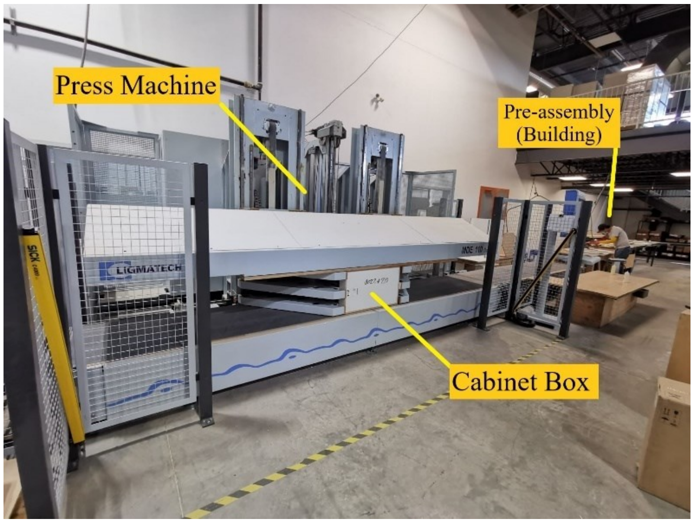


**Figure 13:** Press machine

The blue cart goes to panel wrapping, where the operator cleans the panel edges of any remaining glue, wraps the panel, and puts it back onto the cart. Figure 14 shows blue carts that have panels waiting to be wrapped.

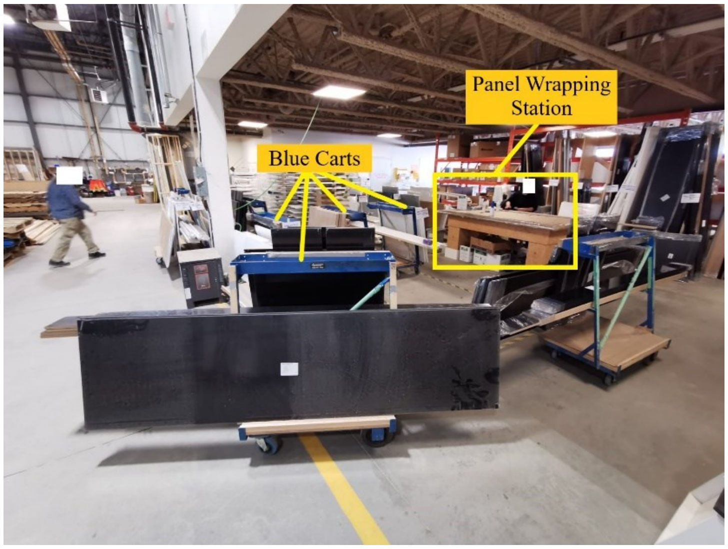


**Figure 14:** Blue carts (WIPs) for panel wrapping

The door rack goes to the BHX for the doors to be drilled. After drilling, the final assembly operators clean glue from the fronts' edges and return it to the door rack so it is ready to be installed on the cabinet box. Figure 15 shows the cleaning table, which is located between the BHX and the final assembly line.

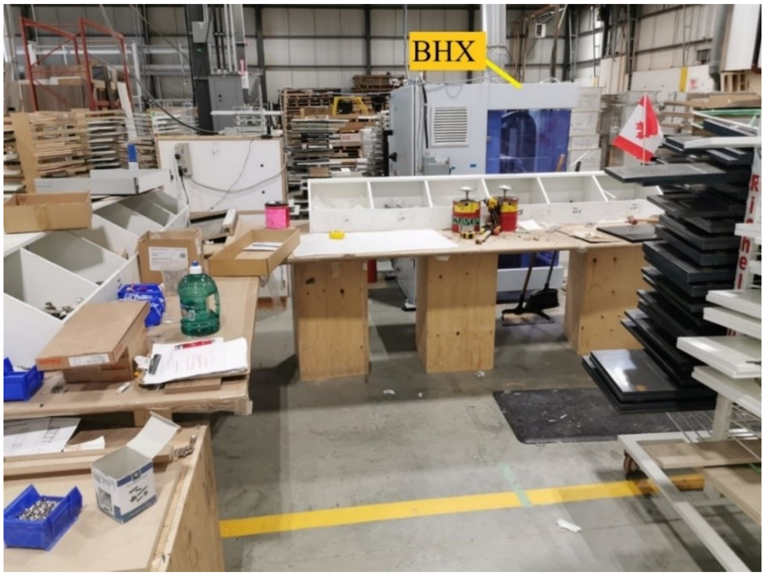


**Figure 15:** Fronts cleaning table

Figure 16 shows the cabinet fronts on door racks waiting to be drilled on the BHX, and other door racks that have drilled fronts that are already cleaned and ready to be installed on the cabinet boxes by the final assembly operators.

**Figure 16:** Door racks WIP for BHX and final assembly

At the final assembly station, the operators install drawers and cabinet fronts, wrap the cabinets, and put them on a palette. Figure 17 shows cabinets stacked on a palette ready for shipping. Figure 18 shows the cabinets on the final assembly line.

**Figure 17**: Palette

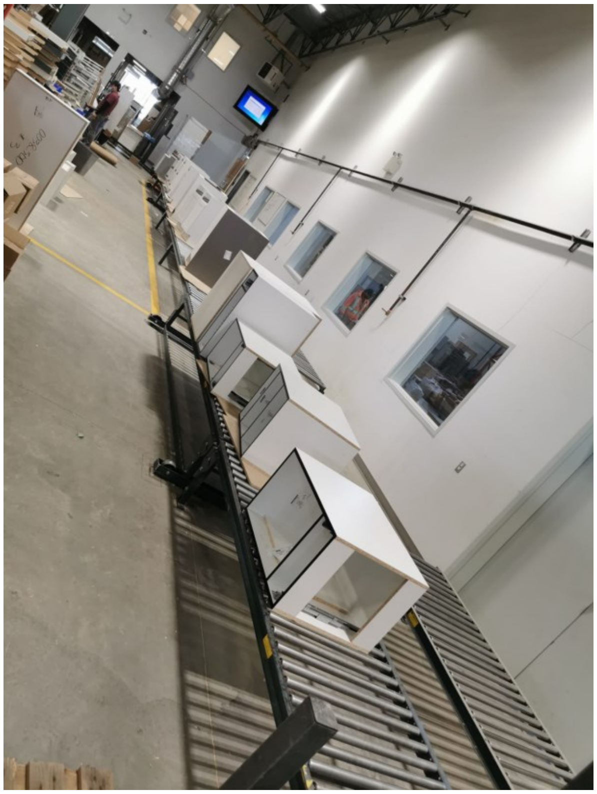


**Figure 18:** Final assembly line

## 3.3 Data Sourcing

### 3.3.1 Ethnography

Different kinds of data were collected for different reasons, and several data sourcing methods were adopted throughout the study. Data were gathered from observations, time and motion studies, interviews, and the company’s database. The action of repeatedly visiting the shop floor over several months and spending half the day there made the study an ethnographical one. Ethnography includes participating in a certain social context to study people in a naturally occurring setting and collect data systematically without any external pressure on the people (Brewer, 2000). Besides the data collected being quantitative in nature (station durations, parts count, cart counts, WIP, etc.), the study revealed a lot about the operators’ behaviour and interaction in a natural setting. Initially, all the operators were resistant to share knowledge and insights about their work. However, as trust was built throughout the days, the workflow became quantitatively and qualitatively clearer. The objective was to identify production problems, which then could be fixed by changing and improving processes. This approach helped extract hidden knowledge that only operators have and that is critical for understanding the underlying problems of the production line. These “informal” interviews and chats with the operators were a main source of inspiration to develop several ideas for improving production; they are the people who understand the most about what is happening on the production line. These improvements are further discussed and analyzed in Chapter 7.

### 3.3.2 Interviews

Another data sourcing method was conducting interviews with the production manager, production control manager, and order desk manager**.** The production manager explained the material flow from the router and panel saw to final assembly. He also explained the role of every station, how the parts flow from station to station, and how raw material (sheets, door hardware, accessories, etc.) and finished products (finished cabinets ready for shipping) are handled. The production control manager explained how the jobs are planned and scheduled, and how they are controlled on the shop floor. The order desk manager helped clarify how the jobs are categorized in terms of workflows, what kind of data are collected for every job, and how the order desk department helps with quality assurance and control. The research ethics office at University of Alberta reviewed the interviews’ content and the approach to ensure data and personal information privacy; they approved the application (study ID: Pro00122260) to conduct the interviews with the managers.

### 3.3.3 Time and motion studies

During the researcher’s time spent on the shop floor, time and motion studies were conducted for every station. The purpose of the time and motion studies is to detect value-adding time, non–value-adding time, production problems, and opportunities for improvements. The task durations collected from the time study do not consider the operators’ non-productive time. If these durations were extrapolated and converted to daily production rate, the numbers would be unrealistically optimistic. Therefore, these durations represent the best-case scenario, which the improvements aim to achieve and closely approximate. They aim to convey a sense of how fast a station produces and what the frequent problems are that delay the operator.

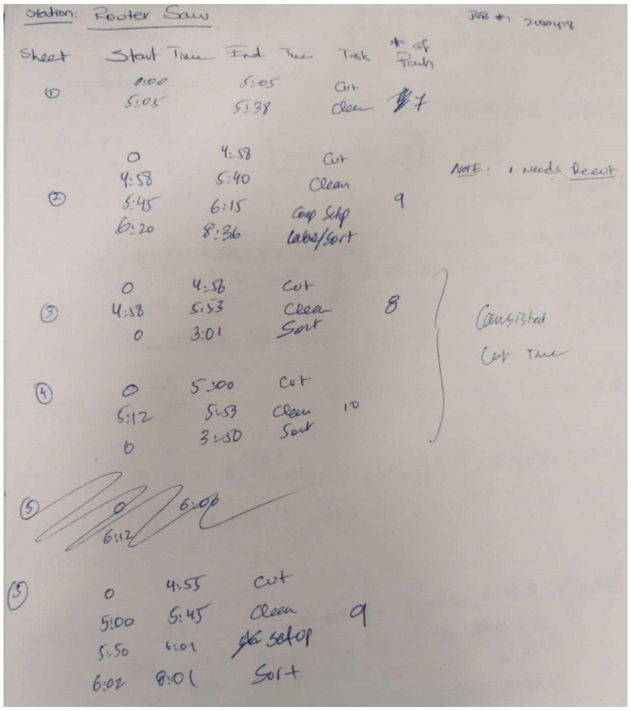
For the motion studies, time was spent on every station to track the repetitive sequence of subtasks needed to perform the work. The objective of the motion study is to understand the exact sequence of subtasks in every station. Moreover, this helped detect any opportunity for decreasing the station cycle time by deleting unnecessary non–value-adding subtasks when possible, or at least improving them. Table 1 shows the motion study for the router.

**Table 1:** Motion studies

| Station | | Motions |
|---|---|---|
| Router saw | | 1. Operator sets the code for the router to start cutting the sheet. |
| | | 2. He uses an air hose to clean all dust as the parts are moved out of the machine on a belt. |
| | | 3. He continues to clean all dust from the machine before ordering another sheet. |
| | | 4. He orders a new sheet. |
| | | 5. He labels the parts after cleaning. |
| | | 6. He sorts them in the router cart. |
| Pre-assembly | Dowelling: Usually, everything that has a dado is dowelled (stretchers, mullion, aprons). | 1. Operator first sets the computer for the code that is needed for the parts. |
| | | 2. She picks up the parts that need dowelling; the machine can take two at a time. |
| | | 3. She puts the first piece in the first spot, waits for it to be dowelled, then moves it to the next spot. Once placed, she puts another piece in the first spot. |
| | | 4. Once the part is done, she places it in the assigned cabinet. (Every part is assigned for a certain cabinet.) |
| | Hardware: Two major types of hardware are put on the cabinets: hinges and drawer guides. | 1. Operator takes the part from the cart, finds the drawing, and checks it. |
| | | 2. Then, she installs the hardware, and puts the drawing on the part. |
| | | 3. Finally, she attaches the part in the assigned cabinet on the line. |
| | Building | 1. Operator puts the parts on the table. |
| | | 2. He starts gluing the holes and the dado gaps. |

| | | |
|---|---|---|
| | | 3. He starts with the top/bottom and builds the parts. He uses a rubber hammer to insert the dowels through the holes. |
| | | 4. He then carries the cabinet from the table to the press machine. |

Figure 19 shows the collection of data for the time study done on the router station. The times needed to cut the sheet, clean the table and the parts, and sort them in the router cart are all collected per sheet.



Station: Router Saw

JOB #: 2000418

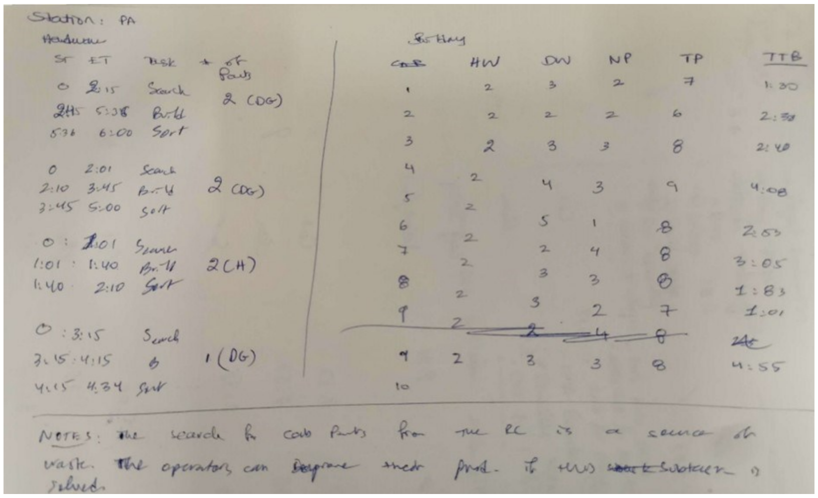
| Sheet | Start Time | End Time | Task | # of Parts |
|---|---|---|---|---|
| ① | 0:00 | 5:05 | Cut | |
| | 5:05 | 5:38 | Clean | 7 |
| ② | 0 | 4:58 | Cut | |
| | 4:58 | 5:40 | Clean | |
| | 5:45 | 6:15 | Comp Schp | 9 |
| | 6:20 | 8:36 | Labels/Sort | |
| ③ | 0 | 4:58 | Cut | |
| | 4:58 | 5:53 | Clean | 8 |
| | 0 | 3:01 | Sort | |
| ④ | 0 | 5:00 | Cut | |
| | 5:12 | 5:53 | Clean | 10 |
| | 0 | 3:50 | Sort | |
| ⑤ | ~~0~~ | ~~6:06~~ | | |
| | ~~6:12~~ | | | |
| ⑤ | 0 | 4:55 | cut | |
| | 5:00 | 5:45 | Clean | 9 |
| | 5:50 | 6:01 | setup | |
| | 6:02 | 8:01 | Sort | |

NOTE: 1 Needs Recut.

Consistent Cut Time

**Figure 19:** Router time study (handwritten)

Figure 20 shows the data collected for the pre-assembly station, which has two main tasks: (1) installing hardware on the cabinet parts and (2) building the cabinet box. The hardware installed can be either hinges for the door fronts or drawer guides for drawers to be installed in final assembly. The building task is straightforward as long as none of the cabinet parts are missing. Both tasks were tracked and timed. The data are then organized and put into MS Excel sheets as shown in Tables 2, 3, and 4.



Station: PA

Hardware

| ST | ET | Task | # of Parts |
|---|---|---|---|
| 0 | 2:15 | Search | 2 (DG) |
| 2:15 | 5:38 | Build | |
| 5:38 | 6:00 | Sort | |
| 0 | 2:01 | Search | |
| 2:10 | 3:45 | Build | 2 (DG) |
| 3:45 | 5:00 | Sort | |
| 0 : | 1:01 | Search | |
| 1:01 : | 1:40 | Build | 2 (H) |
| 1:40 | 2:10 | Sort | |
| 0 : | 3:15 | Search | |
| 3:15 : | 4:15 | B | 1 (DG) |
| 4:15 | 4:34 | Sort | |

Building

| Cab | HW | DW | NP | TP | TTB |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 2 | 7 | 1:30 |
| 2 | 2 | 2 | 2 | 6 | 2:38 |
| 3 | 2 | 3 | 3 | 8 | 2:40 |
| 4 | 2 | 4 | 3 | 9 | 4:08 |
| 5 | 2 | | | | |
| 6 | 2 | 5 | 1 | 8 | 2:53 |
| 7 | 2 | 2 | 4 | 8 | 3:05 |
| 8 | 2 | 3 | 3 | 8 | 1:83 |
| 9 | 2 | 3 | 2 | 7 | 1:01 |
| | 2 | ~~2~~ | ~~4~~ | ~~8~~ | ~~24~~ |
| 9 | 2 | 3 | 3 | 8 | 4:55 |
| 10 | | | | | |

NOTES: The search for cab parts from the RC is a source of waste. The operators can improve their prod. if this ~~start~~ subtask is solved.

**Figure 20:** Pre-assembly (hardware and building subtasks) time studies (handwritten)

**Table 2:** Router time study

| Sample number | Sheet number | Carcass parts | Drawer parts | Recuts | Total parts | Job number | Start time | End time | Total time (min.) | Total handling time (min.) | Task |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 5 | 1 | 0 | 6 | 21### | 0:00 | 5:05 | 5.08 | 8.13 | Cut |
| | | | | | | | 5:05 | 5:38 | 0.55 | | Clean |
| | | | | | | | 5:38 | 5:38 | 0 | | Setup |
| | | | | | | | 5:42 | 8:08 | 2.43 | | Sort |
| 2 | 1 | 9 | 0 | 0 | 9 | 21### | 0:00 | 4:58 | 4.97 | 8.6 | Cut |
| | | | | | | | 4:58 | 5:40 | 0.7 | | Clean |
| | | | | | | | 5:45 | 6:15 | 0.5 | | Setup |
| | | | | | | | 6:20 | 8:36 | 2.27 | | Sort |
| 3 | 1 | 4 | 0 | 0 | 4 | 21### | 0:00 | 4:10 | 4.17 | 6.98 | Cut |
| | | | | | | | 4:10 | 5:01 | 0.85 | | Clean |
| | | | | | | | 5:01 | 5:01 | 0 | | Setup |
| | | | | | | | 5:01 | 6:59 | 1.97 | | Sort |
| 4 | 1 | 10 | 0 | 0 | 10 | 21### | 0:00 | 4:56 | 4.93 | 8.97 | Cut |
| | | | | | | | 4:58 | 5:53 | 0.92 | | Clean |
| | | | | | | | 5:53 | 5:53 | 0 | | Setup |
| | | | | | | | 6:00 | 8:58 | 2.97 | | Sort |
| 5 | 1 | 8 | 0 | 0 | 8 | 21### | 0:00 | 4:48 | 4.8 | 10.03 | Cut |
| | | | | | | | 5:03 | 5:45 | 0.7 | | Clean |
| | | | | | | | 5:45 | 5:45 | 0 | | Setup |
| | | | | | | | 5:52 | 10:02 | 4.17 | | Sort |

### **Table 3:** Pre-assembly time study (hardware subtask)

| Sample number | Part number | Type | Start time | End time | Total Sub task time | Total sample time | Task | Operator |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | Drawer guides | 0:00 | 3:15 | 3.25 | 6.09 | Searching for parts | XXX |
| | | | 3:15 | 5:34 | 2.32 | | Build hardware | XXX |
| | | | 5:34 | 6:05 | 0.52 | | Finding the cabinet on the lines and sorting | XXX |
| 2 | 2 | Hinges | 6:05 | 8:10 | 2.08 | 2.83 | Searching for parts | XXX |
| | | | 8:10 | 8:45 | 0.58 | | Build hardware | XXX |
| | | | 8:45 | 8:55 | 0.17 | | Finding the cabinet on the lines and sorting | XXX |
| 3 | 2 | Drawer guides | 8:55 | 10:45 | 1.83 | 3.83 | Searching for parts | XXX |
| | | | 10:45 | 12:28 | 1.72 | | Build hardware | XXX |
| | | | 12:28 | 12:45 | 0.28 | | Finding the cabinet on the lines and sorting | XXX |
| 4 | 2 | Hinges | 12:45 | 14:15 | 1.5 | 2.58 | Searching for parts | XXX |
| | | | 14:15 | 15:05 | 0.83 | | Build hardware | XXX |
| | | | 15:05 | 15:20 | 0.25 | | Finding the cabinet on the lines and sorting | XXX |
| 5 | 2 | Hinges | 0:00 | 1:50 | 1.83 | 3.22 | Searching for parts | XXX |
| | | | 1:12 | 2:25 | 1.22 | | Build hardware | XXX |
| | | | 2:25 | 2:35 | 0.17 | | Finding the cabinet on the lines and sorting | XXX |

### **Table 4:** Pre-assembly time study (building subtask)

| Sample number (cab) | Job number | Parts having hardware | Dowelled parts | Neutral parts (NO hardware/dowels) | Total cabinet parts | Start time | End time | Total time to build |
|---|---|---|---|---|---|---|---|---|
| 1 | 21### | 2 | 2 | 4 | 8 | 0:00 | 2:48 | 2.8 |
| 2 | 21### | 2 | 2 | 4 | 8 | 0:00 | 1:50 | 1.83 |
| 3 | 21### | 2 | 5 | 1 | 8 | 0:00 | 2:35 | 2.58 |
| 4 | 21### | 2 | 4 | 1 | 7 | 0:00 | 2:32 | 2.53 |
| 5 | 21### | 2 | 2 | 4 | 8 | 0:00 | 2:20 | 2.33 |
| 6 | 21### | 2 | 5 | 1 | 8 | 0:00 | 3:10 | 3.17 |
| 7 | 21### | 2 | 4 | 2 | 8 | 0:00 | 3:02 | 3.03 |
| 8 | 21### | 2 | 3 | 2 | 7 | 0:00 | 1:00 | 1 |
| 9 | 21### | 2 | 2 | 4 | 8 | 0:00 | 1:35 | 1.58 |

### 3.3.4 Observations

No data were available for the WIP levels between stations. This data was collected using observations and parts counting. The objective was to find the current state of the system in terms of amount of WIP and to later assess and validate the simulation model. This is discussed further in Chapter 5. Figure 21 show the WIP of router and blue carts waiting to be processed on the EB.

**Figure 21:** EB WIP waiting to be processed

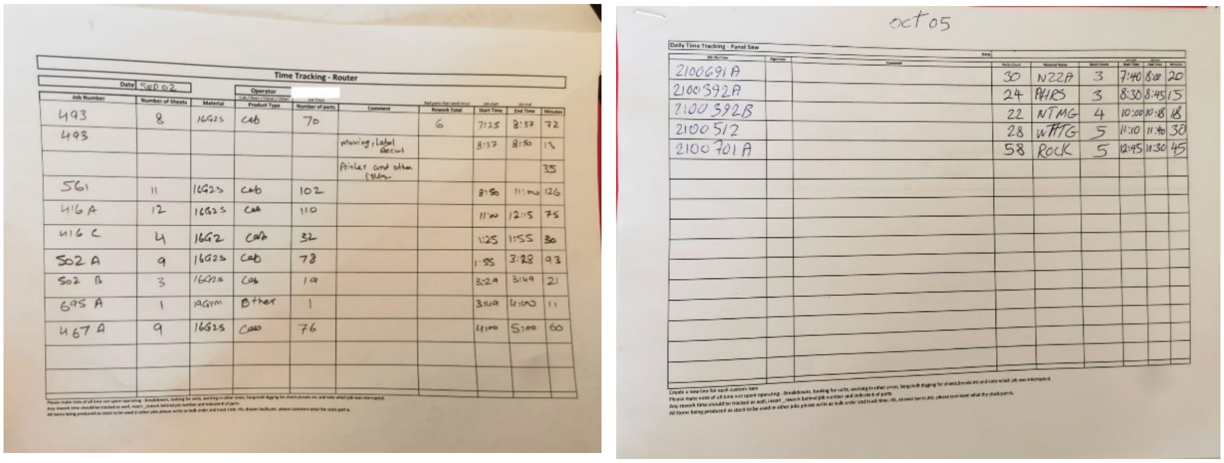
Table 5 shows the parts counting done for different carts behind the EB station. All parts on the carts waiting in different locations were counted and categorized. This data was collected once per visit to the shop floor to track WIP over time (days).

**Table 5:** EB WIP Data and parts counting

| Sample number | Job number | Part | Saw | 0 sides | 1 side | 2 sides | 3 sides | 4 sides | Total sides | Date |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 21### | Carcasses | Router | 9 | 47 | 0 | 5 | 0 | 61 | Feb 3 |
| 2 | 21### | Carcasses | Router | 6 | 37 | 0 | 3 | 0 | 46 | Feb 3 |
| 3 | 21### | Carcasses | Router | 4 | 23 | 0 | 0 | 0 | 27 | Feb 3 |
| 4 | 21### | Carcasses | Router | 3 | 13 | 0 | 0 | 0 | 16 | Feb 3 |
| 5 | 21### | Carcasses | Router | 1 | 9 | 0 | 0 | 0 | 10 | Feb 3 |
| 6 | 21### | Fronts | Panel | 0 | 0 | 0 | 0 | 35 | 44 | Feb 3 |
| | | Carcasses | Panel | 2 | 5 | 2 | 0 | 0 | | Feb 3 |
| 7 | 21### | Panels | Panel | 3 | 1 | 9 | 1 | 16 | 30 | Feb 3 |
| 8 | 21### | Panels | Panel | 1 | 1 | 6 | 0 | 18 | 26 | Feb 3 |
| 9 | 21### | Panels | Panel | 3 | 0 | 3 | 0 | 5 | 20 | Feb 3 |
| | | Carcasses | Panel | 9 | 0 | 0 | 0 | 0 | | Feb 3 |

### 3.3.5 Company database

The company needed to track jobs over the shop floor and how much time a job was spending at each station. Therefore, operators had to fill out provided time sheets, which included the job and the time spent to complete it. Figure 22 shows time sheets for the router and panel saw stations. The objective of this data was to find the daily production rate, which was later converted to an average station cycle time and used to build the SM.



Time Tracking - Router

Date SEP 02

Operator [redacted]

| Job Number | Number of Sheets | Material | Product Type | Number of parts | Comment | Rework Total | Start Time | End Time | Minutes |
|---|---|---|---|---|---|---|---|---|---|
| 493 | 8 | 16G25 | Cab | 70 | | 6 | 7:25 | 8:37 | 72 |
| 493 | | | | | Moving, Label Recut | | 8:37 | 8:50 | 13 |
| | | | | | Printer and other Issues | | | | 35 |
| 561 | 11 | 16G25 | Cab | 102 | | | 8:50 | 11:00 | 126 |
| 416 A | 12 | 16G25 | Cab | 110 | | | 11:00 | 12:15 | 75 |
| 416 C | 4 | 16G2 | Cab | 32 | | | 1:25 | 1:55 | 30 |
| 502 A | 9 | 16G25 | Cab | 78 | | | 1:55 | 3:28 | 93 |
| 502 B | 3 | 16G25 | Cab | 19 | | | 3:29 | 3:49 | 21 |
| 695 A | 1 | 19GYM | Other | 1 | | | 3:49 | 4:00 | 11 |
| 467 A | 9 | 16G25 | Cab | 76 | | | 4:00 | 5:00 | 60 |

oct 05

Daily Time Tracking - Panel Saw

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 2100691A | | | 30 | N22A | 3 | 7:40 | 8:00 | 20 |
| 2100392A | | | 24 | AHRS | 3 | 8:30 | 8:45 | 15 |
| 2100392B | | | 22 | NTMG | 4 | 10:00 | 10:18 | 18 |
| 2100512 | | | 28 | WHTG | 5 | 11:10 | 11:40 | 30 |
| 2100701A | | | 58 | ROCK | 5 | 12:45 | 11:30 | 45 |

**Figure 22:** Stations timesheet (router and panel saw)

### 3.3.5 Video surveillance

With the consent of the management and operators, a video camera was set up to monitor certain stations. The final assembly station was chosen to be monitored, because of how dynamic the station is. The operators rotate from one subtask to another with no repetitive pattern. For example, an operator might be wrapping cabinets and then suddenly go to help with front cleaning. Or an operator would be installing fronts on the cabinets and then go to help another operator in wrapping a palette. This organic nature of this station is necessary with the current state, since there is no sequence defined for the subtasks. On the other hand, the pre-assembly station, for example, goes from dowelling, to hardware, and finally building, all in sequence. The video surveillance helped in identifying patterns in the operators' activities. It also helped in improving the final assembly station and building the future state map. Figures 23 and 24 show how the same operator performs two subtasks: cabinet wrapping (Figure 23) and palette wrapping and moving (Figure 24).

**Figure 23:** Final assembly surveillance

**Figure 24:** Final assembly surveillance

The pre-assembly station was also chosen to be monitored. Installing hardware was found to be a bit disorganized, as the operator has a hard time finding the right cabinet parts and their drawings to install the hardware. The video surveillance helped track motions and time wasted by the operator doing non–value-adding activities.

### 3.4 Conclusions

This chapter gives a general overview on the OSC facility chosen to be investigated. It explains how the company and its shop floor operate in terms of information flow and material flow. Moreover, several data collection methods were thoroughly explained with their respective achieved objectives firstly to understand how the production system works and secondly to understand the current state in terms of production problems and waste generation. This chapter sets the stage for creating a value stream map and viewing the current state from a lean perspective, which are discussed in Chapter 4.

# Chapter 4 – Value Stream Mapping

## 4.1 Introduction

A value stream is all the actions performed throughout all stations to transform raw material (sheets) into customer-ready products (fully assembled cabinets). Rother and Shook (2003) classified these actions as (1) value-adding, (2) non–value-adding but necessary, or (3) non–value-adding (pure waste). For production, value-adding activities or actions directly contribute to doing the right work to transform the material and bring the product a step toward being ready for the customer. e.g., installing hardware, edge taping sides, drilling fronts). Necessary non–value-adding activities do not contribute in shaping the material but cannot be eliminated from the task being done based on current situations (e.g., filling time sheets, setting up the machines). Non–value-adding activities are considered to be pure waste; they do not create any value to external (clients) or internal (succeeding stations) customers, and they waste resources (e.g., time spent by humans and machines). Non–value-adding activities can be eliminated from the process without affecting it (operator/machine idle time, rework, etc.).

VSM helps in visualizing what types of actions are happening on the shop floor and where the focus should be directed in terms of improving the production system. It gives a snapshot of how the stations are operating and what is happening in between them. This helps managers and operators have a better understanding of the state of the production system in terms of stations' cycle time, WIP between the stations, PLT, and total processing time (TPT). The activity of mapping the value stream reveals hidden problems within the production system, especially when managers start to look at the root causes of surface problems. The VSM tool inspires managers to develop solutions as the map is being created. It also gives a sense of ownership to participants when it is done collaboratively; it motivates the team to develop improvements for the future state of the system and to devise a plan for implementing them. After focusing on different stations and studying them individually, VSM helps practitioners understand the whole rather than just the parts. This chapter explains the logic used to create the value stream map and later build the SM, implementation of the VSM technique to create the current state, and conclusions drawn from this exercise.

## 4.2 Logic Explanation

The production process for OSC cabinet making includes different types of material used, starting from upstream stations where wooden sheets are processed and ending with final assembly, where doors and fronts are installed on cabinet boxes. Different stations have different input and output units, which makes it difficult to understand the contribution of every station station to the final output (*cabinet*). It also makes it difficult to create the value stream map and build the SM.

Figure 25 describes the categorization of stations and the material flow throughout production. The router and panel saw stations were named *driving stations*, since they are the most upstream stations that drive production. They process sheets (raw material) and generate the work needed for all stations downstream; anything generated by the driving stations is conserved (in terms of volume) throughout the production line to finally become cabinets. Therefore, all stations after the panel saw and router were named *processing stations*. This helped in solving the issue of having different input and output units by trying to have a unified unit for all stations starting with the driving stations and moving down to the last processing station. The unit *cabinets* was chosen to represent the input and output of every station. This implies a logical and reasonable understanding of how a sheet is transformed throughout the whole process to form a cabinet. To achieve the aforementioned goal, two objective questions are considered:

- *How many cabinets does one sheet create on average?* Answering this question helps illustrate how much the driving stations generate work for the processing stations, in terms of cabinets.
- *How many parts does one sheet create on average?* This second question builds on the first: after the number of cabinets generated from one sheet is identified, knowing how many parts every sheet produces helps translate parts into cabinets.

So, the first question helps in the unit conversion from sheets to cabinets, and the second helps in the unit conversion from parts to cabinets. This requires studying the data of every station and calculating the ratio of parts to cabinets to unify all units. Table 6 shows the input and output units of every station.

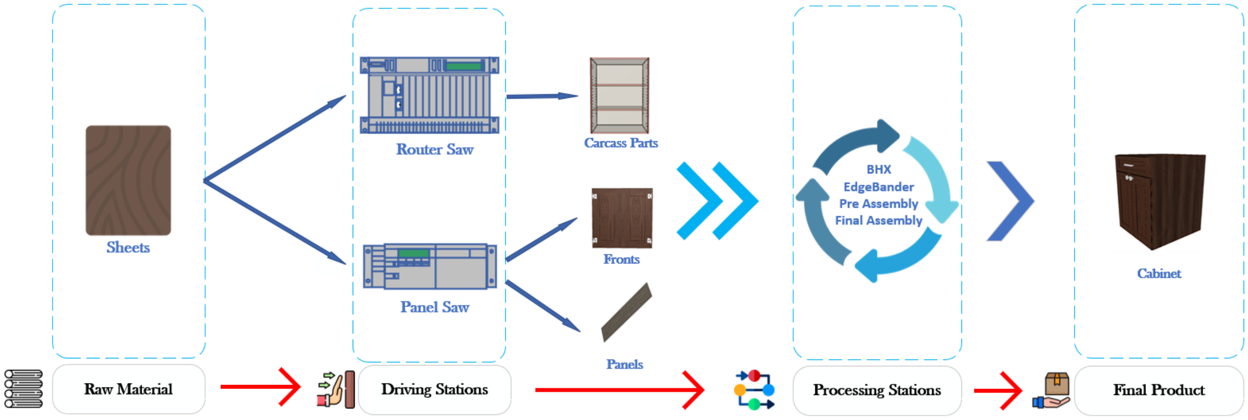


**Figure 25:** Material flow overview from raw material to final product

**Table 6:** Stations' input and output units

| Station | Input unit | Output unit |
|---|---|---|
| Router saw | Sheets | Carcass parts |
| Panel saw | Sheets | Fronts |
| | | Panels |
| EB | Carcass parts | Carcass parts |
| | Fronts | Fronts |
| | Panels | Panels |
| BHX | Fronts | Fronts |
| Pre-assembly | Carcass parts | Cabinets |
| Final assembly | Cabinets | Cabinets |

### 4.2.1 Unifying units of the driving stations

From the company database, job data was used to calculate ratio of sheets to cabinets. Table 7 shows, for every job: (1) the number of cabinets generated, (2) the number of fronts needed for the cabinets, (3) the number of panel parts that come out of the panel saw per job, (4) the number of sheets that are cut on the panel saw to generate fronts and panels, (5) the number of carcass parts generated to form the cabinet, and (6) the number of sheets cut on the router to generate the carcass parts.

**Table 7:** Job production data

| Job number | Cabinet count | Number of front parts | Number of panel parts | Sheet qty (panel saw) | Number of carcass parts (router saw) | Sheet qty (router saw) |
|---|---|---|---|---|---|---|
| 21##### | 19 | 25 | 18 | 7 | 133 | 18 |
| 21##### | 1 | 2 | 0 | 1 | 5 | 1 |
| 21##### | 4 | 4 | 0 | 1 | 32 | 5 |
| 21##### | 18 | 19 | 1 | 3 | 126 | 19 |
| 21##### | 22 | 13 | 1 | 2 | 152 | 23 |
| 21##### | 10 | 11 | 9 | 3 | 58 | 7 |

As shown in Table 6, the router processes sheets to generate carcass parts, and the panel saw processes sheets to generate fronts and panels. To convert the output unit of both the router and panel saw from sheets to cabinets, the ratio of sheets to cabinets is calculated from 364 jobs to find a reliable average that can be used to unify the units and then used for the value stream map and SM.

As shown in Equations 1 and 2, the total number of sheets processed for the jobs is divided by the total number of cabinets produced. The assumption made is that every sheet processed on the router generates the cabinet parts needed for 1 cabinet. However, on the panel saw, every sheet processed generated fronts and panels needed for 2 cabinets. This implies that the output of these two driving stations is now unified as cabinets, and the input is still expressed in terms of sheets. This answers objective Question 1.

Equation 1 (router sheets to cabinets ratio):

$$Input\ (Router\ ) = \frac{\sum \text{Sheets}}{\sum \text{Cabinets}} = 0.978\frac{Sheets}{Cabinet} \cong 1\frac{Sheet}{Cabinet}$$

Equation 2 (panel saw sheets to cabinets ratio):

$$Input\ (Panel\ Saw) = \frac{\sum \text{Sheets}}{\sum \text{Cabinets}} = 0.452\frac{Sheets}{Cabinet} \cong 0.5\ \frac{Sheet}{Cabinet}$$

### 4.2.2 Unifying units of the processing stations

#### *4.2.2.1 Edgebander (EB)*

After unifying the output unit of the driving stations to cabinets, the input of the processing stations (internal customers of the driving stations) is also in cabinets. Therefore, the input (parts) of these processing stations should also be converted to cabinets. This is addressed by objective Question 2.

From Table 7, Equations 3 and 4 are derived to calculate the average number of parts generated from every sheet:

Equation 3 (router parts to sheets ratio):

$$Parts\ per\ sheet\ (Router\ Saw) = \frac{\sum \text{Carcass Parts}}{\sum \text{Sheets}} = 7.68 \frac{Parts}{Sheet} \cong 8\ \frac{Parts}{Sheet}$$

Equation 4 (panel saw parts to sheets ratio):

$$Parts\ per\ sheet\ (Panel\ Saw) = \frac{\sum \text{Front Parts} + \sum \text{Panel Parts}}{\sum \text{Sheets}} = 8.21 \frac{Parts}{Sheet} \cong 8\ \frac{Parts}{Sheet}$$

This implies that on average, 8 parts are generated from 1 sheet processed on the router and 8 parts from 1 sheet processed on the panel saw. This answers objective Question 2. Since every cabinet requires 1 sheet from the router and 0.5 sheets from the panel saw, then 1 cabinet unit represents an average of 12 parts edge taped on the EB.

#### *4.2.2.2 BHX*

The input and output units of the BHX station are in fronts. To convert fronts to cabinets, Equation 5 was used:

Equation 5 (BHX fronts to cabinets ratio):

$$Fronts\ per\ Cabinet\ (BHX) = \frac{\sum \text{Front Parts}}{\sum \text{Cabinets}} = 1.78 \frac{Fronts}{Cabinet} \cong 2 \frac{Fronts}{Cabinet}$$

Therefore, it is safe to assume that 2 door fronts are needed to build 1 cabinet. This confirmed from the observations during the time study conducted at the final assembly station. The operator installs on average 2 doors per cabinet, which is validated by data as shown in Equation 5.

#### *4.2.2.3 Pre-assembly and final assembly*

After unifying the EB station output unit to cabinets, the pre-assembly station input (internal customer of the EB) becomes cabinets. This poses no need to convert the units, since the output unit of the pre-assembly station is already in cabinets. The same applies for final assembly, where the input and the output unit is cabinets.

## 4.3 Value Stream Map

The aim of creating a value stream map is to study the material and information flow throughout a production system. As discussed earlier, this study is limited to production control and manufacturing. Moreover, this study investigates the material flow in more detail. The objective of mapping the value stream is to bring to the surface visible sources of waste. Table 8 defines the key concepts needed to create the value stream map.

**Table 8:** Value stream map definitions

| Concept/term | Definition |
|---|---|
| Cycle time (C/T) | The duration needed for a station to process 1 cabinet unit. |
| Changeover time (C/O) | The time needed for a station to switch from one product type to another. |
| Uptime | A percentage of available production time that the station would be operating. |
| Available resource time | The total time of operation in one shift |
| Production lead time (PLT) | The time it takes one cabinet to move all the way through the value stream, from the router and panel saw to final assembly. |
| Total processing time (TPT) | The sum of all station cycle times from start to finish, excluding the waiting time between stations. |

Before creating the value stream map, several points need to be clarified. The first task is to limit the scope of the value stream and only include what fits the purpose of the study. As described in the introduction, the study aims to give a door-to door holistic perspective of how the production system is behaving. Therefore, the following assumptions are made to create the value stream map:

1- **External suppliers are not included in the scope of the value stream map**: Suppliers provide two main material types: sheets and buy-out doors. The sheet stockpile always has a buffer of sheets, and the driving stations never stop because of shortage of sheets. Similarly, for buy-out doors, the procurement department orders out-sourced doors, which are always delivered before assembly.

2- **The shipping department is not included in the scope of the value stream map**: The shipping department always ships orders within two days after final assembly, which is already accounted for in the site layout. Moreover, shipping orders are strongly affected by the customers' site conditions, which are also outside the scope of this study.

Therefore, the study is only limited to the internal production system that transform raw material to final product. Table 9 shows major questions that were answered to create the value stream map.

**Table 9:** Value stream map major questions

| Question | Answer |
|---|---|
| What is the average daily demand processed by the production system? | The scheduling department makes sure that that no more than 400 cabinets are scheduled every week. Therefore, it is assumed that the demand is 400 cabinets/week, which can be translated to 80 cabinets/day (5 days of operation). |
| On what basis is production scheduled? | The scheduling department sends the weekly schedule to the production control which schedules the stations accordingly on a weekly basis. |
| How many hours does the shop floor run per day? | The shop floor runs 10.5 hours per day, 5 days a week. There is a total of one 1-hour break per day. Therefore, the operating time per day is assumed to be 9.5 hours (570 minutes). |
| What is time bracket chosen? | One week. |
| Do all stations have same operation times? | No. The router, panel saw, EB, and BHX operate 5 days/week (Monday to Friday). This totals 2850 minutes per week. Pre-assembly and final assembly stations operate 4 days/week (Tuesday to Friday). This totals 2280 minutes/week. |

It is worthy to mention that the data were mainly collected between the months of February and April, in which work was picking up before the summer season. It is assumed that this is the regular demand that the company mostly expects excluding seasonality of the demand. This assumption is made because the company promises a fixed lead time to deliver the job, and this lead time is sufficient as a buffer for high demand. This helps regulate production to a certain extent, where the shopfloor state is not affected much with the demand.

Figure 26 shows a hand-drawn sketch of the value stream map created during site visits conducted over one week; it is created based on observations and revised based on feedback from operators and managers on the shop floor. The cycle times are represented as deterministic values based on average durations measured on site (and validated by the time studies). The WIP between stations are also based on counts made on site. This fits the purpose of building the value stream map and having a good understanding of the current state.

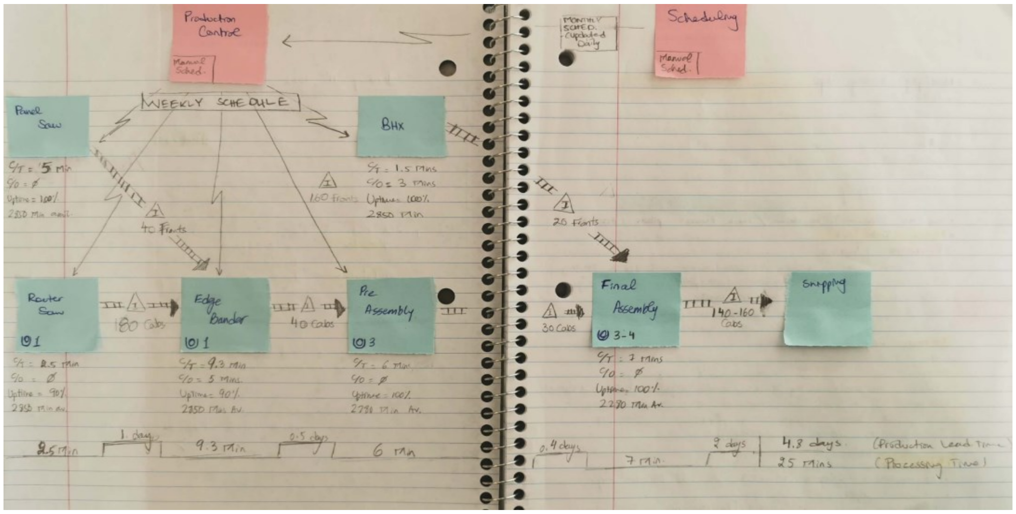


Figure 26: Value stream map sketch

The value stream map sketch in Figure 26 was made on the shop floor. Shipping was included at that time and then excluded later, as there are many variables controlling it that are outside the scope of the value stream map. The inventory between stations (carts carrying different cabinet parts) was calculated in terms of cabinets using the logic explained in this section. The PLT was calculated by adding the waiting time from inventories between stations. Equation 6 was used to obtain the waiting time:

Equation 6 (waiting time between stations):

$$Waiting\ Time = \frac{\text{Inventory (Cabinets)}}{\text{Daily Demand}\left(\frac{\text{Cabinets}}{\text{day}}\right)} = WT\ (days)$$

With a daily demand of 80 cabinets, the inventory counted was divided by 80 to calculate the average waiting time the WIP is waiting between stations. Figure 27 shows the current state map excluding the shipping station.

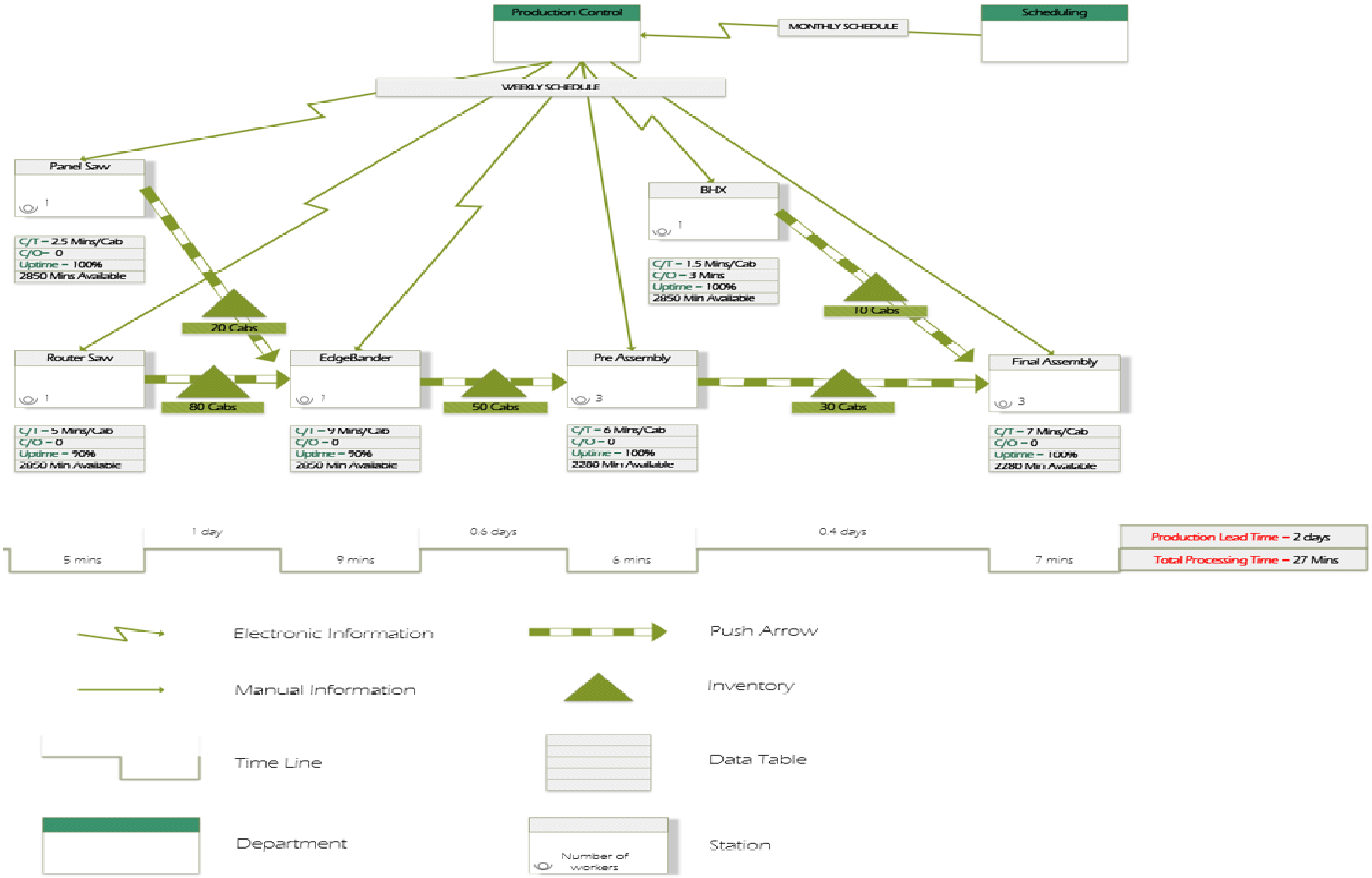


**Figure 27:** Current state map

## 4.4 Validation

Several parts of the value stream map were validated independently. The station cycle times were validated by the operators as well as the time studies completed on the shop floor. Inventory numbers were based on actual observations and parts counting conducted on the shop floor. Moreover, they were also validated by the production manager who confirmed that numbers reflect average numbers; this fits the purpose of the value stream map. Moreover, the production manager also validated the logic and sequence of the stations. This helped in building the correct understanding of the production system, which is a crucial milestone for building next steps.

## 4.5 Conclusions

The exercise of creating the value stream map helped in understanding what to include and what to exclude for the scope of the study, defining areas for improvement, and building an SM that serves a specific purpose. The conclusions drawn after creating the value stream map are accounted for in the SM. They are summarized in the following points:

1. A significant difference exists between the total PLT (2 days) and TPT (27 mins).
2. Three WIP locations will be studied further: (1) between the driving stations and the EB, (2) at the pre-assembly line, and (3) at the final assembly line. They are likely the major contributors to unbalance in the production system and causing the substantial difference between PLT and TPT.
3. The BHX WIP location is affected by the suppliers that provide buy-out doors, therefore it cannot be represented accurately and is considered outside the scope of this case study.

This chapter lays the foundation for building an appropriate SM with a sufficient level of abstraction. The SM is designed to (1) help in analyzing the current state in terms of several metrics and then (2) be used to simulate interventions aimed to improve the production system.

# Chapter 5 – Simulation

## 5.1 Introduction

After developing a value stream map to visualize waste and identify areas that can be improved, simulation is used to further investigate the performance of the production system with respect to throughput, lead time, station utilization, and WIP inventory. VSM gives a preliminary understanding of the state of the system, since it serves as a screenshot of the current state; however, it is limited in terms of its ability to assess the system in the long term. Simulation plays a role in providing predictability of the production system's long-term performance given the current state. With time studies and accurate data collection, stations can be represented with stochastic cycle times that better reflect reality. Simulation also provides insights into certain lean metrics that are of interest in this study, such as WIP inventory and PLT, which aid in optimizing production holistically from processing raw material to producing the final product. Lastly, simulation is used to study the effect of several lean interventions that were inspired throughout the study. The resulting tool will help decide which interventions best serve production as a whole. The software used is Simphony.NET, which is built for the purpose of construction engineering and management applications (Hajjar & AbouRizk, 2002).

In this study, two types of simulation are utilized for different reasons. DES is used to mimic the production workflow and extract data for analysis. Monte Carlo simulation is used with fuzzy analysis to simulate and evaluate the performance metric of TPT/PLT developed in this study, which is further explained in Chapter 6. This chapter explains: the steps taken to build the SM; model verification and validation; and model results and discussion.

## 5.2 Simulation Objectives

Before building the SM, the objectives are defined and used as a reference to tailor and modify the model. The sole purpose of the model is to meet the defined objectives in a simple yet powerful way that fits the purpose. The following objectives are met using DES:

1. Calculate the production rate.
2. Calculate the WIP inventory in three main locations: (1) between the driving stations and the EB, (2) at the pre-assembly line, and (3) at the final assembly line.
3. Calculate station utilization.

4. Calculate the total PLT.
5. Calculate the TPT.

### 5.3 Model Assumptions

The following assumptions are inspired from observations made during the study and were validated by the production manager:

1. BHX WIP inventory is built both by doors processed in-house and doors bought from external suppliers. Therefore, it is not considered in the model.
2. Final assembly operators always find doors that need to be installed; they never wait on the BHX to drill doors. Therefore, BHX is considered to be part of the final assembly station.
3. Along with the BHX, which supplements the final assembly by making doors ready, the drawer station is also considered a substation of the final assembly station, because it supplements assembly by readying drawers for installation.
4. The labour allocation in terms of number of operators for each station is consistent throughout production and is assumed to stay so.
5. The sheet stockpile is always stocked; thus, the router and panel saw always have sheets to process.

### 5.4 Input Modelling

The production system is simulated at the activity level rather than subactivity level. This means that every station is represented as one task rather than being broken down into subtasks. This level of abstraction fits the purpose of meeting the objectives stated. From the time studies conducted on the shop floor and production data provided by the company, data points of station cycle times are obtained and fit into probabilistic distributions. The goodness of fit test used to select distributions is the Kolmogorov-Smirnov (K-S) test, which is automatically done on Simphony.NET. The null hypothesis is that the data comes from a specified distribution, while the alternate hypothesis is that the data does not come from the specified distribution. All stations have 20 sampled data points. With a significance level (alpha level) of 10%, the critical K-S value is 0.264. For every station, the distribution with the minimum K-S value is chosen to represent the cycle time of the station. For all stations, the K-S value was less than the critical value, meaning the null hypothesis is not rejected and therefore deemed to be true (the data follows the specified distribution). Table 10 summarizes the distributions every station cycle time follows.

**Table 10:** Station cycle time data fitting

| Station | Distribution | Mean (min./cabinet) | Standard deviation (min./cabinet) | K-S value |
|---|---|---|---|---|
| Router saw | LogNormal | 9.445 | 2.966 | 0.26355 |
| Panel saw | Weibull | 12.964 | 4.854 | 0.1802 |
| EB | Pareto | 8.976 | 1.593 | 0.17955 |
| Pre-assembly | Gamma | 7.617 | 3.215 | 0.214 |
| Final assembly | Pareto | 8.04 | 3.02 | 0.184 |

### 5.5 Simulation Model

The model logic explained in Chapter 4 is used in the SM. Figure 28 shows the model built on Simphony.NET. The entities running through the model are considered to be cabinets. The entities first enter as sheets from the created elements at the beginning of the model, are processed by the driving stations, and then are transformed into cabinets that are processed by the processing stations. As explained, the router generates 1 cabinet per sheet, and the panel saw generates 1 cabinet per 0.5 sheets. Therefore, every entity (sheet) that enters the router exits as 1 cabinet; however, every entity (sheet) that enters the panel saw exits as 2 cabinets. The model is designed to run the average daily demand, which is 80 cabinets per day; every day is 570 minutes. So, the panel saw has a daily demand of 40 sheets per day, and the router has a daily demand of 80 sheets per day, so both are equivalent to 80 cabinets per day.

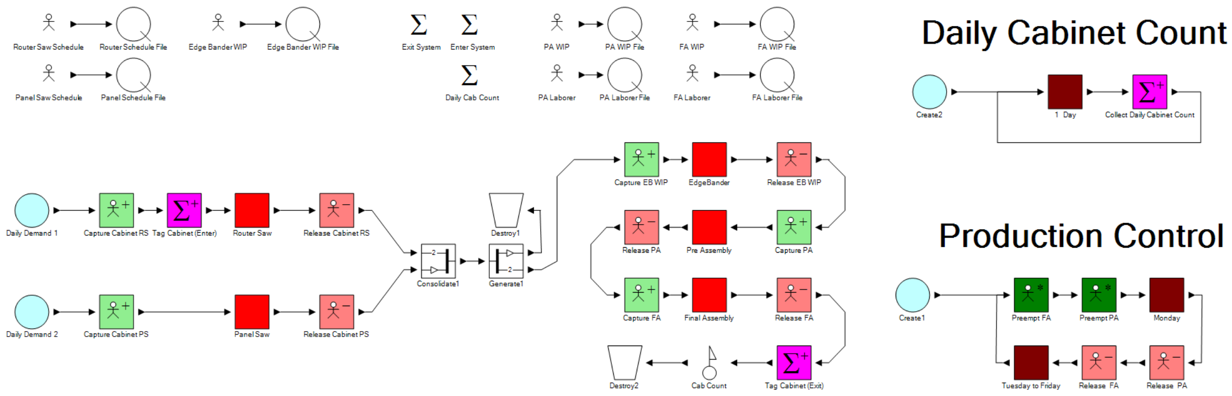


**Figure 28:** Simulation model

Every station is modelled as a task having a stochastic duration with a resource aimed to regulate the cabinet flow. The stations are assumed to process one cabinet at a time; therefore, all stations' resources have one server. The WIP between stations has a designated resource. A cabinet is captured by the WIP resource before being captured by the station. If a cabinet arrives at a station and the station is already processing a cabinet, the arriving cabinet remains captured by the WIP resource server. It is only released when the queue ahead of it (cabinets that reached before the arriving cabinet) is processed. Therefore, the WIP is regulated by the number of servers. The WIP location behind the EB is assumed to have a capacity of 80 cabinets and is thus modelled as 80 servers. The pre-assembly line is assumed to have a capacity of 20 cabinets, and 30 cabinets are assumed for the final assembly line.

Several statistics are collected in the model, based on the objectives stated. Every cabinet is tagged with a timestamp just before it enters the router for processing and immediately after it exits final assembly. This helps in studying the time spent by every cabinet in the system (PLT). A counter is placed after the final assembly station to track the number of cabinets generated. The "Daily Cabinet Count" cycle tallies the count number every 570 minutes to track the daily cabinet production. Moreover, the "Production Control" cycle pre-empts pre-assembly and final assembly stations once per week to mimic how production runs in reality (pre-assembly and final assembly do not operate on Mondays).

### 5.6 Model Verification

The modelling process adopted in this research is based on Sargent (1981). Figure 29 shows the modelling process simplified to three main stages starting with the problem entity or the system, which is next conceptually modelled and then programmed on a computerized model.

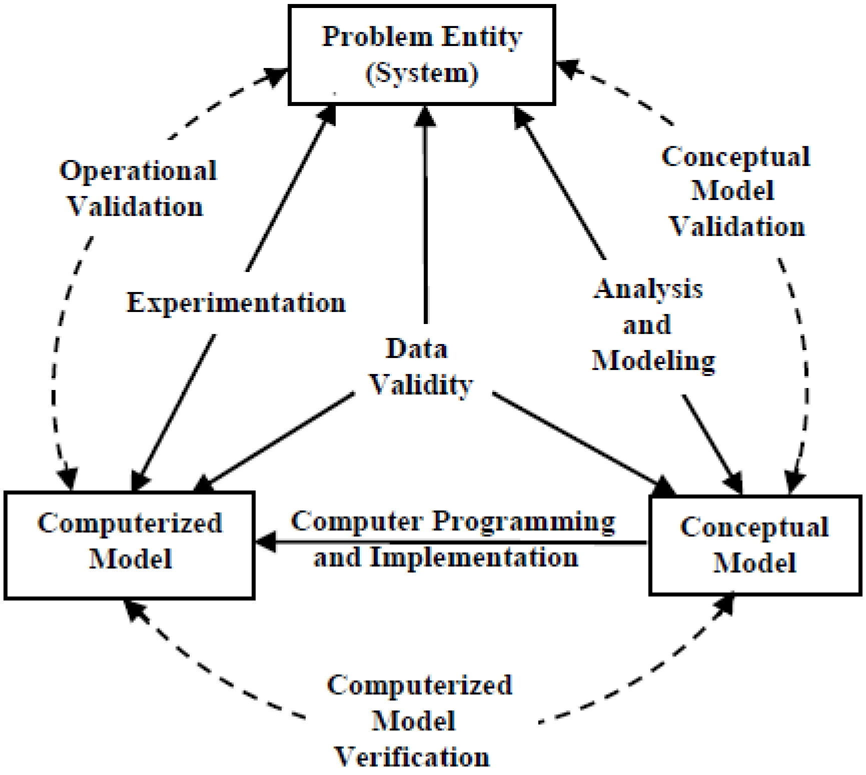


**Figure 29:** Simulation modelling process (Sargent, 1981)

In this study, the system is the production shop floor. The conceptual model aims to investigate a part of the problem entity; in this case, the value stream map is the conceptual model that aims to study the current state of the system in terms of value and waste. Validation of the value stream map is addressed in Chapter 4 and fits the purpose of the study. The computerized model, built on Simphony.NET, is verified to make sure the model is correctly built and represents the conceptual model. Several techniques based on Whitner and Balci (1989) were used to verify the model, such as desk checking, black-box testing, and white-box testing.

### 5.6.1 Desk checking

Desk checking is the investigation of the logic and consistency of the model. The logic is straightforward; there is one definite path and a hard logic for how the cabinets are generated. This made the simulation model simple yet powerful for studying the system. The cabinet is processed as a sheet by the driving stations and cannot proceed to edge taping until components from both driving stations are present. Then after edge taping, the cabinet is assembled in pre-assembly and final assembly. This logic is also inspected and validated by the company.

### 5.6.2 Black-box testing

Black-box testing focuses on the model function in terms of its output, without consideration of what happens in between. It focuses on the relationship between inputs and outputs. This is checked by simulating a predetermined number of cabinets as a testing input to the model. The number of cabinets entering the system was consistent with the number exiting it, therefore the volume was conserved in terms of input to output. The output is also close to what the model is expected to generate. This acts as a rough indicator that there are major flaws in the logic and function of the model.

### 5.6.3 White-box testing

White-box testing is the investigation of how the elements of the model interact before reaching the output. This verification technique ties back into the model's objectives and the purpose of the study. The goal of this study is to assess and improve the state of a production system by studying what is happening in between stations, and not only what the system produces. This makes white-box testing essential in verifying the model. The model's objectives also include studying WIP levels in between stations and cabinet waiting time in the system. The WIP capacities are not exceeded because they are capped at their limits whenever the station is overwhelmed. This applies to the WIP behind the EB, pre-assembly, and final assembly stations.

Regarding PLT, every cabinet that entered and left the system generated a data point that indicates its PLT. The data points were collected in the statistic modelled and conformed with the number of cabinets generated. Lastly, the cabinets that entered the system passed through all stations before being counted as produced. This was verified by checking the number of times every station processed an entity.

### 5.7 Model Validation

Validation is the process of ensuring that the model represents the real system to an acceptable degree based on the model objectives. Moreover, validity is the usefulness and usability of the model (Landry et al., 1983). To make sure that the correct model is built, several techniques were used based on Sargent (2010) to validate the model, including face validity, event validity, and internal validity.

#### 5.7.1 Face validity

Face validity is achieved by obtaining expert opinion about the model and its behaviour. The model was presented to the company with the underlying assumptions and the obtained results on daily production, station utilization, PLT, and WIP levels. The general manager and the production manager agreed that the assumptions were reasonable and the logic was correct. Moreover, they were frequently and regularly asked for feedback throughout the modelling process. Lastly, all the results were justified and accepted with respect to the current state of the production shop floor.

#### 5.7.2 Event validity

Event validity is achieved when the occurrences of certain phenomena modelled in the simulation are similar to the real system. The production rate fell within the expected range of 60 to 80 cabinets per day. Moreover, the obtained station utilization reflected what was observed throughout the study. The router is utilized much more than the panel saw, the EB and pre-assembly are operating most of the time, and final assembly is always occupied. These were reflected in the model results, which are discussed later in this chapter.

The WIP levels obtained from the model reflect the repetitive pattern occurring in reality. The buffer built on Mondays occupies pre-assembly and final assembly throughout the week; however, the pre-assembly station consumes this WIP before the end of the week and tends to have minimal to zero buffer by Friday. The final assembly line is always full and occupied, just as the model predicted.

With respect to PLT, the first cabinet produced in the model is expected to spend between 595 and 600 minutes in the system. The first day is assumed to be a Monday, in which no production takes place but the driving stations and the EB still process cabinets. With 570 minutes a day and an average TPT of 27 mins, the first cabinet spends between 590 and 610 minutes in system. The PLT increases as the simulation advances, which is expected because of the buffer built throughout the weeks. This validates the function of the production control loop, TPT, and PLT.

### 5.7.3 Internal validity

The variability within the model elements is also examined because of the stochastic nature of the model. Internal validity is the process of determining whether this variability is acceptable or not. This is studied by running the model several times to check the difference between the runs. The average PLT, average production rate, average station utilization of each station, and the average WIP levels had variability limited to 5% between simulation runs. This implies that the variability within the model elements in terms of the results generated is controlled and deemed acceptable.

## 5.8 Model Results and Discussion

The model was run to simulate the production of 1500 to 1600 cabinets, which would take 2 to 3 months to produce in real life. The results obtained give insight into how the shop floor functions over time. The results were validated first and then used as a basis for improving the current state. They are studied from a lean point of view, where sources of waste are pinpointed and later targeted to study how they impact the entire system. Daily production rate, cabinet PLT, WIP inventory levels, and station utilization were obtained from the model and are explained below.

### 5.8.1 Daily production rate

The cabinets are counted every 570 minutes throughout the run to check the daily production count. This helps in detecting variability in daily production and confirms whether the model reflects what the shop floor produces in real life.

Figure 30 shows the daily cabinet count over 5 production weeks. The days on which the cabinet count is 0 are Mondays, since pre-assembly and final assembly stations only operate from Tuesday to Friday. The current production system produces 60 to 80 cabinets per day, which is indeed reflected in the model, as shown in Figure 30. During low production days, the daily count can drop to 67, as in days 3 and 8. On higher production days, the daily count can reach up to 79 cabinets, as in day 20. This variability is expected and occurs on the shop floor. The production rate of the system based on current conditions is 5.85 cabinets/hour.

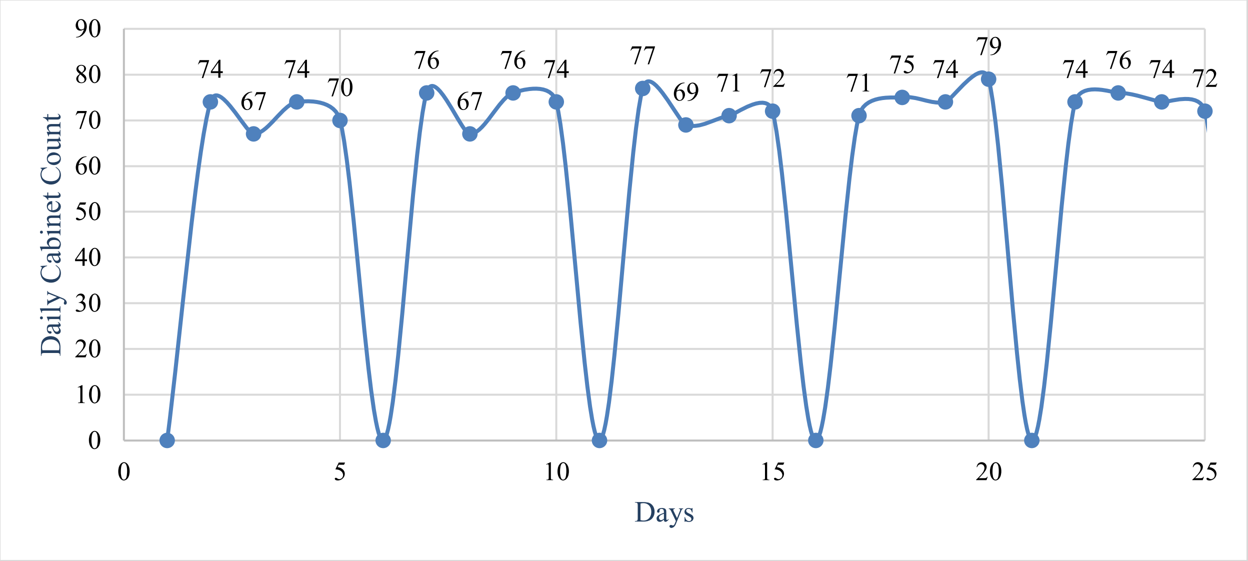


**Figure 30**: Daily cabinet production

### 5.8.2 Cabinet production lead time

In the model, every cabinet is tagged with a timestamp to measure the time passed from the moment it enters as a sheet until it leaves as a completed cabinet. This helps demonstrate how much stress is being built in the production system. If a cabinet is in system for a significant time before it is produced, this indicates that the stations are unbalanced, buffer is building up, and the production state is stressed. It also gives insight into the state of the production system. Any two systems can be producing at the same rate, but the production rate can differ between a product that takes days or weeks to exit the system and a product that takes minimal time to exit.

Figure 31 shows the time spent (in minutes) by every cabinet that entered the system. The cabinet number is represented on the *x*-axis where the ascending order reflects the order of cabinets entering and exiting the system. The first cabinet inevitably spends 570 minutes assuming that the first day the model starts running is a Monday. The jumps in PLT also reflect Mondays, because cabinets that are still in the system on Friday would have to wait another 570 minutes of operation time before production resumes. This build-up in PLT indicates that the production system is unbalanced and the buffer built up on Mondays is more than what production can handle in a week. This excess buffer is considered waste, and it stresses the production system by increasing variability and overwhelming stations. The more time a cabinet spends in the system, the more vulnerable it is to having defects and other quality problems.

Moreover, this leads to reduced flexibility. If a cabinet reaches final assembly after spending 5 days on the shop floor and turns out to have a defect, then it becomes exceedingly difficult to produce that cabinet again given the state of the production system and the queue built throughout the system.

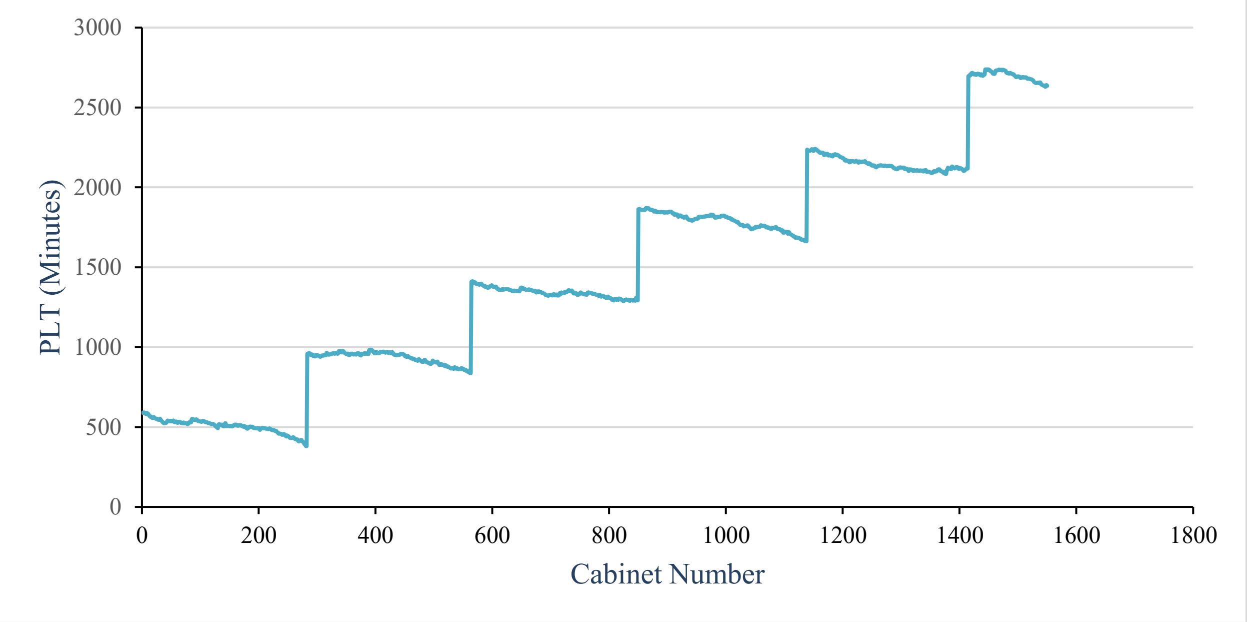


**Figure 31:** Production lead time (PLT) of all cabinets based on their cabinet number

### 5.8.3 Station utilization

Station utilization represents the percentage of operation time a station is in use. In this study, station utilization comprises both productive and non-productive time. This means that if a station is utilized, it has WIP waiting to be processed; it does not mean that it is productively processing it. The percentage of time the station is unutilized is the time that the station is starving for work from its preceding station(s). Station utilization helps demonstrate whether the load (demand) matches capacity (production rate) of a certain station. Moreover, it helps in measuring how balanced the station cycle times are. If a certain station has a shorter cycle time than its preceding station, then it will be underutilized. The opposite is also true: if a station has a higher cycle time that its preceding station(s), then it will be overutilized. Being over- or underutilized affects the station on a micro level. Also, it affects the production system on a macro level, where certain critical stations may be bottlenecks that affect all other stations and impede the performance of the production system as a whole.

Figure 32 shows station utilization mean and standard deviation for every station. Based on current state conditions, final assembly is the bottleneck of the system, with an average utilization of 99%. This means that the final assembly station always has cabinets on an average utilization of 92.8%; however, it has some time buffer. The panel saw is clearly underutilized, with an average of 58.8%. This indicates that the station cycle times are not well balanced, so some stations are overwhelmed with work and others are starving for work.

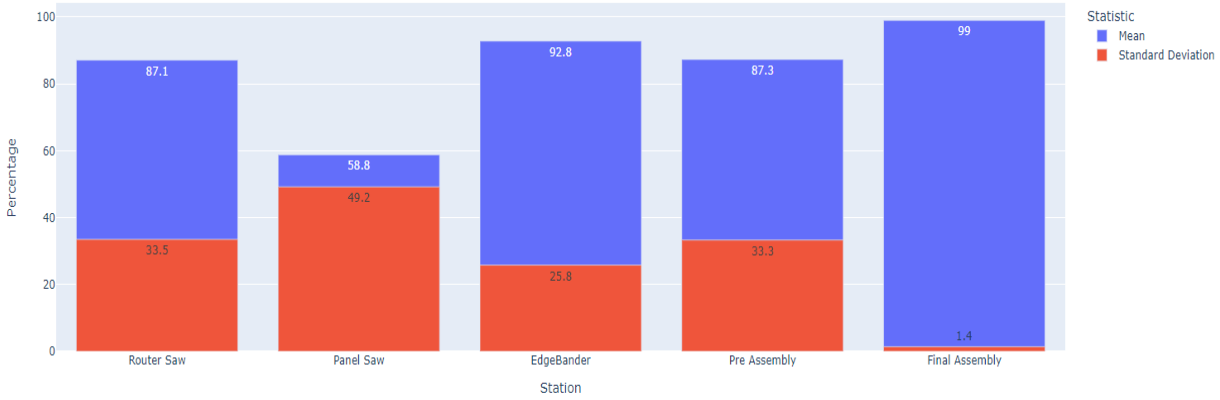


**Figure 32**: Mean and standard deviation of every station

Table 11 shows the utilization coefficient of variation (CV) for every station, expressed as a percentage. CV measures the relative dispersion of data points around the mean. In this context, CV indicates the degree of variation of every station's utilization. The closer CV is to 100%, the more variable utilization is. The panel saw has the highest CV of 83.7% indicating that the station is unpredictable with respect to its utilization. The final assembly station has the lowest CV, since it is mostly utilized over the simulation run. It is better to reduce CV within every station and reduce the differnce in utilization between stations, as one step in improving station and system performance.

**Table 11:** Coefficient of variation (CV) of station utilization, expressed as percentage

| Station | Coefficient of variation (%) |
|---|---|
| EB | 27.8 |
| Final assembly | 1.4 |
| Panel saw | 83.7 |
| Pre-assembly | 38.1 |
| Router saw | 38.5 |

### 5.8.4 WIP inventory levels

The three WIP inventory locations are examined in the model. Every location has a certain maximum capacity beyond which no more cabinets can fit. The EB can have a maximum of 80 cabinets waiting behind it to be processed, the pre-assembly line can hold up to a maximum of 20 cabinets, and the final assembly line has a maximum WIP capacity of 30 cabinets. These capacities are defined in the model and are shown in Figure 33.

**Figure 33:** WIP levels of EB, pre-assembly, and final assembly stations over simulation time

Figure 33 shows how WIP builds up over simulation time behind the EB, pre-assembly, and final assembly. Final assembly is clearly fully occupied almost 100% of the time, whereas pre-assembly shows a certain pattern that reflects what was observed on the shop floor. The jumps indicate the buffer built during Mondays; the station starts consuming this buffer on Tuesday and catches up with the EB before Friday, since it has a lower cycle time. At the end of the week, pre-assembly operates at the speed of the EB, and it has minimal WIP on its line. The final assembly line is always fully occupied over time, because it is the bottleneck of the system. The

WIP built and maintained on the line indicates that the station is significantly slow and unbalanced compared the stations upstream. The EB WIP level is built over time because of the driving stations preceding it. It increases at a slower rate than pre-assembly and final assembly. When the EB WIP level reaches 80, the shop floor is overcrowded with carts behind stations, the state of the system is completely unbalanced, all stations are overwhelmed with work, and productivity is at its lowest. Occasionally, the production manager stops the driving stations to dissipate the large buffer built and regulate the state of the system. This only happens when the WIP level reaches its capacity. This indicates that the current state of the system is unbalanced and needs improvement on both the micro level (stations) and macro level (production system).

## 5.9 Conclusions

This chapter explains the modelling process of the shop floor performed on Simphony.NET. It explains the objectives the SM was built to achieve and the assumptions made prior to building the model. Moreover, the chapter explains different model verification and validation techniques used to verify and validate the SM. Verification techniques include desk checking, black-box testing, and white box testing. Validation techniques include face validity, event validity, and internal validity. The results extracted from the model are based on the objectives stated initially. The metrics that are of interest to this study are: (1) production rate, (2) cabinet PLT, (3) station utilization, and (4) WIP levels of the three studied locations of EB, pre-assembly, and final assembly. The results indicate that the stations are not well balanced, leading to an increase in buffer between stations. The station utilization rates indicate a significant variation between stations. The PLT trend increases over time, indicating that the load entering the system is not being processed and is building up over time. Overall, the results indicate that the production system is stressed based on the current conditions. This chapter gave insights on the micro level; Chapter 6 explains the fuzzy analysis conducted to build a model that assesses the production holistically.

# Chapter 6 – Fuzzy Analysis

## 6.1 Introduction

Every production system is unique; there are no universal metric values that can be used to assess and distinguish system states. The production system state can be described as profitable or non-profitable, chaotic or organized, balanced or unbalanced, lean or fat, and so on. It all depends on the perspective one is taking when assessing a given production system. This implies that "production system state" can be described as a linguistic variable whose values are words or phrases (Zadeh, 1988); thus, the concept can be freely defined by anyone. There is a degree of vagueness and subjectivity in assessing a linguistic variable, and fuzzy logic aims to tackle this problem (Kosko & Isaka, 1993). Fuzzy logic allows variables to be defined as multi-valued rather than having a Boolean value (Hellmann, 2001). In the context of production system state assessment, the first step is to select the set of states that will be used to define the production system. The second step is to find consensus on what metric will be used to evaluate the state and what the value range for each state is. Since fuzzy logic allows gradual transition of system states, it increases flexibility and decreases sensitivity when defining a metric to assess the production system state. Moreover, fuzzy logic helps account for subjectivity and having a system state with multiple values or a range of values. This leads to different states overlapping rather than having a fixed threshold value subjective to what managers might select.

A new metric *TPT/PLT* is introduced for using with fuzzy analysis to assess the production system state. This chapter explains how TPT and PLT were derived from the simulation models, and it explains the ratio and the indications of the values obtained from dividing TPT by PLT. The chapter also elaborates on how Monte Carlo simulation was used to generate TPT/PLT values and how they were then fitted in the fuzzy diagram. Lastly, this chapter explains the reasoning and the methodology adopted to systematically assess the production system state in a holistic manner.

## 6.2 TPT/PLT

To obtain an all-inclusive perspective on the production system, a metric is introduced to serve as an indicator of the production system state, as calculated using Equations 7 and 8:

Equation 7:

$$TPT = \sum Cycle\ Time\ of\ stations\ on\ the\ critical\ path$$

Equation 8:

$$\frac{TPT}{PLT} = \frac{Total\ Processing\ Time}{Production\ Lead\ Time}$$

TPT reflects the maximum time a cabinet would spend being processed by stations. The only stations in the system that run parallel are the router and panel saw; all stations downstream of these driving stations are in series. Comparing the router and panel saw cycle times, the router needs more time to process one cabinet than the panel saw and thus is concluded to be on the critical path. This is reflected in the modelling results, where the panel saw is determined to be underutilized, because it is faster than the router and the EB. Therefore, the system critical path is as follows:

1- Router
2- EB
3- Pre-assembly
4- Final assembly

The difference between the processing time and the PLT reflects how well station cycle times are balanced, how much capital costs are tied to WIP, how lean the system is, and how much room for improvement exists. A major difference indicates that the system contains a lot of WIP and waste, and the cabinets are spending more time than they should be to be processed. This means that a significant difference exists between stations' cycle times, and there are bottlenecks stressing the system. Furthermore, the capital costs tied into the system are high, and the risk of incurring quality issues increases because of the unnecessary time wasted by cabinets waiting to be processed. Lastly, this problem serves as an significant indicator that something should be changed and improved in the system.

The value stream map gave an average overview of the TPT/PLT metric based on observations, where both metrics were deterministic. Obtaining TPT and PLT from simulation, both metrics can be represented stochastically, reflecting a more reliable value, using Equations 9 and 10:

Equation 9 (PLT range):

$$TPT < PLT < \infty$$

Equation 10 (TPT range):

$$0 < TPT < \infty$$

TPT/PLT is bounded between 0 and 1 as shown in Equations 11 and 12. In reality, PLT is much greater than TPT. Moreover, PLT has a lot more variability and fluctuates a lot in the system. TPT is expected to be bounded between 25 and 35 minutes and is not expected to decrease significantly even when the lean interventions are implemented. This is because the critical path comprises 4 stations, and to improve TPT significantly a large amount of capital must be invested in the machinery. Therefore, the analysis focused on how PLT changes within the system before and after the interventions. If the PLT is much greater than the TPT, then the TPT/PLT metric approaches closer to 0, indicating a highly unbalanced production system. On the other hand, as the PLT decreases, the metric approaches closer to 1, indicating a balanced production system state where cabinets do not spend much time in the system before exiting. An ideal case scenario is a "one piece flow" where no WIP exists between stations and cabinets, in which case PLT would be equal to the sum of stations' processing times.

Equation 11 (TPT/PLT upper limit):

$$\lim_{PLT \to TPT} \frac{TPT}{PLT} = 1$$

Equation 12 (TPT/PLT lower limit):

$$\lim_{PLT \to \infty} \frac{TPT}{PLT} = 0$$

In reality, PLT cannot be less than the TPT. Since both metrics are represented stochastically, sampling from distributions can lead to either negative values of the individual metrics, or a ratio greater than 1. Both scenarios are regarded as non-behavioural and are disregarded in the analysis.

## 6.3 Monte Carlo Simulation

PLT data was obtained from the simulation models and graphed to show the pattern of cabinet waiting time in the system. The data was also fitted into a distribution to sample from it. A program evaluation and review technique (PERT) simulation model was used to obtain the TPT, since every station cycle time has a different distribution. Figure 34 shows the PERT model developed on Simphony.NET to obtain data points for TPT, which were later fit into a distribution.

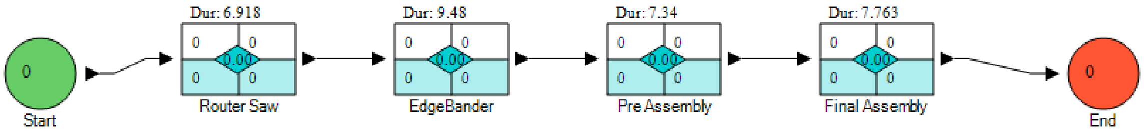


**Figure 34:** Station TPT simulation using a PERT network

Both metrics were fitted into distributions to build a Monte Carlo simulation model and then divide to obtain TPT/PLT, which is projected on a fuzzy diagram for system state assessment. Both metrics had a large sample number and were fitted to a normal distribution. Table 12 shows the mean, standard deviation, and K-S value for each metric. For both metrics, the significance level chosen is 10%, and the sample number is 500. Equation 13 was used to define the critical K-S value. Two null hypotheses were posited, one for TPT and one for PLT, stating each was normally distributed. The KS value for both metrics was less than the critical value; therefore, these two null hypotheses are accepted.

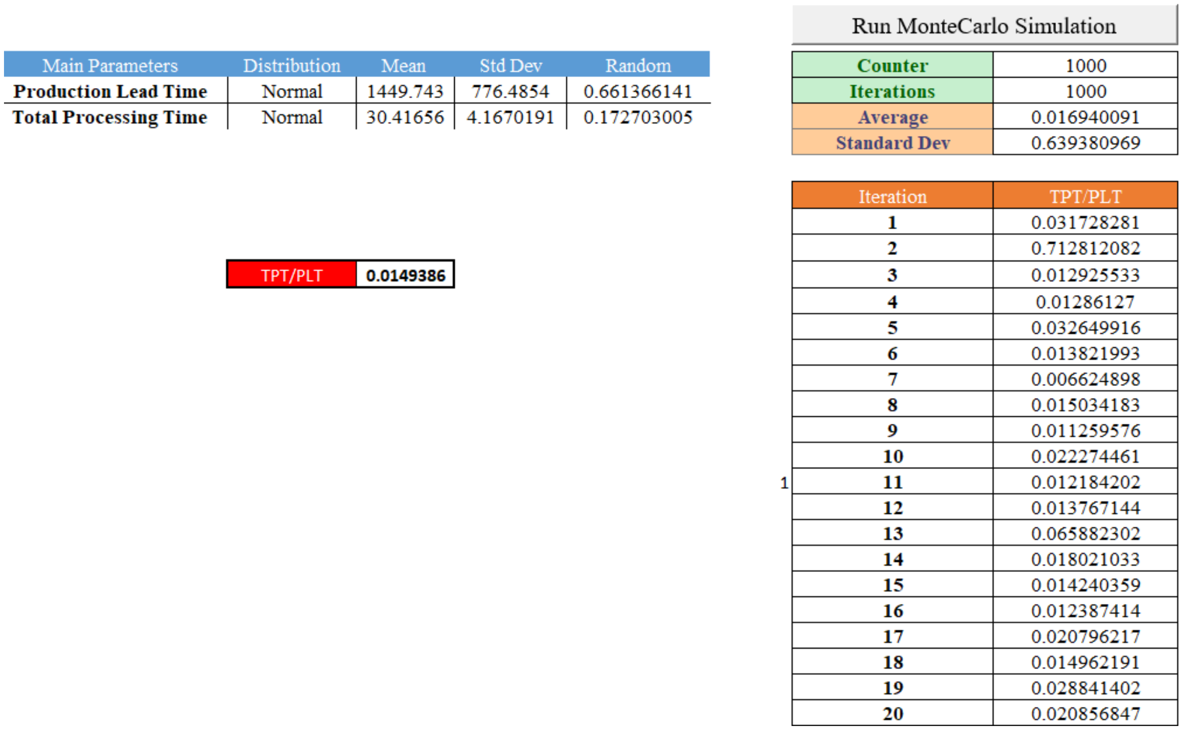
Equation 13 (KS critical value for N = 500):

$$KS\ critical\ value = \frac{1.22}{\sqrt{N}} = 0.0385$$

**Table 12:** PLT and TPT normal distribution parameters and KS values

| Model | Metric | Mean (min.) | Standard deviation (min.) | K-S value |
|---|---|---|---|---|
| Current state | PLT | 1449.74 | 776.49 | 0.02861 |
| | TPT | 30.42 | 4.17 | 0.0221 |

Figure 35 shows the Monte Carlo simulation model built on MS Excel. The distributions reflect the PLT and TPT based on the current state. In every iteration, the model samples a random number from each parameter and divides them to obtain TPT/PLT. The model runs for 1000 iterations.



| Main Parameters | Distribution | Mean | Std Dev | Random |
|---|---|---|---|---|
| **Production Lead Time** | Normal | 1449.743 | 776.4854 | 0.661366141 |
| **Total Processing Time** | Normal | 30.41656 | 4.1670191 | 0.172703005 |

| TPT/PLT | **0.0149386** |
|---|---|

| | |
|---|---|
| **Counter** | 1000 |
| **Iterations** | 1000 |
| **Average** | 0.016940091 |
| **Standard Dev** | 0.639380969 |

| Iteration | TPT/PLT |
|---|---|
| **1** | 0.031728281 |
| **2** | 0.712812082 |
| **3** | 0.012925533 |
| **4** | 0.01286127 |
| **5** | 0.032649916 |
| **6** | 0.013821993 |
| **7** | 0.006624898 |
| **8** | 0.015034183 |
| **9** | 0.011259576 |
| **10** | 0.022274461 |
| **11** | 0.012184202 |
| **12** | 0.013767144 |
| **13** | 0.065882302 |
| **14** | 0.018021033 |
| **15** | 0.014240359 |
| **16** | 0.012387414 |
| **17** | 0.020796217 |
| **18** | 0.014962191 |
| **19** | 0.028841402 |
| **20** | 0.020856847 |

**Figure 35:** Monte Carlo simulation model

### 6.4 Fuzzy Diagram

To build the fuzzy diagram, the system states of their membership functions should be defined. The membership function defines the range of values each state occupies. A collaborative meeting was held between the general manager, the production manager, and the order desk manager to agree on how to define a system state and how each state can be translated quantitatively. The consensus was to define three system states and decide what each state means. The system states, which are fuzzy sets, are defined as either “unbalanced,” “balanced,” or “near-optimal.” The managers agreed that if a cabinet spends 1 day to exit the system, then the production system would be “near-optimal.” If a cabinet spends 2 days on the shop floor before it exits final assembly, the system state would be considered “balanced.” The worst-case scenario is when a cabinet spends 4 days in the system before exiting; the system state would be considered “unbalanced.”

The durations agreed on were used to define the membership function of each set. This consensus gave context to the fuzzy analysis in which the states reflect the specific shop floor studied. These durations that define the system state were translated to TPT/PLT metric: durations for each state are substituted for PLT and TPT is taken to be 30 minutes which is the average obtained from the analysis. Equations 14, 15, and 16 describe triangular membership functions of the following fuzzy sets respectively: “unbalanced,” “balanced,” and “near-optimal.”

Equation 14, membership function for the unbalanced state:

$$\mu_{UB}(x) = \begin{cases} \dfrac{x - 0.02038}{0.01315 - 0.02083}, & 0.01315 \leq x \leq 0.02083 \\ 1, & 0 \leq x < 0.01315 \\ 0, & otherwise \end{cases}$$

Equation 15, membership function for the balanced state:

$$\mu_{B}(x) = \begin{cases} \dfrac{x - 0.01315}{0.02083 - 0.01315}, & 0.01315 \leq x \leq 0.0283 \\ \dfrac{x - 0.0526}{0.02083 - 0.0526}, & 0.0283 < x \leq 0.0526 \\ 0, & otherwise \end{cases}$$

Equation 16, membership function for the near-optimal state:

$$\mu_{NO}(x) = \begin{cases} \dfrac{x - 0.02038}{0.0526 - 0.02038}, & 0.02038 \leq x \leq 0.0526 \\ 1, & 0.0526 < x \leq 1 \\ 0, & otherwise \end{cases}$$

Figure 36 shows the fuzzy diagram of the three fuzzy sets. The diagram is intentionally built to be symmetrical, so every point would be normalized to give three percentages that add up to 100%. This means every iteration of TPT/PLT projected on the fuzzy diagram indicates the percentage of time the system would be “unbalanced,” “balanced,” and “near-optimal” based on the conditions of the sample iteration, which reflect an average and a holistic image of the system in the long term. Sampling 1000 iterations would give a reliable and confident average percentage of each system state.

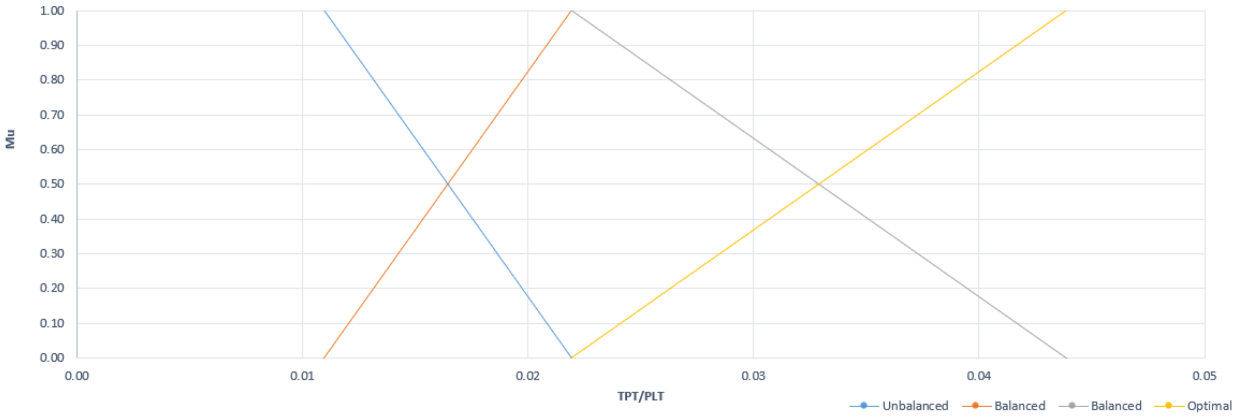
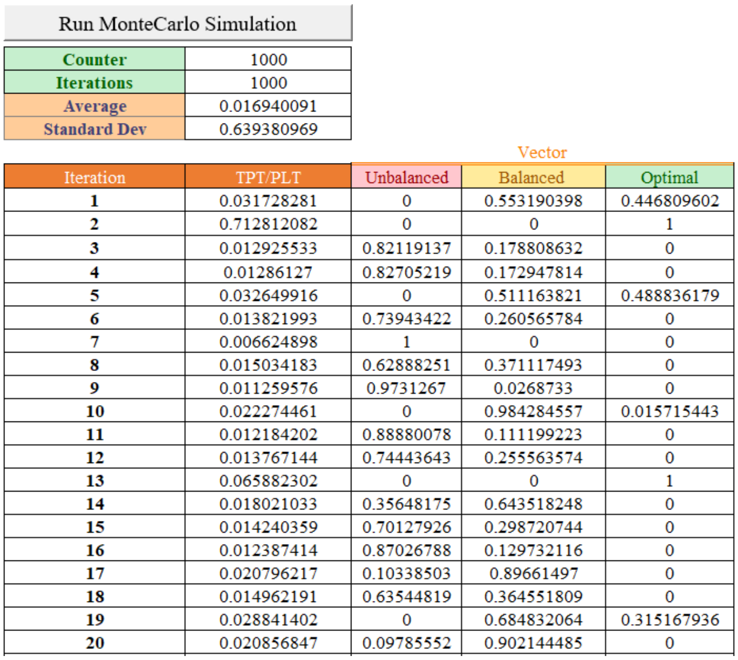


**Figure 36:** Fuzzy diagram

Figure 37 shows the substitution of iterations in the three membership functions, which in turn gives a value between 0 and 1 for each state; every iteration would have a total vector summation of 1 due to the symmetry of the fuzzy sets. Then, for each state, the average percentage is obtained by summing the percentages of the state from all iterations and dividing it by the total number of iterations as shown in Equation 17. This reflects the probability of occurrence for each state, where the sum of the three probabilities equals 100%.



| | |
|---|---|
| **Counter** | 1000 |
| **Iterations** | 1000 |
| **Average** | 0.016940091 |
| **Standard Dev** | 0.639380969 |

| | | Vector | | |
|---|---|---|---|---|
| Iteration | TPT/PLT | Unbalanced | Balanced | Optimal |
| **1** | 0.031728281 | 0 | 0.553190398 | 0.446809602 |
| **2** | 0.712812082 | 0 | 0 | 1 |
| **3** | 0.012925533 | 0.82119137 | 0.178808632 | 0 |
| **4** | 0.01286127 | 0.82705219 | 0.172947814 | 0 |
| **5** | 0.032649916 | 0 | 0.511163821 | 0.488836179 |
| **6** | 0.013821993 | 0.73943422 | 0.260565784 | 0 |
| **7** | 0.006624898 | 1 | 0 | 0 |
| **8** | 0.015034183 | 0.62888251 | 0.371117493 | 0 |
| **9** | 0.011259576 | 0.9731267 | 0.0268733 | 0 |
| **10** | 0.022274461 | 0 | 0.984284557 | 0.015715443 |
| **11** | 0.012184202 | 0.88880078 | 0.111199223 | 0 |
| **12** | 0.013767144 | 0.74443643 | 0.255563574 | 0 |
| **13** | 0.065882302 | 0 | 0 | 1 |
| **14** | 0.018021033 | 0.35648175 | 0.643518248 | 0 |
| **15** | 0.014240359 | 0.70127926 | 0.298720744 | 0 |
| **16** | 0.012387414 | 0.87026788 | 0.129732116 | 0 |
| **17** | 0.020796217 | 0.10338503 | 0.89661497 | 0 |
| **18** | 0.014962191 | 0.63544819 | 0.364551809 | 0 |
| **19** | 0.028841402 | 0 | 0.684832064 | 0.315167936 |
| **20** | 0.020856847 | 0.09785552 | 0.902144485 | 0 |

**Figure 37:** TPT/PLT substituted in the membership functions

Equation 17, probability of occurrence for each system state:

$$System\ State\ (percentage) = \frac{\sum_{i=1}^{N} Mu_{System\ State}}{Total\ Number\ of\ iterations}$$

Based on current conditions of the production system, the system state is unbalanced 32.46% of the time, balanced 41.22% of the time, and near-optimal 26.32% of the time; Table 13 summarizes these results. The simulation was run 100 times to obtain a range for every state percentage. The ranges are limited within 5%, which also increases the reliability of the results. Moreover, the ranges indicate that the results may vary and are not 100% precise, but rather accurate with respect to the true state of the system. The most important takeaway is to know how the system is behaving based on current conditions. The percentages reflect a holistic assessment of the production system. The analysis performed at the micro level validates the results obtained in this model, since for a significant percentage of time the cabinets spend more than 4 days in the system before exiting. This model will be used for analysis of lean interventions as a tool for assessing the system state before and after the changes suggested.

**Table 13:** Percentage of each system state

| **Model** | **System state** | | |
|---|---|---|---|
| | **Unbalanced (%)** | **Balanced (%)** | **Near-optimal (%)** |
| Current state | 32.46 +/- 3.49 | 41.22 +/- 4.98 | 26.32 +/- 1.55 |

### 6.5 Conclusions

In this chapter, a novel metric "TPT/PLT" was introduced for assessing the production system state. The metric is based in lean thinking, since it reflects the degree of waiting time in the system with respect to actual processing time by the stations. It is intended to reflect how much waste is embedded and thus what the state of the system is. The chapter also explains how Monte Carlo simulation was used to compute TPT/PLT and how the metric is used with fuzzy logic to assess the system state, which is a linguistic variable. Three system states, represented as fuzzy sets with membership functions, were defined: "unbalanced," "balanced," and "near-optimal." Based on the current state, the system state is unbalanced 32.46% of the time, balanced 41.22% of the time, and near-optimal 26.32% of the time. This indicates great room for improvement, since for a significant percentage of time, the cabinets are expected to wait 4 or more days in the system before exiting. This serves as a reference on which several lean interventions will be suggested and simulated to be compared to the base scenario (current state), which is thoroughly explained in Chapter 7.

# Chapter 7 – Improving the Production System State

## 7.1 Introduction

The comprehensive and detailed study of the stations and the workflow is paramount and serves as a critical prerequisite to putting effort into improving the production system. People cannot improve what they cannot measure, nor what they do not understand. Moreover, having little knowledge about a topic is dangerous. Therefore, understanding the problem using available data and potential data to collect solves half of the problem of improving the production system. The approach in troubleshooting production problems is based on scientific and saturated judgment of the production system. This lies in at foundation of lean philosophy and is reflected in the 14 principles of the Toyota Way (Liker, 2004), two of which are as follows:

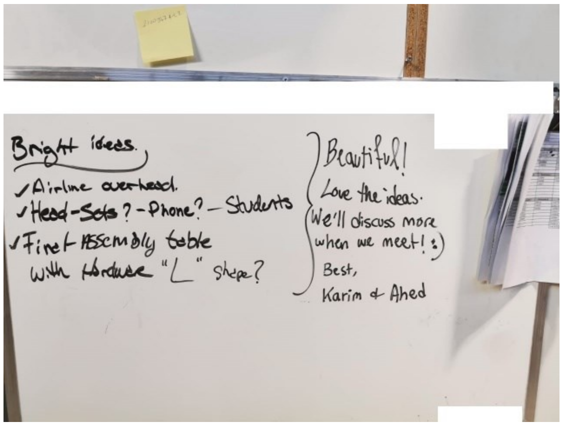
- Principle 12: "*Go and see for yourself to thoroughly understand the situation.*"

Problems arising in production have deeper root causes that cannot be unveiled unless one observes them directly. Instead of hypothesizing about the basis of opinions and reports, one should verify the data themselves by going to the shop floor and looking for the source of their problem. Understanding the problem superficially leads to sub-optimal or in some cases ineffective improvements.

- Principle 13: *"Make decisions slowly by consensus, thoroughly considering all options; implement decisions rapidly."*

Decisions and solutions to problems come from a collective effort rather than an individual one. This principle was carried out throughout the study, especially during the time spent on the shop floor. The ethnographic nature of the approach helped collect ideas from the operators themselves who turned out to know lean philosophy intrinsically, without knowing that it is called "lean." Production problems affect the operators directly, and thus they should be directly involved in the process of improving the production system. After understanding the problem and collecting data, the options are presented for further investigation. Based on the analysis of the result of this initial investigation, an action plan is set for rapidly implementing the decisions agreed on.

Some solutions or interventions impose a radical change on the way the production system functions and are considered to be major and costly. These require the acceptance of upper management and senior level personnel. However, a lot of solutions that are practical, effective, and instant also affect both production and operators positively. These solutions are often suggested by the operators, because they understand the repetitive pattern of their work and thus are able to suggest practical improvements that would make their work easier. During the study, we asked the operators to write on a whiteboard any improvement idea that comes to their minds while they are working. Figure 38 shows a few ideas suggested by an operator that would improve the workflow and boost the team's morale. The air hose was a tripping hazard and suggested to be overhead; moreover, the operators suggested headsets or phones for a means of communication between stations rather than leaving the station to talk to other operators. Lastly, the last idea suggested an "L" figuration of the final assembly cleaning table which makes the work easier for people cleaning the cabinet fronts.



Bright ideas.
✓ Airline overhead.
✓ Head-Sets? - Phone? — Students
✓ Final Assembly table
With Hardware "L" shape?

Beautiful!
Love the ideas.
We'll discuss more
when we meet! :)
Best,
Karim & Ahed

**Figure 38:** Operators' improvement ideas

These suggestions need to be addressed and discussed frequently with the operators. The ideas should never be taken for granted, or else the momentum will fade and operators will feel demoralized knowing that their voice has not been heard. The act of tapping into the knowledge of operators should be accompanied with the intention of applying this knowledge and giving credit to those who proposed the ideas. This kind of work culture encourages everyone to participate and share their ideas, and this permission-based leadership culture promotes innovation. Moreover, operators will be more likely to look forward to work every day knowing that they are part of the improvement process.

The most important factor is consistency. For the abovementioned cultural change to happen, the right mindset should start with the upper management. This requires time and patience, because this change is hard and exceptionally slow; it does not happen overnight. With consistent effort and encouragement for operators to take part in the improvement process, the momentum will increase and the floor will then run as if on autopilot. The secret lies in the leap of starting this change and sticking to it until it becomes the new norm.

This chapter explains the lean interventions inspired from the researcher's time spent on the floor, the data collected, and the results obtained from the SM and fuzzy model developed. Lastly, the chapter elaborates on the results generated from simulating the interventions and compares them to the current state to quantitatively study the impact of these interventions.

## 7.2 Lean Interventions

After assessing the state of the production system and understanding the operations at a high level of detail, suggestions for improvement are proposed based on a lean point of view.

### 7.2.1 Intervention 1: Organizing and standardizing the final assembly station

The final assembly station is the most dynamic station in the shop floor. The time motion study breaks down the station into a sequence of activities: (1) cleaning the cabinet boxes, (2) cleaning the fronts, (3) installing hardware, (4) installing the fronts, (5) wrapping the cabinet with cardboard, (6) wrapping the cabinet with plastic wrap, (7) moving the cabinet onto a palette, and (8) wrapping the palette with plastic wrap. With 4 operators working, the station becomes dynamic, because there is no dedicated operator for every task or even group of tasks. The operators keep moving from one place to another doing what they judge to be necessary. This creates waste in terms of time (searching for a task, moving around without adding any value, etc.) and production (doing tasks in the wrong sequence, missing tasks, etc.). Moreover, this causes rework, decrease in production rate, deterioration in quality, and increase in cycle time variability. Most importantly, it causes stress for operators in terms of being able to follow the delivery schedule and produce cabinets on time.

These challenges are addressed by standardizing the work sequence and giving operators a specific task or group of tasks to do. This will minimize missing any steps; narrow the focus of operators to a certain task or group of tasks, which helps them perform correctly the first time; improve quality and production rate; and decrease cycle time variability.

With the assumption that 4 operators are working on final assembly, the suggestion is to group the activities into 4 subtasks and assign each operator to one subtask. Table 14 shows the categorization of activities into subtasks.

**Table 14:** Final assembly subtask division

| Subtask | Activities |
|---|---|
| 1 | - Clean door fronts<br>- Install hardware |
| 2 | - Clean cabinet boxes<br>- Install door fronts and drawers on the cabinet |
| 3 | - Wrap the cabinet with card board and plastic wrap |
| 4 | - Place the cabinet on the palette<br>- Wrap palettes |

### 7.2.2 Intervention 2: Sorting cabinets and re-designing the router carts

The router carts move cabinet parts between three stations: (1) between the router and the EB and (2) between the EB and the pre-assembly stations. After the router cuts the sheets into cabinet parts, the cart goes to the EB, where the operator takes every part to tape it and then puts it back into the cart. The cart then goes to pre-assembly, where the operator takes all parts from the cart and makes cabinet boxes. Lastly, the cart returns to the router to be filled with cabinet parts again. The end customer of the router cart is the pre-assembly station, and the current cart design is hindering the performance of the pre-assembly station significantly.

The pre-assembly station has 3 main subtasks: (1) dowelling, (2) installing hardware (drawer guides and shelf pins), and (3) building the cabinet box. Figure 39 shows the cabinet with different parts that are all received at pre-assembly (except the drawer guides). For dowelling, only the top stretchers and the cabinet bottoms are dowelled. For installing hardware, only gables are used to install drawer guides and/or shelf pins. These parts are assembled and built together to complete the box at the building subtask.

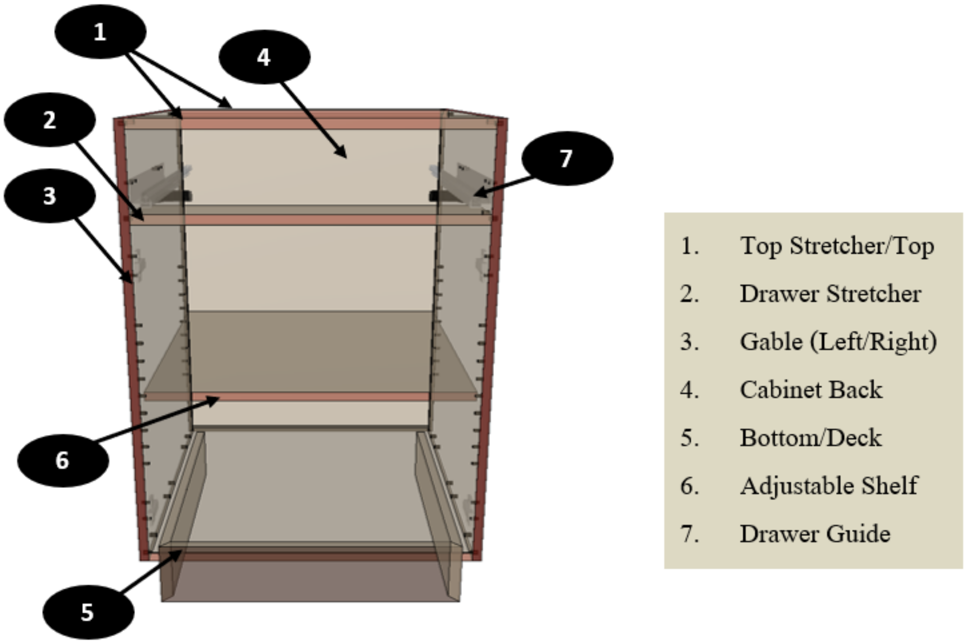


**Figure 39:** Cabinet parts

As explained in Chapter 3, every cabinet part is labeled with a cabinet number; thus, every part belongs to a certain cabinet. First, the operators receive the cart for a certain job, put the backs on the pre-assembly line, and start searching for the right cabinet part to work with. The operators dowel the top stretchers and cabinet bottom, install hardware on the gables, and then put them on their designated cabinet back (they all have the same cabinet number). The operators are responsible for sorting all cabinet parts on the line based on their cabinet number. The time the operators waste searching for the right parts in the cart hampers production and workflow. Moreover, the operators feel demoralized searching for parts every time. Sometimes, a job might have 2 or 3 router carts carrying the cabinet parts. Operators have to search through all these carts to find the right parts and the right cabinet number.

Figure 40 shows the operator searching for the second gable that belongs to a certain cabinet. Even when the operator finishes installing hardware on the gables, he or she will waste time searching for the cabinet parts on the line to put the gables above them. This is because neither the pre-assembly line nor the router carts are sorted based on cabinet number or cabinet parts. The parts are assumed to be all in the cart without any order. To reduce the time wasted on sorting cabinet parts and to eliminate the probability of having missing parts, the router carts need to be redesigned, and the cabinet parts generated from the router should follow a pre-defined order.

**Figure 40:** Pre-assembly operator searching for parts

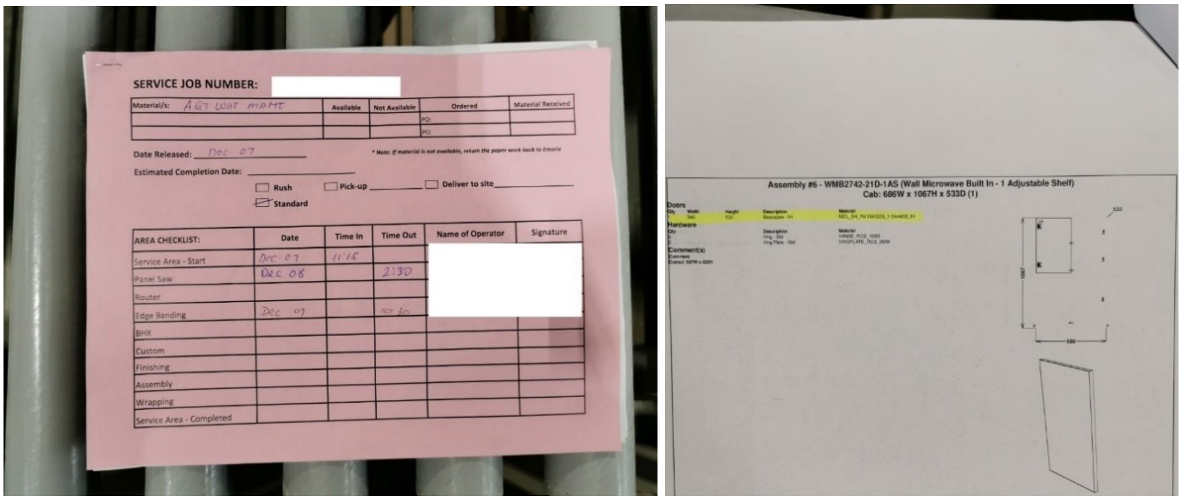
Currently, the operator of the router picks a job and orders the router to cut it. The machine automatically optimizes the cutting pattern of the sheets to minimize the waste parts cut from the sheets. However, the parts cut from a single sheet do not necessarily belong to a single cabinet. For example, one sheet can generate one gable for cabinet number 3, two stretchers for cabinet number 15, and one back for cabinet number 5. The sheets are only cut per job, but not per cabinet. The sorting of different cabinet parts per type and per cabinet number is done at pre-assembly.

The solution includes two main changes on the shop floor: (1) optimize the cutting pattern of sheets on the router so that cabinet parts generated start from cabinet number 1 ascendingly to the last cabinet number, or (2) redesign the router cart to have compartments where every compartment is for a certain cabinet number.

### 7.2.3 Intervention 3: Implementing Kanban for service jobs and recuts

The service station handles orders coming from the installation crew on site. After a job is manufactured and shipped to site, the installation crew is responsible for installing the cabinets as per drawings and specs given by the customer. If cabinets are damaged during shipping or on site or are not built correctly as per the specs, the crew reports the problem and sends affected cabinets back to manufacturing with specific instructions. The service station handles these problems and tracks all orders coming from site. The order might be a cabinet part, a panel, or even sometimes a full cabinet. The operator receives the order and the date for reshipping it back to site. He or she is responsible for going to the stations and asking operators to cut specific part types or full cabinets and then tracking them to make sure they are ready for shipment.

The service station is not part of the production process; however, it affects production performance and the value stream. The material, labour hours, and operating time consumed on service parts are considered waste, because they do not generate new revenue and are not part of production. Service is inevitable and necessary in every production facility; however, it needs to be minimized. The root cause of installation problems comes mainly from design. The design department should have full and final design specs and drawings before sending a job for manufacturing. When design specs are assumed or miscommunicated, the problem only surfaces when the installation crew receives the order on site. However, this does not mean that effort should not be put towards organizing service jobs on the shop floor. The service operator first goes to the router and/or panel saw with a service sheet indicating the job number, part specs and drawings, and type of service order ("standard" being non-critical and "rush" being critical). Figure 41 shows a service sheet for a specific job that requires a part to be cut on the panel saw and then taped on the EB. The drawing specifying the specs is attached to the service sheet.



SERVICE JOB NUMBER: [redacted]

| Material/s: AGT WHT MAHT | Available | Not Available | Ordered | Material Received |
|---|---|---|---|---|
| | | | PO: | |
| | | | PO: | |

Date Released: Dec 07

Estimated Completion Date:

* Note: If material is not available, return the paper work back to Emorie

☐ Rush ☐ Pick-up ☐ Deliver to site

☑ Standard

| AREA CHECKLIST: | Date | Time In | Time Out | Name of Operator | Signature |
|---|---|---|---|---|---|
| Service Area - Start | Dec 07 | 11:15 | | [redacted] | [redacted] |
| Panel Saw | Dec 08 | | 2:30 | [redacted] | [redacted] |
| Router | | | | [redacted] | [redacted] |
| Edge Banding | Dec 09 | | 10:20 | [redacted] | [redacted] |
| BHX | | | | | |
| Custom | | | | | |
| Finishing | | | | | |
| Assembly | | | | | |
| Wrapping | | | | | |
| Service Area - Completed | | | | | |

Assembly #6 - WMB2742-21D-1AS (Wall Microwave Built In - 1 Adjustable Shelf)
Cab: 686W x 1067H x 533D (1)

Doors

Hardware

Comment(s)

**Figure 41:** Service sheet

A lot of times, the saw operators took the sheet and forgot about it if they were busy cutting a certain job. The service operator is responsible for keeping up with them and reminding them to cut the required parts. After that, the operators need to tape the parts so they are ready for shipping or track the cabinets through the stations for assembly if the order includes cabinets. This way of handling service jobs leads to several problems: (1) it puts the operator under stress of tracking service jobs and completing them on time, (2) interrupts driving stations halfway through production (especially if the service job needs to be cut right away, as for a rush order), and (3) impedes production performance and workflow.

The ideal solution is to minimize service jobs starting from the design department. Nonetheless, service operations need to be improved on the shop floor. Instead of going back and forth between stations asking for operators to cut specific cabinet parts for a service job, the responsibility should be shared among all operators on the shop floor and a standardized way should be devised to receive, cut, and ship service orders. A Kanban system can solve regulation of the service process and smooth the disruption caused by service jobs and recuts. Using scrap material, wooden pantries dedicated to service can be built beside the panel saw, router, and EB stations. Service sheets can be placed beside the pantries at the beginning of the day, and operators would be able to finish service jobs after cutting all the regular jobs scheduled for that day. The service parts could be put in the pantry after cutting them, then the service operator would either move them to the next station if needed or put them aside for shipping if ready. This would help improve the production rate and workflow of the driving stations and the EB. The solution would eliminate work interruption and help in tracking service jobs efficiently. Moreover, it would help share accountability and responsibility among operators to finish service jobs on time instead of putting all the responsibility on the service operator to track them. Lastly, it would help utilize the time buffer available for the driving stations more efficiently. The operators would process service jobs when they do not have any job waiting to be processed, which would increase the utilization of the station and stabilize the workflow instead of stressing it.

### 7.3 Intervention Simulation

The station cycle times modelled in the current state have variability embedded. The cycle time reflects the value-adding and non–value-adding time all in one production rate. The interventions proposed are simulated using different approaches depending on the available data.

### 7.3.1 Intervention 1 simulation

After organizing the station into four different subtasks that can run simultaneously, the production rate of final assembly will be that of the slowest subtask. The time and motion studies helped give an estimate of how fast the station is able to produce if this intervention is implemented, because the activities were tracked at the level of subtasks. However, the production data retrieved from the company's database only reflect the final production rate as cabinets. Table 15 shows the average cycle times calculated for each subtask based on the time studies completed.

**Table 15:** Final assembly station subtasks and their cycle times

| Subtask | Activities | Average CT (min.) |
|---|---|---|
| 1 | - Clean door fronts<br>- Install hardware | 2.101 |
| 2 | - Clean cabinet boxes<br>- Install door fronts and drawers on the cabinet | 3.205 |
| 3 | - Wrap the cabinet with card board and plastic wrap | 2.954 |
| 4 | - Place the cabinet on the palette<br>- Wrap palettes | 5.87 |

The last subtask is the bottleneck, since it has the largest cycle time; it controls the pace of production. However, this configuration will still improve the station overall. Organizing and standardizing the tasks will improve production quality by minimizing mistakes given every operator will have a dedicated task that he/she is responsible of. Comparing the current cycle time to the one after the intervention, it is improved by 27%.

### 7.3.2 Intervention 2 simulation

The pre-assembly station is more organized compared to the final assembly station. This helps detect and record the repetitive wasted time searching for parts. This intervention impacts pre-assembly and final assembly because sorted cabinets would also help final assembly with cabinet counting. Operators on both stations would now know if any cabinet is missing and can search for the root cause. Based on the current state, this problem surfaces right before shipping when the last cabinet count is made.

Although redesigning the router cart and sorting cabinets ascendingly based on their numbers would affect both stations directly, the impact is limited to the time wasted searching for parts and sorting cabinets on the line in pre-assembly only. To simulate this intervention, the wasted time recorded in the time studies is removed. Table 16 shows the mean and standard deviation of the pre-assembly cycle time before and after the intervention.

**Table 16:** Pre-assembly cycle time before and after intervention 2

| | **Mean (min./cabinet)** | **Standard deviation** |
|---|---|---|
| Current state | 5.981 | 1.221 |
| With intervention 2 | 4.2711 | 0.525 |

This intervention improves both cycle time and variability of the station. The variability decreases because it came from the time wasted to search for the cabinet parts and sort them on the pre-assembly line. The station cycle time improved 29%.

### 7.3.3 Intervention 3 simulation

Service jobs and recuts mostly impact the router, panel saw, and EB. Interruption of the router and panel saw requires additional setup time to resume to the job the operator was cutting before the interruption. With respect to the EB, the operator has to stop edge taping to change the tape to the one specific to the service parts, tape the parts, and lastly change the tape back to continue his or her work. This interruption impacts the station cycle time negatively, disrupts momentum, increases waste, and impacts operators’ morale. The cycle times of the EB and router include recuts and service as non–value-adding time; they slow down production and do not contribute to the final product of new cabinets.

From the production data obtained from the company, it was clear that the service jobs and recuts are mostly sent to the router rather than the panel saw. Therefore, the data for recuts and service jobs assigned to the router are used for analysis. To simulate the impact of this intervention, it is assumed that the recut orders and service jobs received for the router are the same as the ones received for the EB. The orders first go to the router as sheets to cut, and then to the EB as parts to tape. Also, the percentage improvement in the router or panel saw cycle time is also assumed to be the same for the EB.

From the production data, service jobs and recuts make up an average of 21% of sheets cut on the router. By implementing a Kanban system, both the router and the EB stations can improve value-adding time throughout their production. Moreover, Kanban facilitates using station time buffer to finish service jobs and recuts only after finishing scheduled jobs for the day. Therefore, this intervention is assumed to replace the 21% non–value-adding sheets by value-adding sheets contributing to final production. Thus, cycle time of both stations is assumed to improve by 21%.

### 7.4 Results and Discussion

The interventions were simulated to study their impact on the production system. PLT, station utilization, WIP inventory levels, and the system state based on the fuzzy model were obtained and analyzed. First, the interventions were simulated individually, and then different combinations were tested to find their impact. Lastly, the combination that yielded the best results was recommended.

#### 7.4.1 Production lead time (PLT)

All interventions were effective in improving specific stations; however, some had different impact on the performance of the system as a whole. Figure 42 shows the PLT of cabinets based on different conditions. The red dashed line shows the PLT of cabinets based on current conditions. Intervention 2 had no effect on the overall PLT, since final assembly was still hampering overall production, and cabinets would still wait on the final assembly line although the pre-assembly station was significantly improved.

Intervention 3 and intervention 2&3 negatively impacted PLT. PLT tends to increase to infinity, since the driving stations and pre-assembly became much faster than final assembly. This leads to stressing the system and building buffers between stations, since final assembly is not able to dissipate the load behind it. On the other hand, intervention 1, intervention 1&2, intervention 1&3, and intervention 1&2&3 improved PLT significantly. Implementing any of these combinations would decrease PLT on the long run. Intervention 1&2&3 had the most significant impact on PLT where cabinets would spend less than 2 days before exiting the system. Moreover, the trend is consistent and controlled rather than increasing compared to other intervention combinations and the current state. Therefore, intervention 1&2&3 is the most effective in improving PLT.

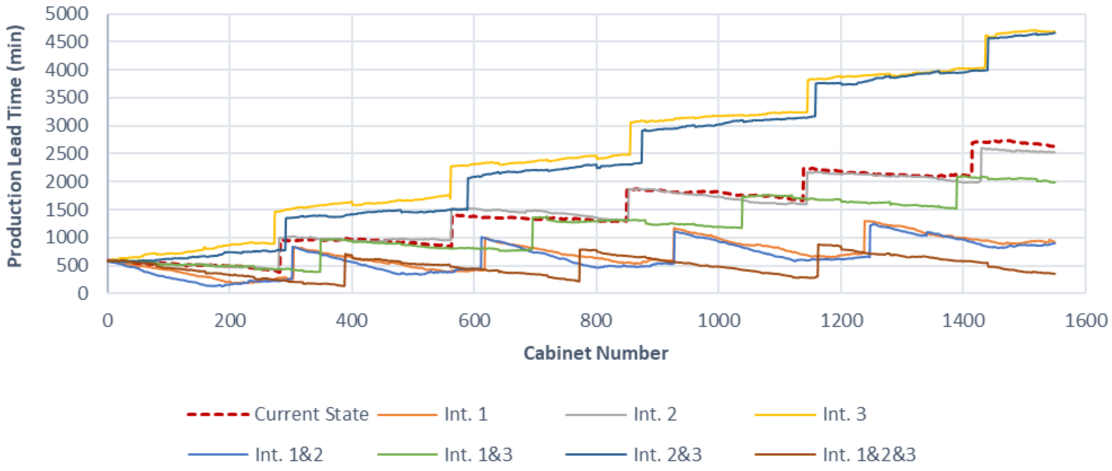


**Figure 42:** PLT based on different models

### 7.4.2 Station utilization

The interventions also impacted stations individually. The mean and standard deviation of each station utilization is shown in Figure 43. The bar graphs help visualize variability within each station and the difference in utilization between stations. A high standard deviation indicates a high variability in utilization, and a discontinuous line joining the bars with significant jumps or drops shows difference in utilization between stations. Difference in station utilization indicates unbalanced cycle times, which impacts the production rate and stations' performance. If the cycle times are unbalanced, slow stations with long cycle times are usually overwhelmed, and fast stations with short cycle times would starve for input. The ideal case is to have all stations balanced with equal cycle times; however, it is unrealistic to achieve this scenario consistently over time but possible to closely approximate it. Based on the current state, final assembly is the bottleneck, since its utilization is 100% with almost 0% standard deviation, meaning that the station is always occupied.

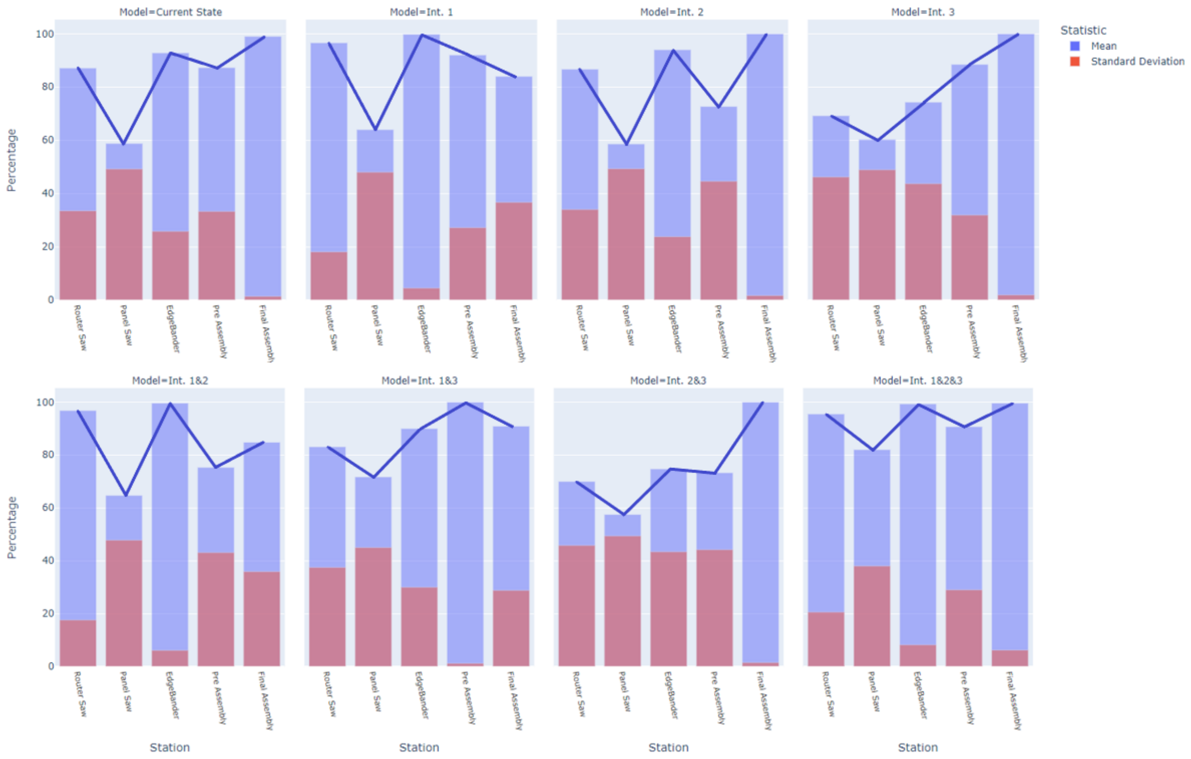


**Figure 43:** Station utilization based on different models

Compared to the current state, intervention 1 improved the final assembly station by stabilizing its utilization and the router by increasing its utilization by 9%. However, this intervention negatively impacted the EB station, making it the bottleneck. Intervention 2 sped up the pre-assembly station, leading to a drop in its utilization as it became faster than its preceding and succeeding stations; thus, it starved for work. Intervention 3 also improved the router and EB stations significantly, leading to a decrease in their utilization as their capacity increased with no change in their load. Moreover, final assembly was still the bottleneck and was still driving production based on its production rate and impeding all stations upstream.

Intervention 1&2 improved both the final and pre-assembly stations, and the router and EB stations became the bottlenecks of the production system. Intervention 1&3 improved the final assembly and driving stations, leading to overwhelming the pre-assembly station where it became the bottleneck. Intervention 2&3 negatively impacted all stations: final assembly was still the bottleneck, and utilization decreased significantly in all preceding stations. This is because improving certain station performances without considering the bottleneck increases the stress on the production system, as the difference in station performances increases and cycle times become more unbalanced. All interventions, except intervention 1&2&3, had minimal impact on the panel saw utilization, where it still showed the lowest utilization percentage.

Intervention 1&2&3 led to the best results in improving station utilization, since all utilizations increased to more than 80%, variability within every station utilization decreased, and the difference between utilizations also decreased. This indicates a significant improvement in balancing cycle times and improving both station and system performance. Table 17 shows the mean, standard deviation, and CV of every station utilization based on different interventions and their combinations. Moreover, the deviation of every utilization mean from the maximum utilization mean obtained in the model is calculated to highlight the greatest difference between station utilizations. A significant difference indicates an unbalanced system with unbalanced cycle times. CV indicates the degree of variation within a station; high CV indicates a variable and unstable station. The highest CV and the maximum deviation are highlighted in orange. As discussed above, the panel saw was underutilized and showed the highest variability. Only intervention 1&3 and intervention 1&2&3 decreased CV of the panel saw and closed the gap between stations' utilization to less than 30%.

**Table 17:** Station utilization mean and standard deviation obtained from different models

| **Model** | **Station** | **Utilization** | | | |
|---|---|---|---|---|---|
| | | Mean (%) | Std. dev. (%) | CV | Deviation from max. (%) |
| Current state | EB | 92.8 | 25.8 | 0.278 | 6.2 |
| | Final assembly | 99.0 | 1.4 | 0.014 | 0.0 |
| | Panel saw | 58.8 | 49.2 | 0.837 | 40.2 |
| | Pre-assembly | 87.3 | 33.3 | 0.381 | 11.7 |
| | Router saw | 87.1 | 33.5 | 0.385 | 12.7 |
| Int. 1 | EB | 99.8 | 4.5 | 0.045 | 0.0 |
| | Final assembly | 84.0 | 36.7 | 0.437 | 15.8 |
| | Panel saw | 64.0 | 48.0 | 0.750 | 35.8 |
| | Pre-assembly | 92.0 | 27.2 | 0.296 | 7.8 |
| | Router saw | 96.6 | 18.1 | 0.187 | 3.2 |
| Int. 2 | EB | 94.0 | 23.8 | 0.253 | 6.0 |
| | Final assembly | 100.0 | 1.7 | 0.017 | 0.0 |

| | | | | | |
|---|---|---|---|---|---|
| | Panel saw | 58.6 | 49.3 | 0.841 | 41.4 |
| | Pre-assembly | 72.7 | 44.6 | 0.613 | 27.3 |
| | Router saw | 86.7 | 34.0 | 0.392 | 13.3 |
| Int. 3 | EB | 74.3 | 43.7 | 0.588 | 25.7 |
| | Final assembly | 100.0 | 1.9 | 0.019 | 0.0 |
| | Panel saw | 60.3 | 48.9 | 0.811 | 39.7 |
| | Pre-assembly | 88.5 | 31.9 | 0.360 | 11.5 |
| | Router saw | 69.2 | 46.2 | 0.668 | 30.8 |
| Int. 1&2 | EB | 99.6 | 6.1 | 0.061 | 0.0 |
| | Final assembly | 84.8 | 35.9 | 0.423 | 14.8 |
| | Panel saw | 64.7 | 47.8 | 0.739 | 34.9 |
| | Pre-assembly | 75.3 | 43.1 | 0.572 | 24.3 |
| | Router saw | 96.8 | 17.6 | 0.182 | 2.8 |
| Int. 1&3 | EB | 90.0 | 30.0 | 0.333 | 10.0 |
| | Final assembly | 90.9 | 28.8 | 0.317 | 9.1 |
| | Panel saw | 71.7 | 45.0 | 0.628 | 28.3 |
| | Pre-assembly | 100.0 | 1.2 | 0.012 | 0.0 |
| | Router saw | 83.1 | 37.5 | 0.451 | 16.9 |
| Int. 2&3 | EB | 74.7 | 43.4 | 0.581 | 25.3 |
| | Final assembly | 100.0 | 1.5 | 0.015 | 0.0 |
| | Panel saw | 57.5 | 49.4 | 0.859 | 42.5 |
| | Pre-assembly | 73.3 | 44.2 | 0.603 | 26.7 |
| | Router saw | 70.0 | 45.8 | 0.654 | 30.0 |
| Int. 1&2&3 | EB | 99.3 | 8.2 | 0.083 | 0.3 |
| | Final assembly | 99.6 | 6.2 | 0.062 | 0.0 |
| | Panel saw | 82.0 | 38.0 | 0.463 | 17.6 |
| | Preassembly | 90.7 | 29.0 | 0.320 | 8.9 |
| | Router saw | 95.5 | 20.6 | 0.216 | 4.1 |

### 7.4.3 WIP inventory levels

The WIP levels in terms of cabinets in the three predefined locations are graphed over simulation time in every model as shown in figure 44. The pattern detected is more important than the exact number of WIP behind stations at a given point in time. The pattern helps identify the problem, its root cause, and possible implications from other stations. Comparing the interventions to the current state, intervention 1 significantly impacted the final assembly WIP levels, dropping them to less than 10 cabinets throughout the whole run. With a capacity of 30 cabinets, final assembly was clearly underutilized and starving for work. Moreover, this did not affect the WIP levels in the other two locations. Intervention 2 also had a myopic impact on the pre-assembly station, where the buffer built on Mondays was consumed faster after implementing intervention 2. This also did not affect the two other locations. Intervention 3 decreased the WIP inventory levels behind the EB station but overwhelmed pre-assembly and final assembly stations, where the levels reached and stayed at their maximums until the end of the simulation. This is because the EB became faster than its succeeding stations, thus overwhelming them with work and keeping the WIP levels at their maximum.

Intervention 1&2 improved both final and pre-assembly WIP levels. Both stations had controlled WIP levels over the simulation time and showed a consistent pattern where the buffer built was consumed during the middle of production week. Intervention 1&3 showed significant decrease in both EB and final assembly WIP levels. Final assembly was starved for work, but the EB station showed controllable and acceptable WIP levels that did not exceed 50 cabinets. Intervention 2&3 improved both pre-assembly and EB WIP levels, leaving final assembly overwhelmed throughout the whole run. Intervention 1&2&3 yielded the best pattern and levels in all three locations. The EB had a consistent WIP level to keep the station busy throughout the week, with levels controlled at less than 30 cabinets. The final assembly station also showed that it was not being constantly overwhelmed throughout the week; however, it was also occupied and utilized with a controllable WIP level behind it. The pre-assembly WIP levels also showed an acceptable pattern, since the buffer was neither building up to overwhelm the station throughout the week, nor was the station being underutilized.

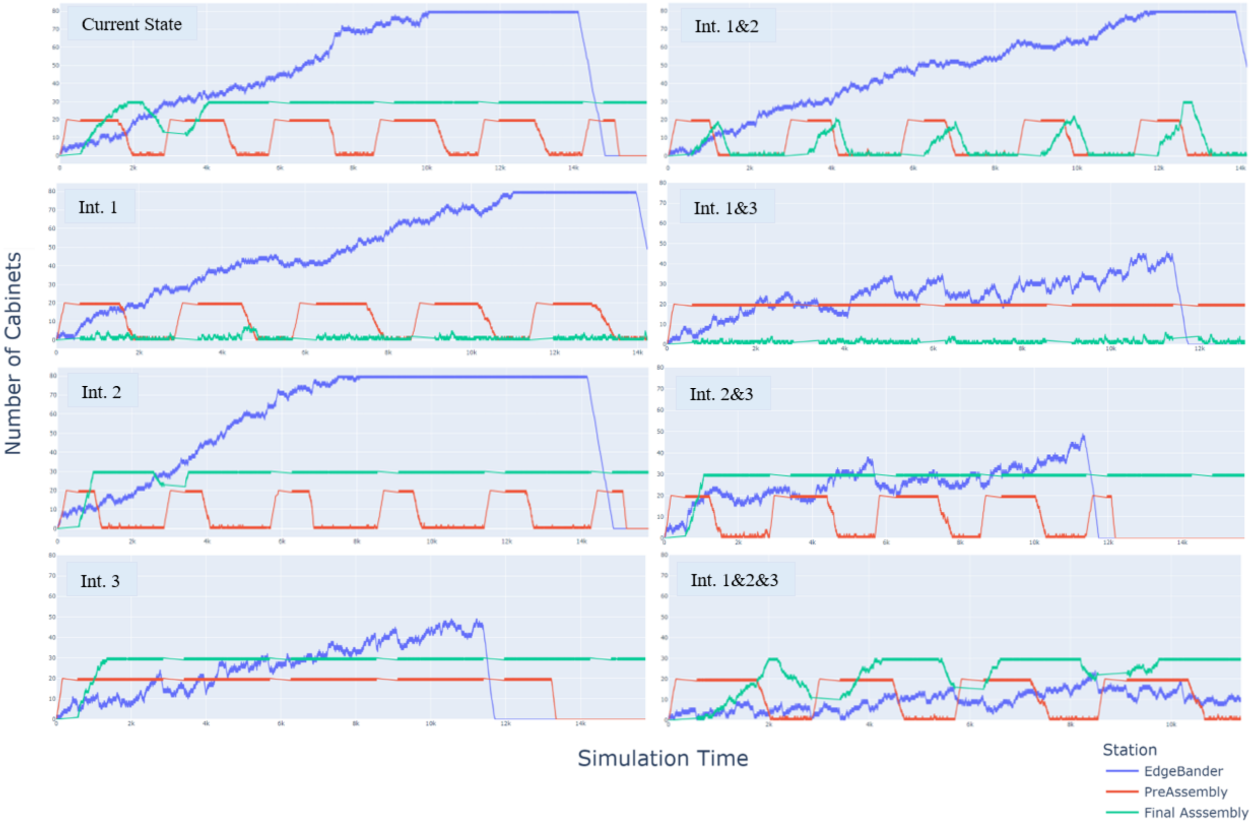


**Figure 44:** WIP levels based on different models

### 7.4.4 Production rate

The system production rate was calculated for every model to reflect the system's throughput. This metric is critical in evaluating a production system's performance, however insufficient when used alone. Production rate is principal for all managers and companies, but it should also be linked to what is happening internally between stations and activities. A fast production system with high throughput might be full of waste, thus is would be inconsistent and crash at a later stage. The aim is to sustain a predictable and lean performance internally and externally. Table 18 shows the production rate of every model and how well the interventions improved the production rate with respect to the current state. Interventions 2, 3, and 2&3 had minimal impact on the production rate, since final assembly remained the bottleneck of the production system. Thus, even though all stations were improved, production was still dictated by the performance of the final assembly station. Interventions 1&3 and 1&2&3 showed the biggest improvement in production rate; these combinations have also been demonstrated to impact the internal performance of the production system, as shown earlier in this chapter.

**Table 18:** Production rate based on different models

| Model | Production rate (cabinets/hr) | Improvement (%) |
|---|---|---|
| Current state | 5.850 | - |
| Intervention 1 | 6.354 | 8.62 |
| Intervention 2 | 5.881 | 0.53 |
| Intervention 3 | 5.851 | 0.02 |
| Intervention 1&2 | 6.414 | 9.64 |
| Intervention 1&3 | 7.112 | 21.57 |
| Intervention 2&3 | 5.875 | 0.43 |
| Intervention 1&2&3 | 7.855 | 34.27 |

### 7.4.5 System state

The system state was assessed based on the tool developed in Chapter 6. The current state was taken to be a reference to compare other models to. Table 19 summarizes the results obtained from the fuzzy model developed after simulating the models and their combinations of interventions. All models showed a decrease in the percentage of unbalanced state except interventions 3 and 2&3. These two interventions decreased the probability of the system to be balanced and near-optimal and increased the probability of the system to be unbalanced. Therefore, the interventions are expected to decrease the performance of the system holistically if implemented alone. They improve specific stations but impede internal and overall system performance and state. This was also apparent in all metrics evaluated.

Interventions 1, 1&2, and 1&3 indicated a significant improvement in all states, since the unbalanced state was decreased immensely and the balanced and near-optimal states increased. Intervention 1&2&3 promised the best improvement, where the system state is expected to vary between being balanced and near-optimal, with a much higher probability of 96% being near-optimal almost all of the time. This was also shown in how WIP levels were always low and controlled with this intervention, meaning a cabinet would not waste time waiting for days in the system before exiting. This also indicates a balance in station cycle times and a smoother flow of material and products on the shop floor.

**Table 19:** Percentage of each system state based on different models

| **Model** | **System State** | | |
|---|---|---|---|
| | **Unbalanced (%)** | **Balanced (%)** | **Near-optimal (%)** |
| Current state | 32.46 +/- 3.49 | 41.22 +/- 4.98 | 26.32 +/- 1.55 |
| Intervention 1 | 1.50 +/- 0.52 | 23.83 +/- 2.45 | 74.67 +/- 2.97 |
| Intervention 2 | 30.95 +/- 5.12 | 45.35 +/- 1.14 | 23.70 +/- 3.98 |
| Intervention 3 | 67.84 +/- 5.58 | 21.69 +/- 2.54 | 10.46 +/- 3.04 |
| Intervention 1&2 | 1.74 +/- 0.77 | 20.61 +/- 3.11 | 77.65 +/- 2.41 |
| Intervention 1&3 | 17.89 +/- 4.97 | 46.89 +/- 2.17 | 35.22 +/- 2.79 |
| Intervention 2&3 | 67.24 +/- 1.35 | 21.45 +/- 4.14 | 11.31 +/- 2.73 |
| Intervention 1&2&3 | 0.00 +/- 0.00 | 4.03 +/- 2.09 | 95.97 +/- 2.09 |

### 7.5 Intervention Validation

The results of simulating the interventions were obtained from models that were based on data input and gathering done throughout the study. To increase the reliability of the reported results, the simulations were validated by the general manager, production manager, and order-desk manager of the company after a thorough presentation of the interventions, simulation models, fuzzy model, and results generated. After all their questions were answered and all ambiguities they had were clarified, the managers were given an intervention assessment form to provide their input on the interventions and the results obtained. The form has a Likert scale of 1–5, ranging from “1 = Strongly Disagree” to “5 = Strongly Agree,” which assesses proposed statements about the interventions. Table 20 shows the average results obtained for each intervention.

**Table 20:** Intervention assessment results

| Statement | Intervention 1 | Intervention 2 | Intervention 3 |
|---|---|---|---|
| The intervention is possible and can be implemented. | 4.13 | 4.067 | 3.73 |
| The intervention is logical and tackles the problem it aims to improve. | | | |
| The intervention's quantitative impacts are logical and sensible. | | | |
| The intervention is significant and proposes a major improvement on production. | | | |
| The simulation results after simulating the interventions are logical, relevant, and reasonable. | | | |

The managers deemed that intervention 1 was the best in terms of implementation and sensibility of results. All interventions showed an opportunity of improvement and the validation results were acceptable and did not highlight any alarming assessment on any intervention. This provided confidence in deeming the interventions and their results possible and logical.

## 7.6 Conclusions

This chapter discusses the lean interventions suggested after analyzing the current state of the production system. The interventions were inspired from the researcher's time spent on the shop floor throughout the study and from the data collected. Moreover, the operators played a huge role in pinpointing major problems on the shop floor that were sensible in justifying results of the current state. The interventions were simulated individually and in different combinations to study their impact on PLT, station utilization, production rate, WIP levels, and system state. Intervention 1&2&3 yielded the best results on both micro and macro levels: it improved all metrics evaluated the most. The results reflected that even while some interventions tend to improve certain stations, their impact on the performance of the production system as a whole might be negative sometimes. Furthermore, from the results generated, the approach of assessing this production system holistically was demonstrated to be better in improving production systems than the myopic approach. The dependence on limited metrics might lead to sub-optimal results with respect to the bigger picture of system performance.

# Chapter 8 – Conclusion

## 8.1 Thesis Summary

This thesis aims to present a new approach in viewing and improving production systems in offsite construction facilities. The research is inspired from lean theory in production and includes the application of several lean tools and techniques along with simulation and fuzzy analysis, based on lean thinking to assess and improve the state of OSC production systems. Although the study tackles offsite construction specifically, the approach can also be applied to any production system.

The thesis started with explaining how OSC impacted the construction industry and how lean theory has also been introduced to construction. The introduction also included an overview on variability in OSC and the problem of having a myopic approach in tackling it rather than looking at it from a holistic point of view. Two research questions were stated to address the stated research gap:

- How can a state of an offsite production system be assessed in a holistic manner?
- How can lean concepts and tools be utilized to improve an offsite production system as a whole rather than its parts?

. The research methodology adopted is DSR, which comprises three main steps: (1) identifying the problem, (2) developing an artefact as a solution to the problem, and (3) evaluating the artefact. The problem stated is the myopic approach to optimizing production systems leading to sub-optimal results. There is a need to study how a production system operates holistically from operations in and between stations to how fast the system is producing in terms of final output. The artefact presented is a framework that aims to highlight a door-to-door holistic lean approach on how production systems need to be evaluated and improved. It was tested on a case study of an OSC facility that builds cabinets. The case study is introduced in Chapter 3, which explains how the shop floor functions and how every station operates. The chapter further explains how data was collected on site and how the data was used throughout the analysis.

The framework highlights three main phases. The first phase aims to systematically study a production system and develop a tool for assessing the system using VSM, simulation, and fuzzy logic. Chapter 4 explains how the data was used to unify all stations' units to *cabinets* in order to build a simple and powerful value stream map. Then, Chapter 5 elaborates on the SM was built, verified, and validated so the results generated can be trusted and considered reliable. Results for PLT, station utilization, production rate, and WIP levels in the system were generated from the model. Chapter 6 introduces a new metric, "TPT/PLT," which was calculated from the results of the SM. The metric was simulated in a Monte Carlo simulation model and used in a fuzzy diagram to assess the current state of the production system. Three system states were defined: "unbalanced," "balanced," and "near-optimal." The fuzzy model developed was used to assess the production system and calculate the percentage of time the system would be in each system state based on current conditions. The tool gave a holistic perspective on the production system based on several lean metrics previously defined. The results of the fuzzy model reinforced the results of the SM. These chapters cover the first phase of the framework, which was intended to assess the production system holistically and develop a practical tool to be used to .

The second phase includes the recommendation of lean interventions based on the assessment completed in phase 1. The last phase is re-assessing different combinations of the interventions based on the tool developed in phase 1. Chapter 7 thoroughly explains the three lean interventions suggested: (1) organizing and standardizing the final assembly station, (2) sorting cabinets and redesigning the router carts, and (3) implementing Kanban for service jobs and recuts. The interventions were based on problems analyzed from the results of the SM and the fuzzy model. These interventions and different combinations of them were retested in the SM and the fuzzy model to study their impact on both micro and macro levels.

Results from both models concluded that intervention 1&2&3 yielded the best results by increasing production rate, decreasing PLT, balancing station utilizations, and decreasing and stabilizing WIP levels throughout simulation time. Lastly, it improved the production system state leading to 0% of the time being unbalanced rather than 32.46%, and increasing the percentage from 26.32% to 95.97% of the time the production system would operate in a near-optimal state. These results are summarized in Table 21.

**Table 21:** Production system state summary comparing the current model with intervention 1&2&3

| Model | System state | | |
|---|---|---|---|
| | **Unbalanced (%)** | **Balanced (%)** | **Near-optimal (%)** |
| Current state | 32.46 | 41.22 | 26.32 |
| Intervention 1&2&3 | 0.00 | 4.03 | 95.97 |

## 8.2 Thesis Conclusion

The metrics from the SM gave a myopic view on how the interventions impacted certain metrics without any insights on how these metrics were interrelated and how they affect each other. The analysis conducted on the metrics tried to link all results together. However, the developed fuzzy model succeeded in giving a holistic perspective on how the production system was operating. The results of the fuzzy model summarizing the percentage of time the system each of would be in the three defined states matched what the results of the SM when analyzed thoroughly. This ties back to the stated research questions:

- *How can a state of an offsite production system be assessed in a holistic manner?*

A state of an OSC production system depends on a combination of metrics that have to be analyzed all together to better understand how the system is operating. This is foundational in lean thinking, since problems are tracked from their root causes and improvements are thoroughly studied before being implemented. Performance is not only limited to a system's output rate; rather, it is all that happens in between stations that leads to a certain output. Fast production is a universal indicator of a well-performing production system; however, from a lean perspective such a system might be full of waste and instead considered to be a poor-performing system. An internally stable and predictable flow of production is much more preferable than a highly stressed system full of waste. Therefore, to holistically assess a production system, the value stream of the system and the amount of waste (under and over-utilization, WIP levels, inventory, transportation, etc.) should be taken into account.

Several interventions, such as interventions 2 and 2&3, improved certain metrics but negatively impacted the other metrics evaluated. This was also shown in the results of the fuzzy model, where the system state became more unbalanced with intervention 2 and less balanced and near-optimal with intervention 2&3. This highlights a major finding of the research: efforts to improve production systems may lead to sub-optimal results if not taken from a holistic perspective, as mentioned by Koskela (2002).

- *How can lean concepts and tools be utilized to improve offsite production systems as a whole rather than its parts?*

The power of lean tools and concepts lies in the thinking behind them. The tools and concepts used in this study were not randomly chosen. VSM was used to place the current state into perspective by analyzing the amount of waste between stations to understand how stressed the production system was in its current state. Moreover, simulation was used to calculate lean metrics such as PLT and WIP inventory to further analyze the state of the production system. These tools were used with a lean thinking approach so they serve the purpose of assessing and improving production from a holistic perspective. As a lean principle, you cannot improve what you cannot understand or cannot measure. This led to introduction of a new metric, TPT/PLT, which succeeded in assessing the state of the production system when calculated in the fuzzy model. Furthermore, the lean interventions were also inspired by lean concepts and tools such as Kanban and 5S. The combination of these tools proved effective in improving production system state holistically.

Finally, one major conclusion was drawn from the researcher's time spent on the shop floor. All the knowledge needed to know what the true state of any production system is and how it can be improved is already available from the operators working. Operators that repeatedly do the work best understand how their stations function, how other stations affect their work, and what improvements can be made. They understand lean concepts very well without necessarily knowing them by that name. The ideas suggested throughout the study were inspired from conversations with the operators. This demonstrates that with a few tools and techniques, and with a lean mindset, a lot can be achieved from listening to what operators and workers have to say.

## 8.3 Contributions

The following contributions were achieved throughout this research:

- The developed framework explained a lean approach of assessing and improving the state of offsite production systems by holistically taking into consideration value and flow perspectives in production, and not only production rate (transformational).
- This thesis demonstrated a combination of tools such as VSM, simulation, and fuzzy logic to analyze and study an OSC facility.
- The developed fuzzy model serves as a DSS for managers, helping them in assessing any improvement(s) suggested and taking into consideration the state of the system rather than parts of it. Three lean interventions were suggested for implementation and were demonstrated through modelling to positively impact production in the facility.
- The results indicated how some improvements can lead to negative repercussions and the importance of looking at production from a ”big-picture” perspective rather than parts of it.

## 8.4 Research Limitations

This research includes the following several limitations:

- The value stream map only included internal operations assuming that all external factors do not affect or hinder production. Though this assumption is validated and safe to apply, data collected on supply chain problems could improve the accuracy of the results and thus portray a better image on the production system state.
- The case study disregarded customized orders and focused on standard orders that have a fixed sequence of stations with predictable cycle times. Customized jobs have a dedicated team to fulfill them but sometimes interrupts production. Although this does not happen often, it is not taken into consideration in the study.
- The fuzzy sets are symmetrical for pragmatic reasons, so that results are automatically normalized adding up to 100%. This could be more accurately represented and plotted to better represent the state of the production system.
- The results were validated only using face validity, since they are generated from the SM and the fuzzy model. To better demonstrate what the model can do and the impact of the

interventions, some interventions could be applied on the shop floor to collect real data and validate the models. The interventions are not costly and can be rapidly implemented.

- PLT and TPT that were used to calculate the new metric TPT/PLT are generated from the SM. These metrics could be better collected using data from the shop floor rather than the SM to better represent the state of the production system.

### 8.5 Recommendation for Future Research

This research lays the groundwork for further studies:

- Develop a real-time digital twin that tracks cabinets in real time to keep continuous track of the system state. This would decrease the time spent on retroactively collecting data to act. Digital twinning requires traceability sensors, such as RFIDs, to track cabinets; so, it is costly to implement.
- Study all parties included in the supply chain to better optimize the whole value chain from the supplier to the customer. This requires a lot of collaboration from all parties to optimize the whole chain. Techniques such as VSM can be a powerful exercise to get buy-in from all parties.
- Study the impact of design on manufacturing and how design and manufacturing can be integrated using lean techniques. This covers the root causes of a lot of manufacturing problems and sparks ideas about how design and manufacturing can be integrated and how communication can be better achieved.
- Investigate the integration of Industry 4.0 technologies to better improve production in the manufacturing facility. This track can also include how these technologies, if implemented, can affect the workforce from a social perspective. The inclusion of all types of impacts – social, environmental, technical, legal, and economical – adds a lot to the body of knowledge, especially when the study focuses on the social impacts, which are often overlooked.

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