Implementing Lean Manufacturing in a High-Mix Low-Volume Environment with Sequence-dependent Changeover and Alternative Routing

Tio Haessig

A Thesis

In

The Department

of

Mechanical, Industrial and Aerospace Engineering

Presented in Partial Fulfillment of the Requirements

for the Degree of Master of Applied Sciences (Industrial Engineering) at

Concordia University

Montréal, Québec, Canada

April 2025

CONCORDIA UNIVERSITY School of Graduate Studies

This is to certify that the thesis prepared

By: Tio Haessig

Entitled: Application of Lean in a High-Mix Low-Volume environment with Sequence dependent Changeover and Alternative routing

and submitted in partial fulfillment of the requirements for the degree of

Master of Applied Sciences (Industrial Engineering)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final Examining Committee:

______________________________ Chair

Ali Akgunduz

______________________________ Examiner

Claudio Contardo

______________________________ Supervisor

Onur Kuzgunkaya

______________________________ Supervisor

Kudret Demirli

Approved by: ____

Chair of Department or Graduate Program Director

____________ 2025 ____

Dean of Faculty

Abstract

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Tio Haessig

This thesis explores the development of a Lean manufacturing system at company ABC that operates in a tailored to a high-mix, low-volume manufacturing environment characterized by sequence-dependent changeovers and alternative routing. To achieve this, a methodical approach was followed to identify the key sources of waste and their root causes, which is demonstrated through the system's current value stream map. Because of the variability in cycle times at the batch processes, sequence-dependent changeover times, and alternative routings in Assembly processes, it’s challenging to create pull sequence at the pacemaker with generic lean guidelines. In order to address these challenges, a new scheduling method, "concurrent scheduling," has been developed. The method consists of controlling the pacemaker through a schedule while simultaneously coordinating the downstream batch process with a product wheel, and introducing a sequential pull system between the two processes. The schedules and the product wheels are offset by a delay to enable the pacemaker to supply the batch process efficiently. The batch process is the pivotal point of the value stream to determine the lowest possible production interval, also known as Every-Product-Every-Interval (EPEI), and the optimization model also aims to minimize the EPEI. Once the pacemaker scheduling and EPEI is determined, the quantities of the finished goods supermarket and the necessary work-in-progress of the First-In-First-Out lanes have been determined to achieve a lean flow. The study results have been summarized into a future state map, providing the company with a framework to improve its production system.

The results indicate significant improvements, including a 58.2% reduction in total production lead time, total control and predictability over inventory levels, a standardized value stream and management, improved production flexibility, and greater expected customer satisfaction. While the individual solutions and the methodology's application can assist manufacturers facing similar problems in achieving operational excellence, this thesis provides insights into the overall application of Lean in High-mix, Low-volume environments.

Keywords: Lean, High-mix low-volume, Alternative routing, sequence-dependent changeovers, Value Stream Mapping

Acknowledgments

I would like to express my deepest gratitude to my supervisors and teachers, Dr. Onur Kuzgunkaya and Dr. Kudret Demirli, who showed an unquestionable patience and perseverance facing the conditions in which this thesis had to be written.

Their constructive feedback and deep knowledge about Lean, optimization and manufacturing environments pushed me to surpass myself and strongly deepen my understanding of each of these fields.

Thanks should also go to Concordia University for subsidizing a substantial part of my studies and allowing me access to numerous resources that helped further this study.

This thesis is dedicated to my family, who made this journey possible, my partner Lucie, who supported me during the whole process and my former teacher Bernd Langer, who developed my interest in manufacturing environments and Lean in general.

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List of Abbreviations

BS: Buffer stock

CS: Cycle stock

CSM: Current-state-map

CV: Coefficient of variation

C/O: Changeover

C/T: Cycle time

DVAR: Decision variable

EPEI: Every-Product-every-interval

FIFO: First-In-First-Out

FSM: Future-state-map

LT: Lead time

MRP: Material resources planning

MTZ: Miller-Tucker-Zemlin

NVA: Non-value-adding

OPF: One-piece-flow

PA: Pre-assembly

SM: Supermarket

SS: Safety stock

TPS: Toyota production system

T/T: Takt time

VA: Value-adding

WAWC: Weighted-average-work-content

WC: Work content

WIP: Work-in-progress

1 Introduction

1.1 Lean and waste reduction

The traditional production system popularized by Henry Ford reached its limitations following the Second World War. With the post-war economic pressures and the diversification of consumer needs, a "one-size-fits-all" solution was no longer sufficient. These economic conditions launched a general movement within the Japanese Manufacturing industry, setting up the premises of what is today called Lean Manufacturing.

In response to the economic challenges, Toyota engineers in the 1950s sought alternatives to classical mass production. The goal was to manufacture products with shorter lead times (LT), superior quality, and reduced costs. This pursuit led to the development of a revolutionary philosophy and innovative methods. During this process, Japanese engineers drew inspiration by visiting European and American manufacturers. The success of these efforts became evident in the 1980s when Japan's automotive market share equaled that of Europe and the United States. By 2022, Toyota had become the world's largest car manufacturer, with an 11.5% global market share (Carlier, 2024).

The cornerstone of the Toyota Production System (TPS) lies in the concept of one-piece-flow (OPF), a stockless production model centered on batch sizes of one. While achieving OPF is the ultimate goal, process-related obstacles (e.g., necessary batch processing for injection molding) or infrastructural limitations (e.g., process-separating firewall) often prevent its practical implementation. OPF cannot be achieved without reconsidering the changeover (C/O) times of their processes. While “traditional” manufacturers consider the C/O times as fixed and calculate their Economic Order Quantities around it, Lean will reduce the C/O times to minimize the batch size. Companies should strive toward achieving OPF and embrace the principles of the TPS, providing them with a final goal to improve and adapt their processes effectively.

Central to Lean and waste reduction is the elimination of Work-In-Progress (WIP), parts that have undergone value-adding (VA) activities but have yet to be completed or sent to the customer. VA activities are defined as those for which the customer is willing to pay.

Reducing WIP over the entire value stream positively affects the three pillars of Lean manufacturing: Delivery, Quality and Costs. The most important is the reduction in total production LT which is directly proportional to the WIP levels. The reduction in LT improves delivery times, increases the flexibility to respond to customer demand variations, and finally leads to higher customer satisfaction.

A second advantage is capital efficiency. Lowering the levels of WIP reduces tied-up capital, freeing resources for other VA activities and enabling the company to expand faster.

Moreover, maintaining low levels of WIP offers significant benefits, including reduced quality risks and faster detection of defects, as issues are identified and addressed more promptly. In contrast, high WIP can obscure process reliability problems, which may lead to excessive product defects and rework.

The fourth advantage of WIP reduction is the identification of process inefficiencies within the system. High levels of WIP often hide these forms of waste as they provide a buffer for downtime or defective parts, creating a false sense of stability. With less WIP to handle the process's instabilities, the system's underlying issues are exposed, fostering a culture of continuous improvement.

Finally, exposing the issues opens new opportunities to improve and streamline processes. The Kaizen philosophy (Continuous Improvement Process, CIP) is fundamental in sustaining Lean practices. Kaizen promotes a proactive approach to error prevention and process optimization by involving employees in problem-solving and improvement activities. Figure 1 illustrates the relationship between WIP levels, hidden inefficiencies, and the potential for improvement.

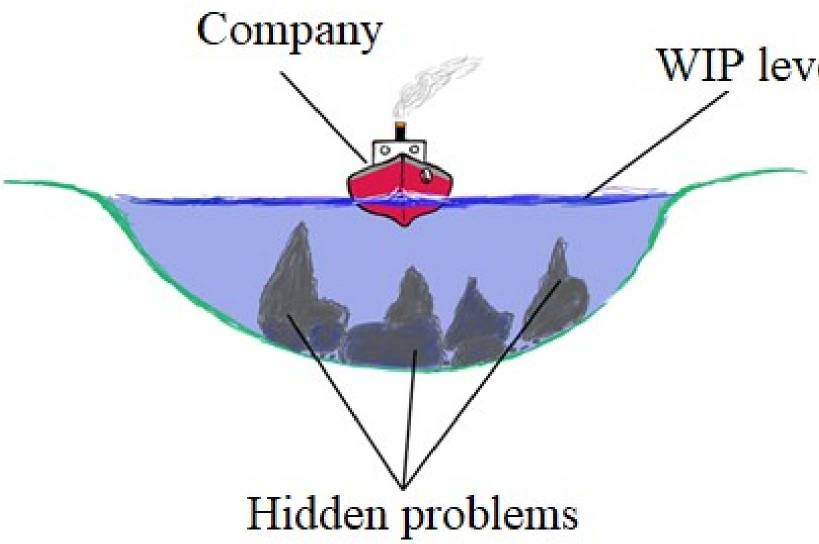

Figure 1: Graphical representation of Kaizen

1.2 Problem statement/ Context

ABC Company operates three manufacturing plants, each producing various products and functioning within an internal supplier-customer system. The company faces high inventory levels across all three plants, contributing to high production LT. Erratic customer demand fluctuations, often due to part shortages from external suppliers or changes in demand from the final customer, leads to instability within the system.

Specificities of the Assembly process within the manufacturing facility's value stream make implementing a Lean manufacturing system (LMS) particularly challenging. These challenges consist of sequence-dependent C/O times and variable C/T. Additionally, with two Assembly lines operating in parallel, some products can be produced on either line, while others are restricted to a specific line. These unique features complicate the integration of the Assembly process, which needs to remain unchanged due to financial constraints, into an LMS. More specifically, one of the central aspects of a Lean Manufacturing being a single scheduling point over the entire value stream, scheduling and/ or synchronizing the Assembly process with the rest of the value stream poses difficulties, highlighting the motivation behind this thesis.

ABC Company has already introduced Lean to its workforce by implementing the preliminary aspects of Lean in its facility. The first standards have been set through a rigorous 5S program, maintained by recurrent self-check loops at every workstation. Managers and engineers have a strong presence on the shop floor and provide constant support to the operators. Many inefficiencies have already been addressed through standardized problem-solving activities, which allow workers and supervisors to propose and implement workplace improvements based on insights gained during daily operations. This approach fosters a culture of continuous improvement and mutual support.

The company holds daily shop floor meetings at each process to track progress on the Lean initiatives and evaluate the status of production. These meetings involve the production supervisors and representatives from supporting departments such as Logistics, Quality, and Maintenance. Employees are encouraged to voice their concerns or share improvement ideas during these sessions, promoting an inclusive and collaborative environment.

In summary, ABC-Company has laid a strong foundation for implementing a Lean production system by engaging employees in a culture of continuous improvement and systematically addressing waste reduction.

1.3 Objective of the thesis

The primary objective of this thesis is to provide ABC with a functional future-state recommendation for its facility. The proposed system aims to reduce WIP and other forms of waste across the value stream while effectively integrating the Assembly process into the LMS. By eliminating waste and implementing Lean methods to control the facility, the company can expect to significantly reduce their production LT and gain more flexibility, ultimately enhancing its economic competitiveness.

The plant's management team provided the incentive to implement 5S, shopfloor management, and Lean more generally. Already at the origin of ABC's motivation to embrace the benefits of Lean, it will continue to set the pace for its other plants and serve as a benchmark for deploying the Lean manufacturing philosophy on a company-wide level.

Beyond ABC Company, we expect this thesis to serve as an example to other companies wishing to implement Lean in a High-Mix, Low-Volume (HMLV) environment with similar specificities, while contributing to the existing literature on implementing Lean systems in such environments. As it is mostly unlikely to find the same conditions within another company, it is expected that at least parts of the proposed solution can either be used or inspire other implementations of LMS and/or research projects about the similar topics.

2 Literature review

This literature review outlines the current research on implementing LMS. It positions this study within the context of prior work and demonstrates its significance. Given LMS's vast scope, which encompasses diverse manufacturing environments, this review focuses specifically on Lean implementations within HMLV environments.

2.1 The evolution of Lean literature over time

The literature about Lean manufacturing has evolved significantly since Toyota's automobile manufacturing plant introduced lean in the 1950s. This section will trace the evolution of Lean literature, starting with foundational works on the TPS and progressing towards contemporary approaches and applications.

Although Ohno (1988) and Shingo (1989) published their perspectives on the TPS in the late 1980s, English translations only became widely available a decade later. During the same period, Womack, Jones, and Roos (1991) introduced an American perspective on the methodologies and effectiveness that propelled Toyota to become the leading original equipment manufacturer (OEM) in the automotive industry. However, they remain largely theoretical and leave considerable room for interpretation.

Womack and Jones (1996) provided a comprehensive summary of their findings on Lean, emphasizing key concepts such as value, value streams, continuous flow, PULL, and striving for perfection. Their work gave the Western world a clearer understanding of the transformations required to implement Lean in production systems effectively. The focus is on the foundational concepts that formed the TPS and how to implement them company-wide, as well as the expected outcomes of adopting TPS methods. However, specific methods for achieving Toyota's exceptional performance are not explicitly provided.

Tools like Supermarkets (SM), Kanban, and 5S need detailed instructions on designing or adapting them to different manufacturing environments. This deliberate approach of not over-specifying the tools encourages industrial engineers to adapt Lean principles to their unique needs, rather than relying on a standardized, one-size-fits-all methodology.

The effort to understand and implement these tools in non-Japanese production environments shifted the focus away from building a self-regulating production facility and fostering a culture of continuous improvement. As demonstrated by the articles by Maclean (1989), Baral (2012), Kumar et al. (2018), Heravi and Firoozi (2016), reviewed in this research, there is often a tendency to lose sight of the overall system, with attention instead concentrated on optimizing individual components.

While emphasizing Lean's core values, contemporary literature has become more explicit in guiding the design and implementation of LMS in companies prepared to undertake such transformations. Rother and Shook (1999) introduced a pivotal framework for capturing the current state of a production line, focusing on the most critical information required to identify improvement opportunities. Through their introduction of Value Stream Mapping (VSM), they detailed how concepts such as Takt, First-In-First-Out (FIFO), Heijunka, SM, Pacemaker, and considerations of volume and mix interconnect and how they can be effectively implemented.

A core principle of LMS is achieving OPF to minimize WIP and enhance efficiency. The ideal approach for manufacturing products efficiently and flexibly involves integrating all processes into a single line, producing one unit at a time while precisely replicating the customer's demand pattern in terms of mix and volume. Rother and Harris (2001) provided a comprehensive guide to designing such systems. Their methodology includes analyzing customer demand, defining the takt time (T/T), evaluating work steps and machine capabilities, and systematically identifying and eliminating waste. While achieving OPF for every process in the value stream may only sometimes be feasible, the guidelines strongly advocate for its implementation wherever possible.

Another critical aspect to address regarding the entire value stream is the management of the SMs and the integration of PULL systems. Smalley (2009) provides clear guidelines for analyzing the demand more thoroughly, determining which parts are to be made "to stock" or "to order," and defining the size of the SMs and replenishment rules.

These more recent methods are more adaptable to various situations and offer more specificity than resources from the early 1990s. Smalley also emphasizes the synchronization of the internal transportation system with the production system, ensuring that parts are delivered to the processes at the right time, which is essential for maintaining a PULL system.

While these guidelines help develop an LMS, they are often criticized for the simplicity of the examples used to demonstrate the methods. A typical response to engineers attempting to implement Lean in their company is, "Lean does not apply to our industry/ company." However, Duggan (2012 & 2013) disagrees with this perspective and offers an approach to adapting lean tools to various industries. Its work provides a tailored approach to implementing lean transformations, mainly focusing on High-Mix, Low-Volume (HMLV) environments.

Duggan defined a 10-step guide to apply Lean principles to such systems, showing that LMS can be implemented in nearly any company willing to commit the necessary resources to the change process. However, his work does not address specific challenges, such as alternative routing or sequence-dependent changeovers, which are the main characteristics of the system being analyzed by this study.

2.2 Recent studies on the implementation of Lean

A simple yet powerful tool of the lean methodology is 5S, which focuses on rearranging the workplace to stabilize processes. Implementing 5S is essential to an LMS but should not be considered an end. For example, MacLean (1989) and Baral (2012) explore the 5S methodology and its effects on the shopfloor. 5S is the preconized way of standardizing the first operations within a value stream and stabilizing processes. While many companies begin by rearranging their processes to enhance stability, few undergo further transformations in their Lean transformation journey.

Another tool previously introduced is Value Stream Mapping (VSM), popularized by Rother and Shook (1999). VSM allows management to identify wasteful factors in their system, providing a foundation for developing solutions that can effectively improve the production facility. Additionally, it creates a common ground for communication between management and shopfloor workers, fostering collaborative discussions on potential improvements.

Kumar et al. (2018) utilize VSM to develop Kaizen events, focusing on enhancing the efficiency of individual processes. Heravi and Firoozi (2016) provide a notable example of applying the VSM methodology, followed by Discrete Event Simulation, to validate the proposed improvements in a prefabricated steel frame production plant. Jeyaraj et al. (2013) also contribute to the discussion by rearranging specific processes to align with T/T. However, their approach considers production capacity rather than customer demand to define the T/T.

Despite utilizing tools developed to facilitate Lean transformations, none of these studies adopted a systemic approach to the problem. This reflects the tendency of some to focus primarily on the individual tools provided by Lean rather than undergoing a systemic transformation of the production system and its culture.

In the continuity of the previous studies, the following studies primarily focus on the optimization processes and models employed to enhance Lean tools such as Kanban. As a critical innovation of Toyota, Kanban has gained significant attention in Lean manufacturing research. Consequently, numerous studies have been published on how to implement this tool, particularly in defining and optimizing its parameters

The calculation of parameters for systems such as signal Kanbans historically relied on two key factors: the total number of Kanbans in the system and their individual capacities. According to this method, increasing the number of Kanbans results in higher WIP levels within the system. In contrast, increasing the capacity of each Kanban reduces the frequency of replenishment cycles needed to supply parts to the processes, leading to the incentive to optimize the kanban systems through various methods.

Several studies have been conducted to determine the optimal Kanban size. For example, Widyadana et al. (2010) applied mixed integer programming, Hou and Hu (2011) utilized a multiple-objective genetic algorithm, and Kanet and Wells (2018) conducted a thorough analysis of the 2-bin Kanban system. Each study seeks to identify the most influential parameters for a Kanban system, considering factors such as transportation costs, holding costs, and transfer costs.

Many optimization projects focus on refining the Kanban system for individual processes, often overlooking the broader system. However, once a Lean system is designed for the entire value stream, with processes working in harmony, the appropriate Kanban parameters such as the number of kanbans in the system or the reorder point for the batch kanbans will become evident. The parameters are determined through the size of the SMs, the bin size, and the amount of inventory that needs to be maintained on the lines, ensuring that the overall system is properly designed.

Another method developed to regulate WIP, especially across multiple processes, is the ConWIP system. This system links several processes using FIFO lanes to maintain the order sequence and inventory levels throughout the system. A new order can only enter the ConWIP system once an existing order has exited the final process. The method has the potential to rapidly reduce WIP across multiple processes simultaneously and is regarded as easy to implement.

Yang et al. (2010) developed a future-state-map (FSM) for a TFT-LCD manufacturing system based on multiple ConWIP structures working together. Their objective was to address the reentrant flow required by such products. However, their solution was limited to a single product and offered minimal guidance on managing multiple products with varying mix and volume

Prakash and Chin (2014) attempted to offer a systematic approach for implementing a ConWIP system, but in their case, a single product accounted for 90% of the demand, limiting its broader applicability. Leonardo et al. (2017) addressed demand fluctuations in a High-Mix-Low-Volume (HMLV) environment with Kanban and ConWIP. However, the study emphasizes that their solution is strictly limited to the system and processes they analyzed.

Additionally, regarding ConWIP systems, Olaitan (2019) explores various rules for releasing parts and their impact on WIP levels. While his study addresses high-mix demand, it does not consider the challenges posed by shared resources with high C/O times or alternative routing.

It can be observed that the ConWIP method requires careful consideration when designing a Lean system. Most of the research on the topic focuses on relatively simple value streams and provides limited solutions for applying the method to more complex systems. Additionally, there are concerns regarding the practicality of maintaining the sequence within long ConWIP systems. The temptation for managers to adjust the sequence to expedite "urgent" orders could be a significant threat to the system.

2.3 Lean implementation in HMLV environments

As discussed so far, Lean is a broad topic, with numerous studies exploring its various aspects. The following articles are particularly noteworthy, as they focus on the implementation of Lean systems within more complex value streams.

To address the HMLV demand of an electrical power distribution and control equipment manufacturer, Slomp et al. (2009) proposed merging several workstations to form a cell operating under a T/T, similar to Rother and Harris' (2001) methodology to create a continuous flow of parts. They employed the ConWIP method to maintain a consistent WIP level and regulate the flow of incoming and outgoing parts. Their production approach, based on an

Engineer-to-Order and Make-to-Order strategy, focused on highly customized products. Consequently, the dynamics between the customer and supplier, as well as LT expectations, differ significantly from our context. Additionally, to manage demand fluctuations, the article advocates maintaining excessive, uncontrolled inventory rather than implementing a PULL system.

Joing (2004) presented particularly promising results in his analysis of a complex production line in Scotland. The value stream featured a material flow with shared resources and multiple stations supplying a single station. Given the variability in demand and the high number of circuit card variants, the environment can be classified as HMLV. Joing (2004) successfully improved on-time delivery from 70% to 100%. However, despite referencing Lean methodologies, Joing opted for a Quick Response Manufacturing approach, concluding that Lean did not apply to his situation. The study provides limited detail on how processes should interact or how WIP levels are expected to evolve, leaving gaps in the explanation of the proposed solution.

Similarly, Gates (2004) thoroughly analyzes the current state using Value Stream Mapping (VSM) but fails to address crucial aspects of implementing a LMS. In designing his future state for an HMLV environment, he first excluded parts with "difficult" materials flow and focused only on those with sequential routing through the shop floor. He then merged processes to form cells without aligning them to a specific T/T, which he deemed unfeasible due to high demand variability. Additionally, the production mix and volume leveling were not addressed, and the future state needed more explicit information on cycle times (C/T), SM sizes, and other critical elements. Despite the value of the case study, particularly in addressing reentrant flow, Gates focused solely on products with low variability and linear routings, limiting his approach's applicability.

Additionally, an exciting framework for managing shared resources is provided by Yu (2020). In the context of a Canadian hospital department for cancer treatment, he applies the Lean methodology, particularly the "Offset sequencing" method developed by Duggan (2013), to decouple the schedule from the sequence of patients arriving. Although Yu's value stream shares similarities with our case, the demand in the hospital is highly influenced by the hospital's scheduling, allowing them to plan patient arrivals within specific intervals. This gives them greater flexibility to level the mix and volume of demand over the weeks. Mix leveling ensures that a variety of product types are distributed over a specific production cycle to avoid overproduction. Volume leveling consists of keeping the production output constant to avoid fluctuations in workload. Also, the value stream does not include alternative routings, representing a significant challenge in our system.

Duggan (2013) states that his framework is only applicable to C/Ts that are within 30% of each other. Targeting products with significantly differing C/Ts into the same product family would result in more waste than benefits. In addition to offering a valuable case study on applying Lean in an HMLV environment, Dhananjai (2022) introduces the concept of a "dynamic pitch" to address high C/T variations. Unlike the traditional pitch, this method adjusts the output for each pitch interval according to the product type being produced, enabling mix and volume leveling over a fixed period and offering a manageable timeframe even when C/Ts differ by more than 30%. More generally, if a pitch is missed, meaning not enough units have been produced within a specific timeframe, management can quickly identify the cause of the shortfall. While the output per pitch may fluctuate over time, necessitating more active managerial oversight, it offers greater flexibility for demand leveling in the specific case and helps reduce WIP.

Finally, a significant challenge for LMSs is high C/O times. When C/O times are too long, they hinder the creation of continuous flow by preventing the formation of cells and hinder achieving short production intervals in shared resources. The high C/O times lead to the need for higher inventory levels, which in turn increases LT. While Shingo (1985) revolutionized the reduction of C/O times through standardization, some C/O processes cannot be reduced below a certain threshold or would become prohibitively expensive to improve. Some processes require C/O operations to be performed in a specific sequence. This is well illustrated by the paint shop example in Duggan's "Creating Mixed Model Value Streams" (2013) book, in which the color transition must always go from light to dark to prevent mixing. Other processes may also benefit from a specific sequence to minimize overall C/O time.

These "forced" sequences create additional challenges when leveling demand. One approach to managing such sequences is the Product Wheel, which helps maintain the desired sequence over a specific timeframe, often aligned with the EPEI, and can be adjusted based on current demand. The wheel is divided into segments, each representing the demand for a particular part. As the wheel rotates over time, it determines which parts must be produced next, specifying the quantity and timing. Not every part needs to be included in the wheel as long as the sequence given by the wheel stays unchanged. The Product Wheel functions similarly to an adapted Heijunka Box, ensuring that the correct sequence is followed during each EPEI.

Wilson (2013) provides a general overview of the Product Wheel and its application in manufacturing. He outlines the ten steps to create a wheel, as defined by King (2009), and applies this process to his case study. The study also discusses managing the wheel in the face of fluctuating demand over time, showcasing the appropriate actions to handle multiple demand mixes. However, the case focuses solely on a single process within a linear value stream and does not address a systemic implementation of the wheels. Similarly, Trattner (2018) presents a case study in the baking industry, which involves a different demand profile (high demand/low variability, compared to Wilson's low demand/low variability). Both studies demonstrate improvements through the use of Product Wheels, particularly in reducing C/O times. However, neither incorporates the Product Wheel within the broader context of a systemic LMS nor does it account for scenarios where multiple resources must be controlled simultaneously.

2.4 Summary of the literature review

After a comprehensive review of the existing literature on implementing Lean principles in manufacturing environments, particularly in HMLV settings, it becomes evident that there is a lack of concrete case studies focusing on the transformation of entire value streams. Most research emphasizes individual tools or isolated processes, applying Lean principles in a localized context rather than addressing system-wide improvements. Duggan (2012) highlights the key challenges associated with implementing Lean Manufacturing Systems (LMS) in HMLV environments. Similarly, Dhananjai (2022) provides a valuable framework for systemic Lean implementation, though her "dynamic pitch" solution is specifically tailored to the context of her case study and may not be broadly applicable. Building on the foundational work of Duggan and Dhananjai, this thesis seeks to fill gaps in the HMLV literature by presenting a new case study that incorporates sequence-dependent C/O and alternative routings.

3 Methodology

Inspired by Rother and Shook's Learning to See (1999), Rother and Harris' Creating Continuous Flow (2001), and Duggan's Creating Mixed Model Value Streams (2013), the approach integrates the DMAIC framework, as detailed in Table 1, to systematically analyze and improve the manufacturing processes under consideration.

Table 1: Methodology

DMAIC	Steps
Define	Establish the scope and boundaries of the system under analysis. Identify product families within the portfolio in alignment with Lean principles.
Measure	Map the system and its processes using value stream mapping, following Rother and Shook's (1999) guidelines to design and evaluate a value stream
Analyze	Assess the current state and identify the waste within the system, focusing particularly on WIP and the seven types of wastes defined by Toyota
Improve	Design a future state by addressing the eight questions for designing a future-state-map (Rother and Shook, 1999). Address the specificities of the system by developing a tailored solution outside of the existing literature's scope. Summarize findings into a single future-state-map along with a list of the necessary improvements to achieve the desired final state.
Control	Identify further improvements that may not be achievable immediately but could contribute to the long-term system's efficiency and foster the continuous improvement philosophy.

The DMAIC framework provides a structured approach for decomposing the project into manageable phases, ensuring clarity and organization throughout its progression. One of its strengths lies in addressing both short-term tasks (Define to Improve) and medium—to long-term objectives under the Control phase, fostering culture of continuous improvement, mandatory for the effective implementation of LMS.

While the DMAIC methodology structures the process, Lean principles focused on waste elimination remain central to addressing the inherent complexity of the value stream and enhancing ABC's manufacturing performance. The project aims to provide immediate operational improvements and a foundation for sustainable, long-term efficiency gains by applying this dual approach.

3.1 Define the scope of the project and map the system

The first step in the project is to define its scope and which processes will be included in the analysis. AS all of ABC's products necessitate the same processes and share the same value stream, we will only define one product family, consisting of all the available products. With a single product family, all the facility's processes need to be analyzed. The definition of the scope of the project within an early stage facilitates the development of the solution and avoids surprises during the unfolding of the project.

To specify the value to the customer, it is necessary to collect data about the system and summarize them into a VSM. Rother and Shook's (1999) 6 steps will therefore be followed:

- Define the customer requirements through analysis of the weekly demand. A weekly average, standard deviation, and coefficient of variation (CV) will be calculated for every product, enabling us to classify them for the Design of the SMs. The total demand will also give us the T/T, the core information necessary to create a LMS.
- Measure the total work content (TWC) and the number of operators at every process. The processes are separated by the inventory lying between them. In addition, the possible causes of slowing down the processes, e.g., downtime, scrap, and C/O times, should be added. Finally, define the available time for every process based on the shift lengths and the number of shifts per day.
- Measure the amount of WIP sitting between every process and define whether they are controlled. A controlled inventory is predictable, has an upper limit, or is managed through an SM/ Pull system.
- Add information about how the supplier delivers raw materials in what quantities and quality. This additional information will define the raw materials inventory at the beginning of the VSM.
- After analyzing the material flow, define the information flow through the VSM. The VSM depicts how information about mix and volume, as well as schedule changes, is provided to each process. The individual processes, the customer, and the supplier must be mapped.
- Finally, the LT ladder will be developed by adding every TWC as a weighted average over demand and expressing the WIP as the time necessary to be consumed by the downstream process. The sum of these metrics will give us the total VA time, the Non-value-adding (NVA) times, and the system's overall VA/ NVA-ratio.

3.2 Identify and eliminate waste within the system using the Lean methodology

With the established current-state-map (CSM), the next step involves identifying sources of waste in the system and highlighting opportunities for improvement. A critical part of this phase is determining which processes can be physically adapted to the new system (for example to follow a certain C/T) and which one must remain unchanged. A process that cannot be adapted greatly impacts an LMS and requires the development of specific methods to implement them into the future system.

Once these prerequisites are addressed, we can systematically identify sources of waste and develop targeted solutions. This phase follows the guidelines of Rother and Harris (2001) to identify opportunities for creating continuous flow and the guidelines of Smalley (2009) to define the necessary SM systems. We will also follow Duggan's (2013) recommendations to address aspects unique to HMLV environments. As the existing literature only partially addresses the challenges ABC is facing, a tailored solution will be developed to address the specific characteristics of the system.

The first step in reducing system waste is to define the T/T based on the product family. Following Rother and Harris (2001), processes performed by operators will be broken down into the smallest possible work increments, revealing inefficiencies within individual tasks. The processes will then be merged together into a continuous flow system, eliminating the WIP between the processes concerned. Continuous flow also aims to adapt the process C/T to match the T/T. Achieving T/T will require the elimination of waste within the processes, relying on techniques such as Paper Kaizen and continuous improvement activities. Accurate time measurements for each increment, conducted with experienced operators, will ensure reliable data. The lowest repeatable operation time will serve as a benchmark.

Once processes and machines are streamlined, decisions on automation levels and layout design will follow. Due to limited information about specific work steps, these aspects will not be addressed in detail. However, as the system primarily involves manual processes with minimal machinery, aligning work steps with T/T is expected to be manageable.

The number of operators required for each cell will be determined to finalize the cell design. The system will incorporate allowances ranging from 5 to 7% of T/T for operator variability and ensure machinery operates 20% faster than T/T to cope with potential breakdowns and maintenance issues. This step will guide the distribution of tasks among operators and the creation of initial standardized worksheets. The resulting continuous flow will then serve as the pacemaker for the entire system, acting as the central control point for the value stream. If not every process can follow T/T or multiple OPF cells are created, it is necessary to define the pacemaker as the process which would lead to the less amount of WIP over the entire value stream.

Particularly, some processes will fail to meet OPF requirements due to financial or technical constraints (e.g., expensive batch-processing machinery or irreducible C/O times). These processes will be decoupled from the continuous flow cells and be incorporated into the system through FIFO lanes and SMs. Production and withdrawal kanbans will regulate the transfer of information and the inventory between the processes.

Furthermore, Smalley's (2009) method will be used to design the finished goods SM, accounting for demand variability, downtime, and scrap rates, ensuring system resilience. The SM size will consist of the cycle stock (CS, based on the average demand), the buffer stock (BS, based on the quantity variability of the demand), and the safety stock (SS, based on achievable uptime and scrap rate of the processes).

Once the processes have been aligned with the T/T and their interconnections clearly established, leveling the mix and volume of orders entering the system becomes essential. The product mix will be leveled by determining an EPEI, which depends on the minimum feasible shipping frequency and the ability of batch processes to operate within the resulting production intervals. This EPEI will set up a fixed time interval in which the facility will produce a certain mix of the entire product family. At the beginning of each interval, the customer will send orders to the facility. The facility will then fulfill the demand by either sending the required products to the customer directly or fill a finished goods SM from which the customer can pull products to meet the demand.

In parallel, the production volume will be leveled by establishing a pitch, a time-based control mechanism that limits the amount of production information sent to the system. The pitch is mostly defined by the container size with which the products are being transported within the facility. One Pitch is equal to a certain time frame in which a certain amount of parts need to be produced by the system (based on T/T). The facility becomes able to measure the systems performance by reviewing the output during each Pitch interval, reducing the management time frame and preventing wasteful activities, particularly overproduction.

In ABC's system, the pacemaker is required to supply the Assembly process, which cannot achieve OPF due to high C/O times, variable C/T, and alternative product routings. Consequently, a custom solution will be developed to manage these complexities while effectively adhering to Lean principles. Duggan (2013) introduces advanced solutions, such as offset sequencing and sequenced FIFO lanes, to link processes that cannot be merged into a continuous flow cell, eliminating the need for SMs. Duggan's work will serve as a base for developing a tailored solution to introduce ABC's Assembly process into a LMS.

3.3 WIP optimization and further improvements

The constraining factor for the EPEI is the Assembly process as it is the only process unable to achieve OPF. Reducing the total C/O time at the Assembly process increases the available production time and consequently reduces the achievable EPEI for the system. An ideal sequence could therefore be defined for the Assembly lines to minimize the C/O times and find the lowest achievable EPEI.

The traditional procedure to connect the Pre-assembly lines and the Assembly lines would be to use a SM. While SMs help control inventory and reduce WIP, they are not always optimal for HMLV environments as they require keeping high levels of inventory.

An optimization model has been developed to define the best production sequences for both Assembly lines and Pre-assembly lines. Simultaneously, the model aims to minimize the WIP between the two processes. Ultimately, the developed method avoids the need for an SM between the pacemaker and the Assembly process. An optimization model is necessary to address the complexity to schedule the Assembly process with its sequence-dependent C/O times, variable C/T and variable routings. A certain inventory level is still necessary to handle the discrepancy in C/T between the two processes and avoiding the Assembly lines becoming idle. By minimizing this delay, the model creates a production sequence for the Assembly process and a corresponding schedule for the pacemaker.

The minimum achievable EPEI will be determined through experimentation with the optimization model. The two processes will then be synchronized via multiple FIFO lanes containing a constant level of WIP. Incorporating these elements into the FSM will provide a comprehensive visualization of the improved system. Ultimately, the finalized FSM will outline the proposed solutions and serve as a strategic goal for ABC.

Before attempting to implement the FSM, several preliminary changes and improvements will be necessary. These will be outlined and presented as recommendations for ABC to conduct Kaizen events and concentrate their continuous improvement efforts. Once the required improvements are completed, the newly designed pull system can be implemented to establish the desired state. Additionally, potential efficiency gains from relaxing some constraints given by the company will be briefly discussed, offering ABC a pathway for further enhancements once the future state has been effectively implemented.

4 Current state at ABC-Company

This study focuses on a specific facility that processes approximately 200,000 units annually. ABC's product portfolio consists of nine distinct products, each differing in size, number of parts, and complexity. While some products meet the needs of multiple market segments, others are tailored to specific niches. These products undergo Pre-assembly (PA), final Assembly, Testing, and Shipment to a sister plant for further processing.

Before the beginning of this thesis, a Lean-inspired project was conducted at the PA lines. Following Rother and Harris's (2001) guidelines for creating continuous flow and minimizing batching, this project sought to eliminate waste at the PA lines and reorganize work steps to align with the Assembly process's C/T. Given that the PA lines are predominantly manual and require minimal machinery, we can assume they can be adjusted to align with the desired T/T within reasonable limits. This thesis will utilize only the total work content (TWC) following these improvements without considering the sequence of rearranging workplace processes.

The integration of the PA and Assembly lines was also analyzed during this prior study conducted by ABC company but was considered infeasible due to existing physical constraints, including a separating wall and the limited space available at the Assembly line.

In this chapter, we follow Rother and Shook's (1999) guidelines to design a CSM. The process begins with clarifying the project scope by defining the product family and the processes required to manufacture the selected products. This step allows for analyzing the demand for each product and provides a clearer understanding of the manufacturing environment under investigation. Subsequently, the various entities constituting ABC's value stream are identified, described, and summarized into a comprehensive CSM.

4.1 Defining the product family

The processes required for each product were analyzed and consolidated into a single table (Table 2). The analysis reveals that all products, except for 1 and 2, share identical process steps. As seen in Table 2, products 1 and 2 bypass specific steps, but the shared processes meet Duggan's (2013) criterion of 80% similarity in processing steps. Therefore, ABC's product portfolio can be grouped into a single product family.

Table 2: Process mapping

Products	Pre-assembly	Assembly	Testing	Finishing	Shipping
1	X	X	X		X
2	X	X	X		X
3	X	X	X	X	X
4	X	X	X	X	X
5	X	X	X	X	X
6	X	X	X	X	X
7	X	X	X	X	X
8	X	X	X	X	X
9	X	X	X	X	X

A disparity in WC across the products could necessitate creating additional product families to minimize the waste introduced into the system. A notable outlier, Product 9, deviates by more than 30% from the weighted average work content (WAWC), a threshold that Duggan (2013) identifies as a basis for excluding a product from its family. Despite this, Product 9 must remain within the product family due to its shared value stream with other products. Creating a separate product family would necessitate allocating a part of the processes to this specific product family, something impossible due to the restricted number of resources. The following chapters will conduct a detailed examination of WC similarities across individual processes and products, ensuring any disparities in WC are accounted for without compromising the system's overall materials flow.

4.2 Demand profile

Once the product family and the associated manufacturing processes are defined, the next step is to analyze the demand profile for each product. Table 3 summarizes the average weekly demand for each product, along with key statistical parameters, including the standard deviation (STDEV) and coefficient of variation (CV).

Table 3: Demand profile

Products	Avg. Demand	Proportion	STDEV	CV
1	912	22,4%	64	0,070
2	912	22,4%	42	0,046
3	216	5,3%	39	0,191
4	192	4,7%	26	0,131
5	336	8,2%	70	0,211
6	168	4,1%	19	0,112
7	648	15,9%	72	0,112
8	312	7,6%	15	0,047
9	384	9,4%	19	0,048

An analysis of the CV highlights significant disparities in demand stability across individual products. Products 3 and 5 exhibit higher CVs, indicating more erratic demand patterns, while others like 2, 8, and 9 demonstrate more consistent demand levels.

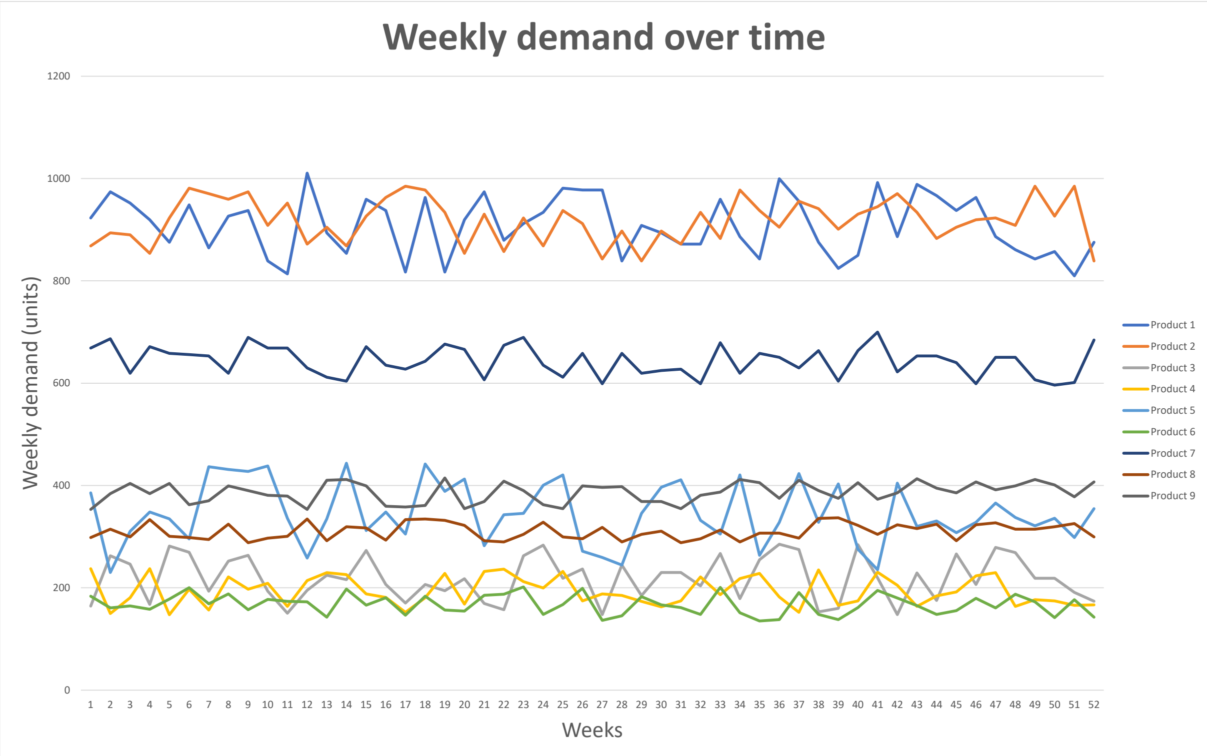

Figure 2: Yearly demand evolution of the individual products

Visualizing the weekly demand over 12 months (Figure 2) The figure reveals sparse and fluctuating patterns for individual products. However, when the demands are aggregated across all products (Figure 3), the total demand becomes stable, providing a consistent profile.

This aggregate demand will be the basis for calculating the T/T in subsequent stages.

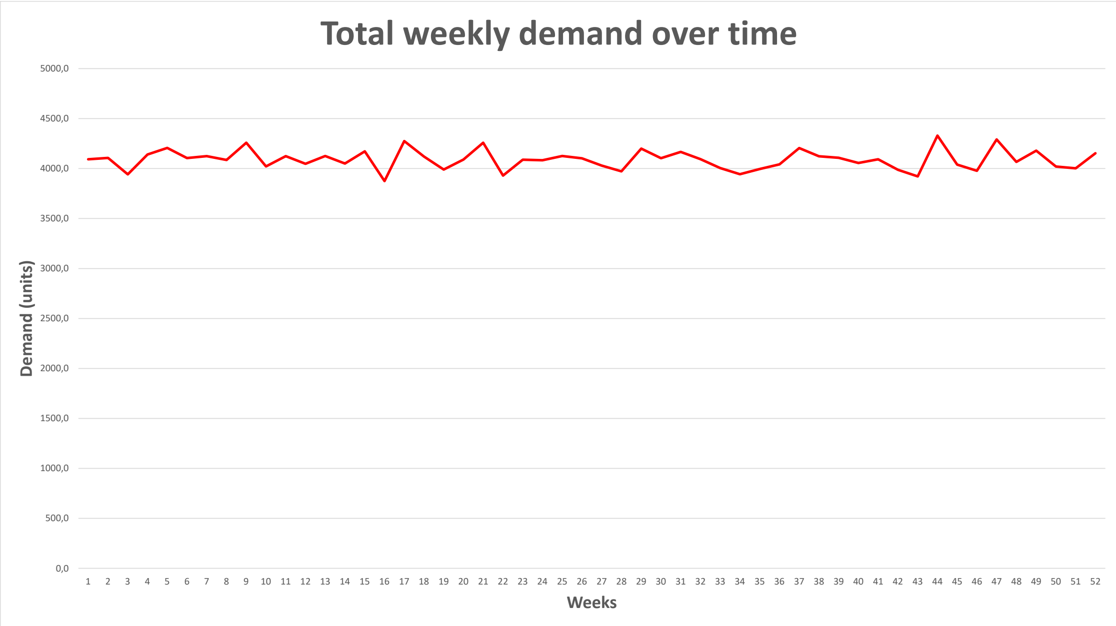

Figure 3: Total demand over time

Demand variation and product diversity confirm that ABC operates in an HMLV environment. Aggregating the demands simplifies system design greatly by balancing the variability of the individual products and enabling the definition of the T/T.

4.3 Creating the Current State Map

The CSM (Figure 4) will represent the processes required to produce the previously defined product family, along with their interdependencies, to gain a comprehensive understanding of ABC's current state. Each production system component will first be analyzed individually to define its primary characteristics.

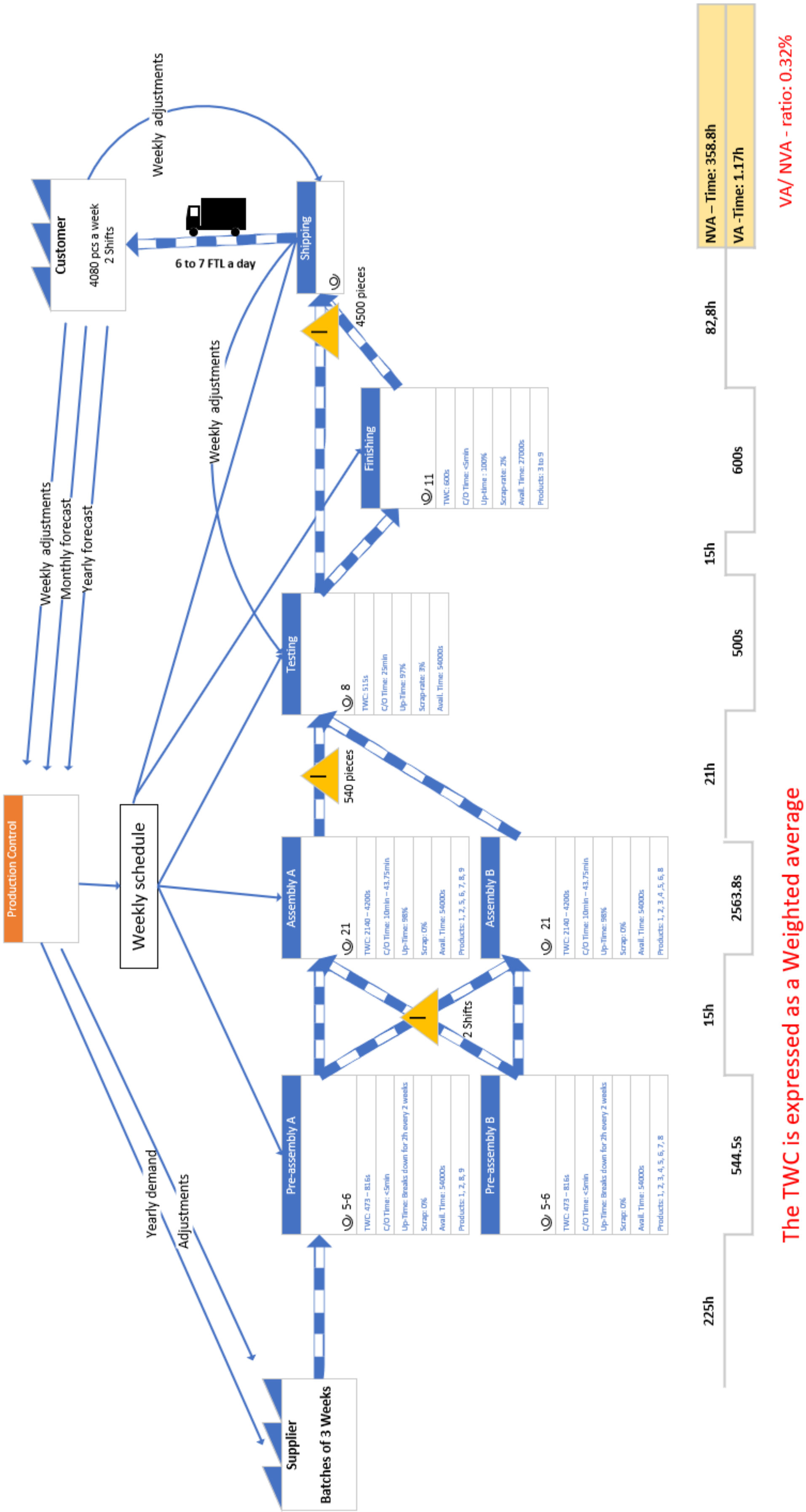

Figure 4: Current-state-map

4.3.1 Production control

ABC currently operates under a PUSH system to manage customer demand, a stark contrast to the principles advocated by Lean Manufacturing. The company relies on an MRP-based (Material Requirements Planning) schedule, which directs each process in the value stream and the suppliers.

This system is significantly challenged by the unexpected disruptions typical of such facilities (machine breakdowns, delayed logistics, and sudden demand fluctuations). These challenges necessitate increased WIP between processes to buffer against unpredictability. Additionally, the unreliability of the processes leads to further increases in WIP due to the need for SS.

The PUSH system's reliance on average LTs, which often do not account for real-time WIP levels, introduces inconsistencies in the production schedule. Such a setup also requires frequent managerial interventions, which Duggan (2012) identifies as a form of waste that detracts from higher-value activities. This lack of real-time adaptability underscores the inefficiencies inherent in ABC's current production control approach.

4.3.2 Supplier

ABC's supplier, a sister plant within the same organization, provides various subassemblies required for production. The supplier currently operates based on an annual forecast from ABC, which is translated into monthly schedules for its operations. This longstanding practice has been credited with achieving high machine utilization rates for the supplier's factory, a historically prioritized metric by ABC's supplier.

However, ABC's reliance on large lot sizes to maintain high utilization inevitably results in excessive raw material inventory. Furthermore, the mismatch between the lot sizes pushed into the factory and the actual consumption rates downstream creates inefficiencies in the value stream. This misalignment disrupts the material flow and adds to systemic waste.

The shared corporate structure between ABC and its supplier presents an opportunity to renegotiate and adjust current practices to align with Lean principles. This relationship could facilitate future improvements in supply chain synchronization and inventory management.

4.3.3 Pre-assembly

The PA process consists of two parallel lines, with the number of operators varying by product. This adjustment accommodates differences in WC across products and aims to synchronize the PA's C/Ts with those of the Assembly lines (refer to Section 4.3.4). During periods when fewer operators are needed, excess personnel are reassigned to tasks such as repairs or participation in Kaizen events.

The PA is the most adaptable area for physical reorganization within the factory and was under investigation for improvement before the project started. Initial assessments indicate that reducing waste and optimizing workplace organization can eliminate at least 30% of WC.

Efforts to enable OPF within the PA cell have also been explored, as OPF would streamline its integration into a LMS. Most of the steps in the PA are manual, with one machine required at the end of the process. This machine lacks automation, requiring an operator for loading, unloading, and operation. C/Os, which only involve switching the components served to operators, are performed manually and take less than 5 minutes.

The table below summarizes the number of operators, work content, and deviations from the WAWC for each product:

Table 4: Pre-assembly current-state work content

Products	Actual # of operators	Workcontent	Deviation from WAWC
1	6	473,0	11,9%
2	6	480,0	10,6%
3	5	534,5	0,4%
4	5	545,4	-1,6%
5	5	502,4	6,4%
6	5	489,8	8,8%
7	5	543,2	-1,2%
8	6	590,8	-10,1%
9	6	816,0	-52,0%

The histogram of the PA WCs (Figure 5) highlights disparities between products, with Product 9 representing a significant deviation from others.

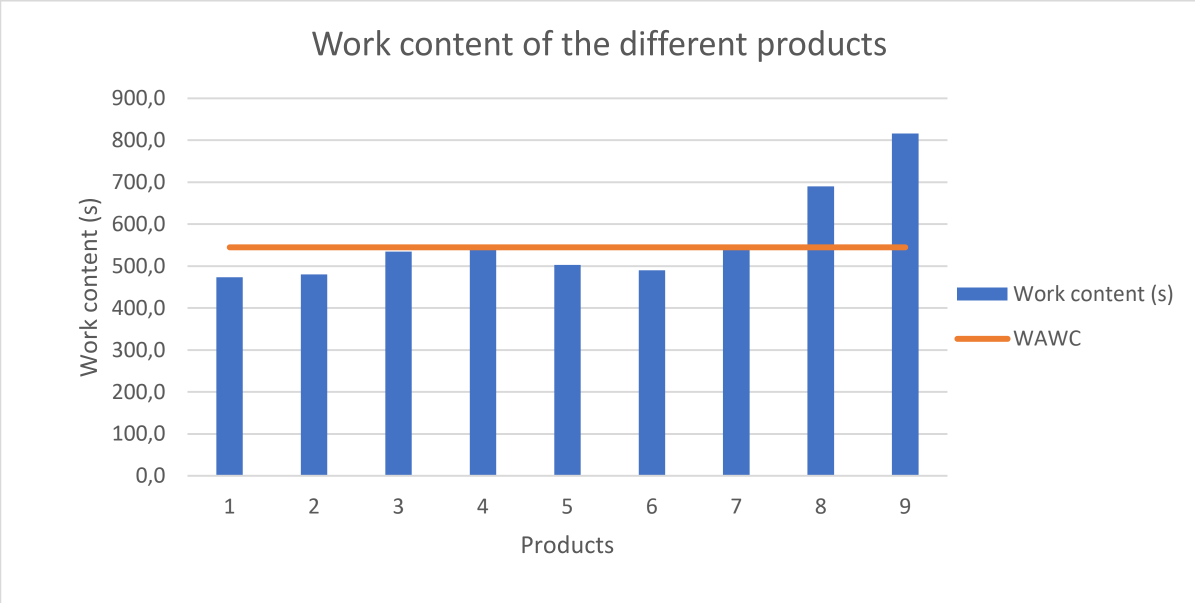

Figure 5: Histogram of the Pre-assembly's work contents

Regarding product allocation, while both PA lines are technically capable of producing all products, certain limitations exist. Some operators have not been trained for specific products, a longstanding practice that ABC still needs to address through cross-training. Table 5 illustrates the product allocation to the PA lines currently capable of producing them.

Table 5: Product allocation at the Pre-assembly

Products	Pre-assembly A	Pre-assembly B
1	X	X
2	X	X
3		X
4		X
5		X
6		X
7		X
8	X	X
9	X	

With only four products assigned to PA Line A, this process's flexibility is significantly constrained, posing challenges to scheduling and operational efficiency.

4.3.4 Assembly

ABC’s Assembly is the central operation within the factory, consisting of two parallel lines, each run by 21 operators. Similar to the PA process, not all products can be produced on both lines, but in this case, the allocation of products to specific lines is due to physical constraints, primarily insufficient machinery on the lines. Table 6 illustrates the product allocation to the Assembly lines.

Table 6: Product allocation at the Assembly

Products	Assembly A	Assembly B
1	X	X
2	X	X
3		X
4		X
5	X	X
6	X	X
7	X	
8	X	X
9	X	

The WC disparity in the Assembly process is similar to that in the PA. As shown in Figure 6 and Table 7, the factory's output can fluctuate significantly, ranging from 135 to 265 pieces per shift, resulting in a near 2:1 ratio between the two production rates. These fluctuations in production rates contribute to waste, particularly in the form of WIP build-up, especially for downstream processes.

Table 7: Work content at the Assembly lines

Products	C/T (s)	Prod per shift	Workcontent (s)	Deviation from WAWC
1	101.9	265	2140	20.5%
2	101.9	265	2140	20.5%
3	128.7	210	2703	-0.4%
4	128.7	210	2703	-0.4%
5	125.6	215	2638	2.0%
6	125.6	215	2638	2.0%
7	145.9	185	3064	-13.8%
8	160.7	168	3375	-25.3%
9	200	135	4200	-56.0%

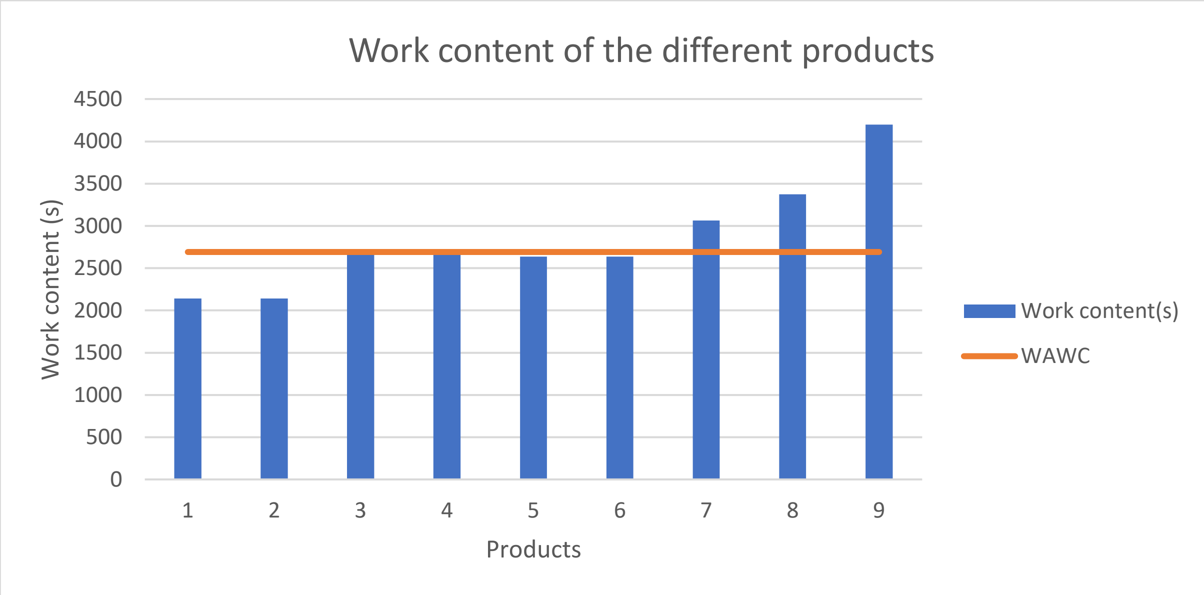

Figure 6: Histogram of the Assembly's work contents

Another critical issue in the Assembly process is the sequence-dependent C/O times. Each product combination requires a different C/O time, ranging from 10 to 43.75 minutes, depending on the modifications needed on the Assembly line. The various C/O times depending on the products-sequences are summarized in Table 8.

Table 8: Changeover-matrix

C/O Time (min)		Changing over to :								
		1	2	3	4	5	6	7	8	9
Changing over from:	1	0	25	25	25	25	25	25	25	43.75
	2	15	0	25	25	25	25	25	25	43.75
	3	15	15	0	10	10	20	20	25	25
	4	15	15	10	0	10	10	20	25	25
	5	15	15	10	10	0	10	20	25	25
	6	15	15	20	10	10	0	20	25	25
	7	15	15	20	20	20	20	0	25	25
	8	15	15	15	15	15	15	15	0	25
	9	26.25	26.25	15	15	15	15	15	15	0

Finally, the Assembly lines are highly mechanized, and modifying the workstations would require substantial investments. As a result, ABC company wishes to keep the Assembly process as a batch process, which introduces additional challenges to developing a Lean system due to its central role in the value stream. Moreover, C/O times will be considered fixed, as analyzing the 81 possible C/O combinations exceeds the scope of this project.

4.3.5 Testing

Following Assembly, all products undergo a rigorous 100% Testing process, which serves as the primary quality control step to ensure conformance with customer expectations. This Testing process is uniform across all products and has a C/T of 500 seconds. Currently, ABC employs eight Testing cells to handle the output from the Assembly.

A significant inventory buffer is maintained before the Testing stage to manage fluctuations in Assembly output. C/O times for the Testing process are approximately 25 minutes, which could be substantially reduced through the implementation of the SMED methodology proposed by Shingo (1985). Presently, the C/O process lacks standardized practices and organization, leaving considerable room for efficiency improvements.

4.3.6 Finishing

The finishing process, the final VA stage in ABC's value stream, is performed on a single line. As outlined in the process mapping in Chapter 4.1, this process is not required for Products 1 and 2. The WC for finishing is consistent across all other products at 600 seconds and consists of manual operations only.

This process operates at a reduced capacity compared to other stages, running only one shift per day and staffed with 11 operators per shift. This discrepancy with the other processes introduces additional variability into the value stream and increases the workload on the Shipping department, which must ensure timely shipping of completed products. Additionally, the finishing process's C/O time requires less than 5 minutes to perform.

4.3.7 Shipping

Although Shipping is not a VA process, it plays a critical role in the overall operation of ABC's value stream. The Shipping department manages the dispatch of 6 to 7 full trucks daily to the customer, determining the product mix within each truck. It sources products from the finished goods inventory or the production line.

The department coordinates truckloads and shipping frequencies and oversees the Testing stations. Based on direct feedback from the customer, the Shipping department sometimes instructs the Testing stations to prioritize certain products, occasionally overriding the production control department's production schedule. Substantial inventory maintained before the Testing stations facilitates this practice.

However, this dual control system, where production control and Shipping influence the materials flow, creates operational conflicts and elevates WIP levels along the value stream.

4.3.8 Customer

Similar to the supplier, the customer of this facility is an internal entity within the company. The customer's strategy for the upcoming year begins with a forecast translated into a Strategic Operations Plan, further refined into an MRP that will constitute the orders for the facility under analysis. Based on these orders, the facility generates its production schedule, incorporating factors like inventory levels and LTs to align supply with demand.

During the year, the MRP is executed as planned unless shifts in final customer demand necessitate adjustments. These changes can vary in type and magnitude, driven by fluctuations in final consumer demand, capacity constraints, or delays in part shipments. To accommodate these unpredictable variations, ABC must maintain high inventory levels.

Demand fluctuations also result in inefficiencies, such as unnecessary material handling that adds no value to the products. These erratic changes highlight the need for a more flexible production system with shorter LTs; an essential objective of this study aims to streamline operations and mitigate such inefficiencies.

4.3.9 Current-state-map

This study adopts the approach outlined by Rother and Shook (1999) to design the CSM. As mentioned in the literature, the CSM serves multiple functions:

- Define customer value and analyze the proportion of VA activities.
- Visualize the entire system and its interactions.
- Identify waste within the system and its root causes.
- Encourage shopfloor involvement and foster operator engagement.
- Provide a foundation for discussion with both management and shopfloor personnel.
- Support change management initiatives.
- Form the basis for developing the FSM
- Offer metrics for comparing the FSM with the CSM.

The CSM consolidates all process-related information and their interactions, including the WIP between processes, collected at a specific point in time. The TWCs of each process displayed at the bottom of the map in the LT ladder are average values.

As we can see in Figure 4, the system exhibits a VA/ NVA-Time ratio of merely 0.32% with 358.8 hours of NVA time and only 1.17 hours of VA time. This calculation excludes internal process waste (resulting from the seven forms of waste) and managerial waste necessary for running the current system. Nevertheless, it provides an accurate overview to identify waste sources and align with the objectives of the CSM. Additionally, the available time shown in the CSM reflects the productive time per shift (e.g., 27,000 seconds or 7.5 hours).

To summarize, ABC's current management of its factory exemplifies the Lean concepts of Muri, Mura, and Muda (Lean Enterprise Institute, 2020) and their detrimental effects:

- Muri (Overburden): Erratic demand changes and the isolated management of processes, characteristic of a PUSH system, create overburden across the value stream.
- Mura (Unevenness): Variability in C/T and outputs at different stages and the Shipping department's frequent interventions in the Testing process exemplify unevenness.
- Muda (Waste): Excessive WIP, unnecessary inventory movements, overproduction, and other forms of waste pervade the system.

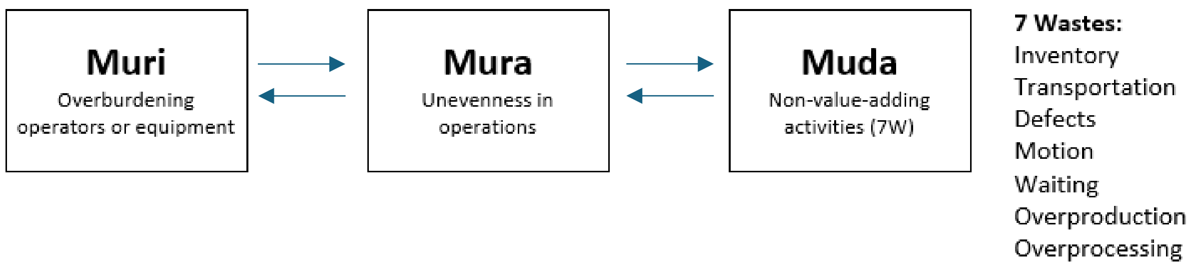

Figure 7: 3M and 7W

These three elements form a self-reinforcing cycle, as depicted in Figure 7 (illustrating the relationship between the 3Ms and the 7 wastes), perpetuating inefficiency. Eliminating waste at all levels is essential to disrupting this cycle and improving the overall system. With the CSM now established and inefficiencies identified, the foundation is set for devising solutions and designing the FSM to address ABC's challenges.

5 Development of the Future-state-map

We will follow Rother and Shook's (1999) 8 questions to design the FSM for an LMS. We will broaden the eight questions to include the additional methods developed by Duggan (2013) for implementing Lean into HMLV environments. The 8 questions are as follows:

1. What is the takt time?
2. Will ABC build to a finished-goods SM from which the customer pulls, or directly to Shipping?
3. Where can we use continuous flow processing?
4. Where will we need to use SM pull systems in order to control production of upstream processes?
5. At what single point in the production chain will we schedule production? (defines the pacemaker process)
6. How will we level the production mix at the pacemaker process?
7. What increment of work will we consistently release and take away at the pacemaker process?
8. What process improvements will be necessary?

This methodology will enable us to eliminate as much waste as possible while respecting the constraints given by the environment of the case study. The eight questions provide us with a structured step-by-step approach to implement each component of the value stream into a LMS while minimizing the risk of overlooking critical information about the system.

5.1 Defining takt and the shipping strategy

To meet the demand of our customers with the minimum amount of waste, we first need to define the T/T. With information about the demand data provided in Chapter 4.2, the T/T is calculated as follows:

$$T/T = \frac{Available\ Time\ in\ a\ week}{Cumulative\ weekly\ demand} = \frac{270000\ s}{4080\ pieces} = 66.2s/piece$$

The available time is based on a week of demand consisting of two shifts per day, eight hours per shift, and half an hour of paid break per shift. The cumulative demand represents the total weekly demand for the facility, calculated as the sum of the weekly average demand for each individual product.

The T/T sets the pace for our LMS and dictates the rate at which the processes must operate to meet customer demand. It also provides ABC with a management time frame for responding to potential issues within the factory, ensuring that the company addresses critical problems as soon as they arise.

Unlike traditional metrics such as output, which focus on volume per hour, the T/T specifies a time frame within which a single part must be produced. This approach requires more process stability, fosters the continuous improvement culture and reduces variability within the process.

After defining the T/T that the new system will follow, it is necessary to define if the system will send its products directly to the Shipping department or refill a finished-goods SM. Despite receiving an annual forecast from its customers, ABC cannot accurately predict weekly demand due to the significant variability of certain products and the frequent demand adjustments. Producing to order is therefore not feasible, hence the necessity of building a finished goods SM.

The quantity of WIP in the SM is directly proportional to the system's EPEI. We can only design the SM once the EPEI is defined. However, since we know the demand characteristics, we can identify which parts will be kept as WIP in the FSM. An ABC product analysis (Smalley, 2009) combined with a comparison of the CV (Figure 9) will guide the decision-making process.

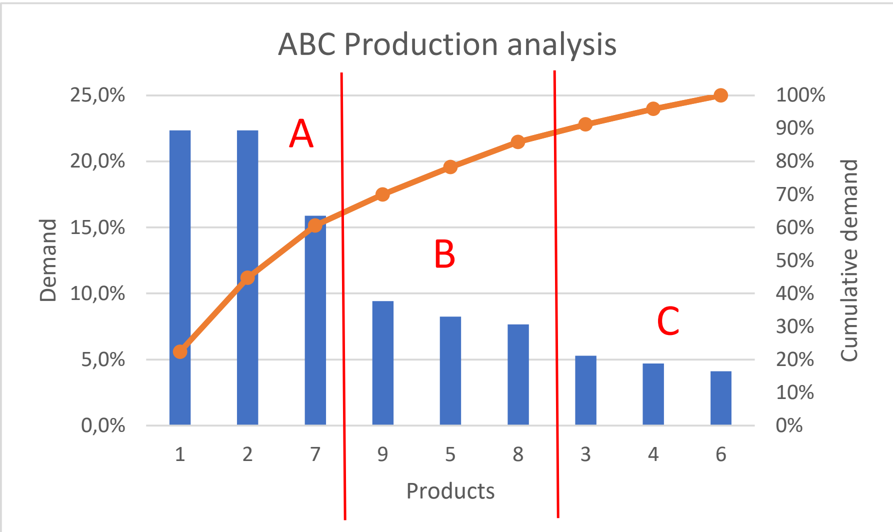

Figure 8: ABC analysis

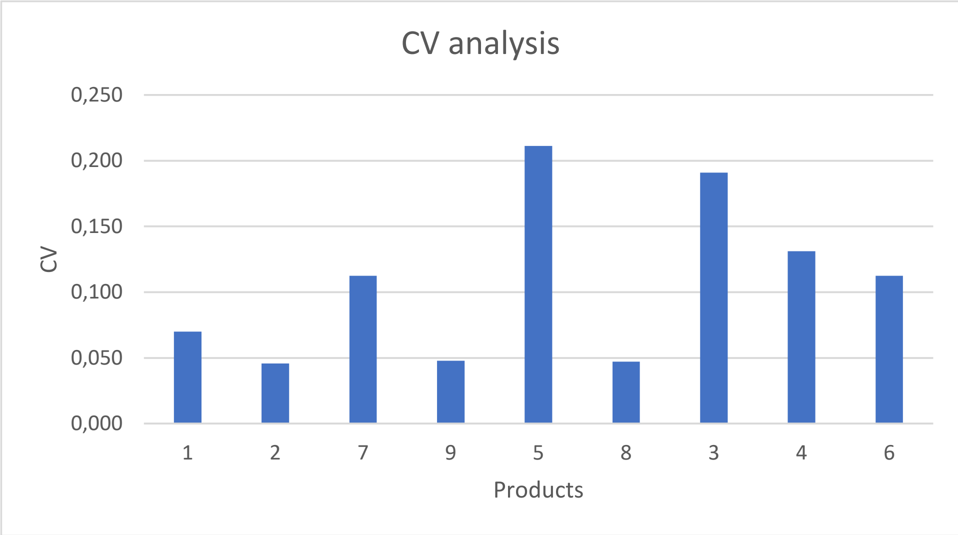

Figure 9: CV Analysis

Based on the demand analysis in Figure 8, Products 1, 2, and 7 account for 61% of the total demand, the A-products, while products 9, 5, and 8 account for another 20% of the demand, the B-products. Products 3, 4, and 6 constitute the remaining 19%, categorized as the C-products.

To determine which products to keep in stock, we will consider the four options given by Smalley (2009): To determine which products to keep in stock, we will consider the four options given by Smalley (2009):

Table 9: Decision about the finished goods supermarket design

	Advantages	Disadvantages	Feasibility?	Decision
1. Hold finished goods inventory for all the products (MTS)	Highest safety against demand variation. Products are always ready to be shipped	High amount of WIP. This means higher LT and more waste	ABC already keeps a high finished goods inventory, space would not be a problem in this case	✓
2. Hold no finished goods at all (MTO)	No WIP, most efficient option in terms of waste reduction	Requires short LT and stability in demand.	Not possible as LT is too long, and demand is too erratic.	
3.a Hold only C-products and produce A- and B- products to order	Second best option in terms of waste reduction.	Necessitates control over the mix every for every time interval and stability of the processes.	Both options are feasible. It will depend on the variations in demand of the single products.	
3.b Hold A and B products and produce C-products to order	Reduced necessity to control the mix	Moderate inventory		

The processes in the FSM will be designed to follow a certain Takt time, which is based on the average demand for each product. If the total demand exceeds the calculated average demand, the processes will not be able to meet the demand on time. To cope with this, the production control will be able to pull parts from the established finished goods SM to level the production while meeting the demand on time for the system. In a traditional Lean Manufacturing implementation, the products that need to be kept within the finished goods SM are being defined through an ABC-Analysis as shown in Figure 8. However, the Assembly process having variable C/T, a variation in the mix of products will also modify the capacity requirements, possibly leading to an overload for the process. Although not explicitly addressed by Smalley's (2009) recommendations, maintaining all the products in the finished goods SM will help ABC to manage these capacity variations effectively. Consequently, the first option has been selected as the most appropriate SM design strategy.

5.2 Develop continuous flow

As discussed in Chapter 3, developing continuous flow serves multiple purposes: merging processes to eliminate WIP, supporting OPF to eliminate waste within the cell, and adhering to T/T. In the case of ABC, the processes cannot be merged together as the Assembly will not be able to meet T/T and the Finishing process does not produce Products 1 and 2.

Improvement recommendations will only be expressed as a percentage of the WC to be reduced to meet the T/T. ABC's engineers and operators will be left to adapt the C/T to the T/T, modify the Layout of the OPF cells and implement the necessary automation as described by Rother and Harris (2001).

Considering the company's desire to keep the Assembly line's current operations as described in Chapter 4.3.4, this analysis will solely focus on the PA, the Testing, and the finishing processes in this part of the study.

The first process to be considered for this analysis is the PA lines. The process is already laid out as a straight line with only one machine inside the cell. While the current process follows a straight-line configuration, redesigning a U-cell has been considered unnecessary as the workstations primarily involve manual operations, requiring constant operator presence. Thus, the straight-line layout with one operator per station will be maintained.

The current products' allocation to each PA line represents a significant constraint for the overall system. This rigidity reduces the process's planning flexibility, thus increasing the necessary WIP between the PA and the Assembly processes and generating waste for the system overall. The process analysis revealed that each product can be produced on both lines, allowing for greater flexibility.

The training required for operators to handle a broader range of products will also foster a more resilient and cross-functional team. Hence, in the future state, it is proposed that all products are produced on both PA lines.

Having two identical and parallel PA lines results in a T/T of 2 * 66.2 = 132.4 s.

To account for the variability in manual operations, we will opt for a 7% allowance for the operators, resulting in a planned C/T of :

$$planned\ C/T = T/T * 0.93 = 132.4\ s * 0.93 = 123\ s$$

Next, we calculate the required number of operators. For instance, product 3 currently has a TWC of 534.5 s and number of operators:

$$\#operators = TWC/(planned\ C/T) = 534.5\ s/123\ s = 4.3$$

Rounding down the number of required operators to the next lowest integer for this specific product, we obtain a revised TWC of:

$$required\ TWC = \#operators * planned\ C/T = 4 * 123 = 492\ s$$

To enable the process to adhere to T/T, the TWC must be reduced by 42.5 s or 8%.

Table 10 outlines the number of recommendend operators, the revised work content and the necessary reductions in TWCs for each product in the PA lines.

Table 10: Improvements at the Pre-assembly lines

Product	Current work content	Required operators	Recommended operators	Revised work content	Reduction in work content
1	473.0	3.8	4.0	473.0	0%
2	480.0	3.9	4.0	480.0	0%
3	534.5	4.3	4.0	492.4	-8%
4	545.4	4.4	4.0	492.4	-10%
5	502.4	4.1	4.0	492.4	-2%
6	489.8	4.0	4.0	489.8	0%
7	543.2	4.4	4.0	492.4	-9%
8	590.8	4.8	4.0	492.4	-17%
9	816.0	6.6	6.0	738.5	-9%

With these improvements, one operator can be removed from each PA line and be reassigned to another department of the factory or be trained to conduct kaizen events for further process optimization. Products 1 and 2 already meet T/T with four operators, and reducing their WC further to meet T/T with three operators would require excessive improvements at this stage. We will, therefore, keep the inefficiencies until a stable future state has been reached, after which further C/T reductions can be pursued.

A previous study concluded that the WC cannot be improved by more than 30% and therefore prevents us to reach four operators to produce product 9 at the PA lines. Meanwhile, keeping five operators for all the other products would represent too much waste. To address this, Duggan (2013) suggests several strategies, using SMs, FIFO lanes and toggling labor resources:

- Level the schedule and keep labor constant. In Duggan's words, "arrange the orders coming out of the SM to build high-content products only after low-work products."
- Level the schedule and build ahead, keeping labor constant. This necessitates knowing the demand in advance and works well when the pacemaker is close to the customer.
- Use a combination of SM and FIFO to keep labor constant. With this method we will pull from a SM if the demand requires more capacity than is available.
- Balance each product to the T/T and vary labor over to time.

Since ABC is already varying the number of operators between 5 and 6 at the PA lines, they can effectively manage the fourth option, balance each product to T/T, and vary labor over time. This option is also the most efficient waste reduction, necessitating no additional WIP. The strategy of keeping four operators for products 1 to 8 and 6 operators for product 9 will be adopted for ABC's case. The C/T and number of necessary operators for the FSM are represented in Figure 10 and Figure 11 respectively.

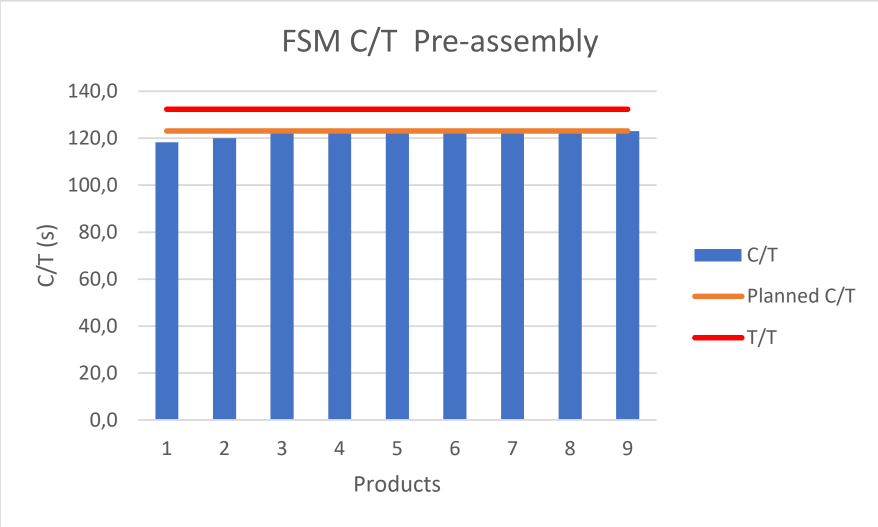

Figure 10: FSM C/T Pre-assembly

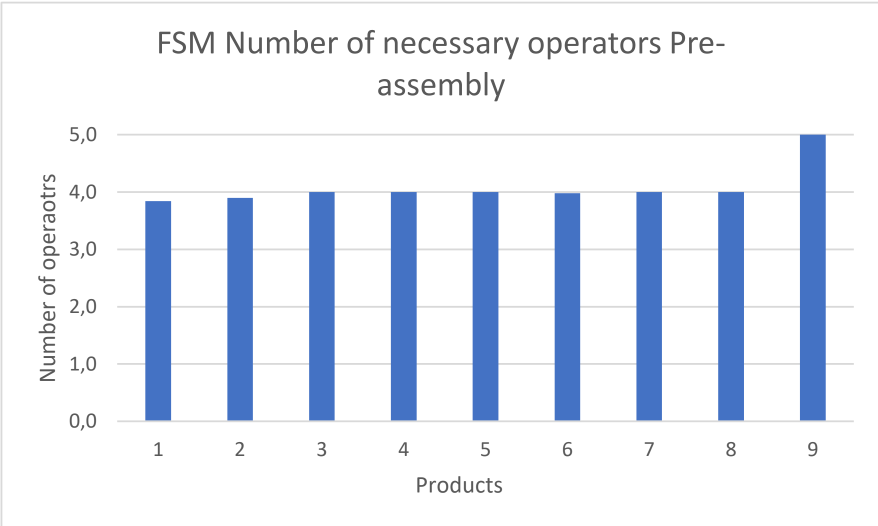

Figure 11: FSM Number of necessary operators Pre-assembly

As only one product requires an additional operator, there is no necessity to schedule product 9 at a particular time, as suggested in Duggan's (2013) case study. The additional operator will be incorporated in the PA line for a duration corresponding to the demand of product 9, multiplied by the T/T.

The next process to be analyzed is Testing. The work content is consistent across all products, so only one work content must be considered for the analysis. Each Testing cell can be considered as an independent production line working in parallel with each other.

With the work at the Testing cells being less subject to variations, we can use a lower allowance than for the PA process. With a lower allowance of 5%, we obtain the following planned C/T:

$$planned\ C/T = T/T * 0.93 = 66.2\ s * 0.95 = 62.9\ s$$

$$\#cells = TWC/\ planned\ C/T = 515/62.9 = 8.2\ cells$$

Rounding down the number of cells to the next lowest integer, we get the following TWC per cell:

$$TWC = \#cells * planned\ C/T = 8 * 62.9 = 503.2\ s$$

To make the Testing cells adhere to T/T, a reduction in TWC of 11.8s or an improvement of 2.3% is necessary.

Additionally, the current C/O time also needs to be improved to introduce the process into the continuous flow system and minimize the necessary WIP downstream of the process. The C/O process consists primarily of exchanging the Testing structures, which are already mounted on moving trays that can be pushed into the cell as soon as the previous tray has been removed. The C/O process currently needs more standardization and organization. It can certainly be substantially reduced by externalization, waste elimination, and standardization of the C/O operation (Shingo, 1995). We assume that the C/O time can be reduced to under 5 minutes, enabling ABC to level the mix as much as necessary.

The Testing process is a critical point in the value stream and is responsible for controlling the quality and performance of the products. We will, therefore, not be able to reduce the scrap rate to 0. However, in the current state, defective products are reworked immediately upon discovery and reinserted into the process.

Since the Testing process consists of an even number of cells, we can allocate half of the cells to Assembly 1 and the other half to Assembly 2, facilitating the balancing and management of the processes.

Finally, Finishing is the last process to be considered in this part of the study. Similarly to Testing, the WC is also constant for all the products. For the work steps consisting entirely of manual operations, we will use an allowance of 7%. However, the finishing process only processes products 3 to 9, resulting in a lower demand for the process and a higher T/T to follow.

The T/T for this process, based on the demand for products 3 to 9, equals to:

$$T/T_{finishing} = \frac{Available\ time}{Cumulative\ demand_{3\ to\ 9}} = \frac{270000\ s}{2256\ pieces} = 119.7\ s/piece$$

We then define how many operators we would need to meet T/T with a 7% allowance:

$$planned\ C/T = T/T * 0.93 = 119.7\ s * 0.93 = 111.3\ s$$

$$\#operators = TWC/\ planned\ C/T = 600/111.3 = 5.4\ operators$$

Rounding the number of operators to the lowest next integer, we obtain the following TWC:

$$TWC = planned\ C/T * \#operators = 111.3\ s * 5 = 556.6\ s$$

To adhere to T/T, the TWC will need an improvement of 43.5s or 7.3%.

To align the finishing process's shift model with the entire value stream, which operates on a two-shift model, we will adjust it from one shift per day to two shifts per day. Under the new system, the process will operate with 10 operators working 2 shifts a day: 5 operators in the morning and 5 in the afternoon. The suggested improvements will allow us to reduce the number of operators by one, improving VA time.

5.3 Implementing Supermarket based Pull systems

After adapting the processes to adhere to T/T, we need to integrate them into the LMS using FIFO lanes, SMs, or other pull systems.

A SM will be placed at the end of the value stream to address the demand and Assembly's capacity requirement variations. Additionally, we will use a SM for the raw materials inventory, from which the LMS will pull from. The parts pulled from this SM will release production kanbans, which, in turn, will fill a kanban post during each EPEI, defining the orders for the supplier. This SM will replace the current inventory at the beginning of the value stream, reducing the waste within the system and providing an effective method to convey ABC's demand to its suppliers. The amount of WIP to be kept in the raw materials SM will be determined by the system's EPEI.

The limiting factor for our EPEI will be the Assembly, as it is the system's only process unable to meet OPF. Optimizing the Assembly's scheduling is therefore crucial to minimizing the system's EPEI.

As the management of the entire system depends on the pacemaker process, it is necessary to first determine which process will be the pacemaker. The pacemaker is the only process in a LMS that should receive information about the demand. A pacemaker at the end of the value stream requires a system, such as a kanban system, to send the orders back to the upstream processes. A pacemaker positioned further upstream can send its parts into FIFO lanes, establishing the sequence for the subsequent processes.

First, we can eliminate the finishing process from the list of potential candidates to become the pacemaker as it does not process all the products. Sending the schedule to the Testing process would require establishing another SM to convey the demand information to the upstream processes. The Assembly process necessitates an optimized sequence, and we need to make sure that this specific sequence of parts arrives at the Assembly. In this scenario, the Testing process would pull from an SM in a specific sequence, conveying the demand to the Assembly process while minimizing the EPEI. The Assembly would, in turn, pull from the PA's SM, further conveying the demand upstream. However, this case would require additional kanban loops and SMs, resulting in additional WIP.

A second option for conveying the demand from the Testing process to the upstream processes is pulling from an SM and sending the kanbans directly to the PA, thereby eliminating the need for an additional SM. However, this approach faces significant limitations. The PA lines and the Assembly lines must follow a different sequence because of their differences in C/T and multiple possible routings at the Assembly lines. Because a kanban system would replicate the pacemaker's sequence and send it upstream, this method would not enable us to minimize the EPEI fully.

Ultimately, the decision lies between the Assembly process and the PA process. Various possibilities have been carefully analyzed and deliberated. We will first discuss the proposed solution and subsequently analyze the remaining possibilities and explain why they could not be implemented in ABC's case.

5.3.1 The proposed solution: Using multiple FIFO lanes with concurrent schedules

Traditional Lean Manufacturing literature are recommending using "just-in-case" inventory to cope with the specificities of the Assembly lines, leading to high WIP levels. The objective of the proposed solution, concurrent scheduling, is to avoid using a SM between the PA lines and the Assembly lines, effectively reducing the necessary inventory between the two processes.

Concurrent scheduling involves simultaneously sending a schedule to the PA and Assembly lines and utilizing multiple FIFO lanes, one for each product. The Assembly will pull from the FIFO lanes based on the schedule that contains the mix of products and the necessary quantities to be produced at each Assembly line. To perform this system, we will use an optimization model that will create a schedule for each PA and Assembly line, define the necessary delay between both Assembly lines and find the lowest achievable EPEI. The optimization model is necessary given the sequence-dependent C/O and the two parallel lines providing alternative routings for the parts. Both schedules will be linked through precedence constraints, ensuring that the necessary parts reach the corresponding FIFO lanes on time.

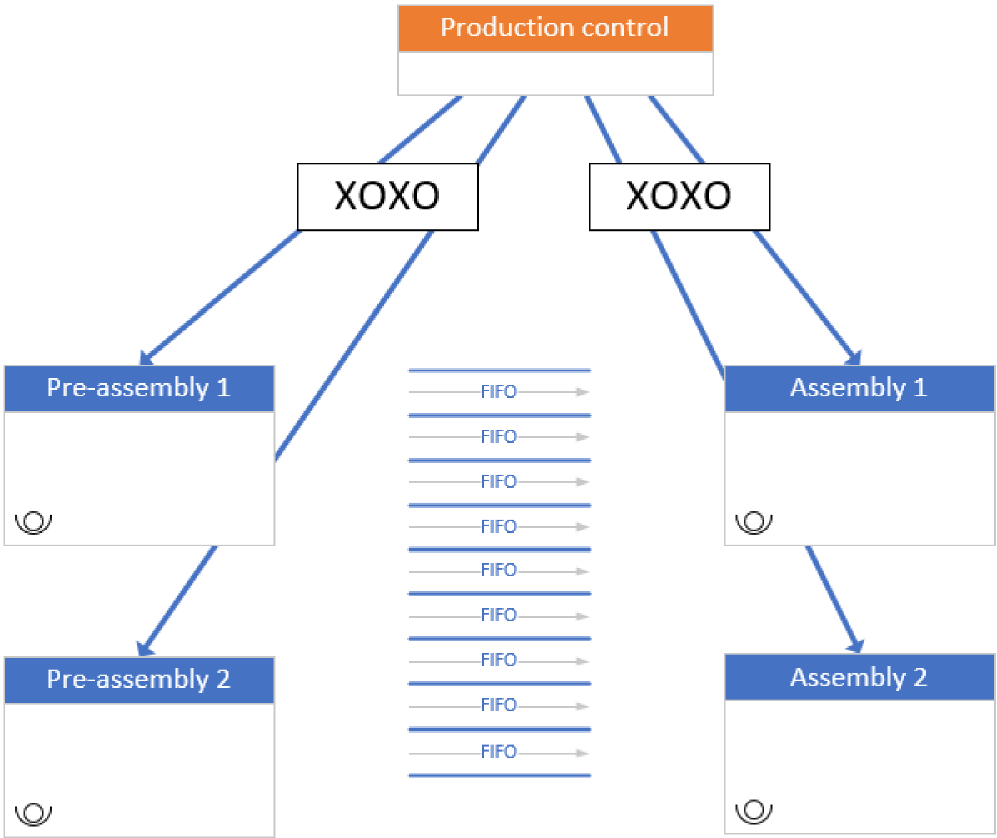

Figure 12: Using multiple FIFO lanes with concurrent schedules

Although traditional lean guidelines recommend sending a schedule to a single process in the value stream, we will adapt this rule by sending concurrent schedules to both processes simultaneously. Being linked by precedence constraints ensures that both processes remain interdependent, preventing them from taking independent actions and overproducing.

This solution, illustrated in Figure 12, enables ABC to maintain a WIP level that is precisely calibrated to maintain an optimized EPEI. The reduced WIP as well as the newly defined EPEI will in turn reduce the production LT of the factory and increase ABC's flexibility to meet customer demand.

Other methods have been explored during the development of the proposed solution. A method to cope with the sequence-dependent C/O and the differences in C/T, would be to send the schedule to the Assembly lines which would then pull from a SM. This SM would then convey the demand to the PA lines through production kanbans. While this approach, depicted in appendix G, would address the sequence-dependent C/O times and the difference in C/T, it requires keeping a large quantity of WIP over time, leading to a substantial increase in LT. Additionally, sending the schedule to the Assembly lines would create difficulties monitoring the pitch, as the hourly output would fluctuate depending on the product being produced. As a result, there might be more effective options in terms of waste elimination.

Another option would be to send the schedule to the PA lines and connect them to the Assembly lines through 2 individual FIFO lanes, one between PA1 and A1 and another between PA2 and A2. This approach, depicted in Appendix H, could represent the most efficient way to convey the demand to the system and minimize the WIP between the two processes, as only a minor delay would have to be kept coping with the differences in C/T and the C/O. However, because of that same C/T difference between the PA lines and the Assembly lines, we would face issues with the workload distribution for the PA lines. For example, producing 100 parts at Assembly line A would take a different time to produce the same 100 parts at PA line 1. Consequently, although the Assembly lines will maintain an equal workload due to the optimization model, this will not necessarily translate to a corresponding workload balance for the PA lines. Such disparities would lead to one of the PA lines being unable to meet the demand. Therefore, this method would not be a viable option for our system.

A variation of the previously mentioned concept involves keeping one FIFO lane per Assembly line while sending the schedule to the PA lines. In this scenario, depicted in Appendix I, both PA lines would supply parts to both Assembly lines. The PA lines would need to be incorporated into the optimization model to ensure that the correct parts are in the FIFO lanes when required by the Assembly lines. This would enable the Assembly to follow the desired sequence and minimize the EPEI. However, this approach requires the PA lines to supply the Assembly lines in a manner that ensures the proper sequence is maintained in each FIFO lane. These additional constraints would increase the required WIP, as it would limit the model's flexibility in scheduling the PA lines. For example, the PA lines could not build a specific part in advance and then fulfill the rest of the order later, as other parts might have been sent into the FIFO lanes by the other process. Also, both lines could not produce different products and feed the same FIFO lane simultaneously. Furthermore, this approach is highly sensitive to disruptions. If one PA line cannot produce, it forces the other to be idle, too, as the sequences in the FIFO lanes are highly dependent on both lines being perfectly synchronized.

With the pacemaker and the method to link the PA and the Assembly processes being defined, we can now design the remaining process connections within the value stream.

5.3.2 Assembly/ Testing

The next process connection to be considered is between the Assembly and Testing processes. The lower C/O times of the Testing process provide great flexibility in the mix of products that can be produced and enable us to connect it with the Assembly process through a FIFO lane.

However, since the C/T for products 7, 8, 9 are higher than T/T in the Assembly, it is necessary to define a certain SS to keep between the Assembly and Testing to prevent the Testing process becoming idle if, in the worst-case scenario, all of these parts are produced at the beginning of the EPEI cycle. When these parts are produced in Assembly, they will either directly go to Testing through the FIFO lane or refill the SS from which the Testing process can pull if necessary. The delay is proportional to the average demand and we will quantify it once the EPEI is defined in Section 5.5.

5.3.3 Testing/ Finishing

Finally, the connection between the Testing and finishing processes must be addressed. As previously mentioned, not all the products need to be processed by the finishing process, which could lead to idle time for the Finishing process in certain circumstances. The highest idle time the Finishing process could experience occurs if both Assembly lines produce products 1 and 2 in parallel at the beginning of the EPEI cycle. This scenario is explained in more detail next.

As mentioned in Section 5.2, we allocate one half of the cells in Testing to Assembly 1 and the other half to Assembly 2. The worst-case scenario is realized if both Assembly lines start with Product 1 in parallel at the beginning of the cycle and Testing would receive only Product 1 to start with. Then, similarly, if both Assembly lines produce Product 2 next, Testing would only receive Product 2. While Testing produces Products 1 and 2 first as described above, this will cause the finishing process to be idle during this time, unless some WIP of other products are kept between Testing and finishing. Hence, we will connect the Testing and finishing processes with a FIFIO lane and use WIP (to serve as SS) to prevent the finishing process from becoming idle.

The WIP level is determined by the maximum potential demand for products 1 and 2 during an EPEI cycle (during which the finishing process might not receive any parts from the Testing process) as shown below:

$$WIP_{T-F} = Max.demand\ product\ 1 + Max.demand\ product\ 2$$

where

$$Max. demand\ i = \mu_{EPEI} + \sigma_i * k * \sqrt{EPEI}.$$

For the maximum demand for products 1 and 2, we assume that the demand follows a normal distribution; μ_{EPEI} represents the average demand over the EPEI cycle for each product, σ_i represents the standard deviation of the weekly average demand for each product i and k ensures the targeted fill-rate. By using a k value of 2.5, we ensure a fill-rate of of 99.4% for the finishing process.

A similar formula will also be used to define the delay between Assembly and finishing and the definition of the BSs in the SMs. Appendix F outlines the rationale and methodology used to apply this formula.

5.4 Optimization of the sequence and the delay between the processes

In the model below, the EPEI serves as an input provided by the model's user. To determine the lowest EPEI, experimentation with the optimization model is necessary to the point at which the model cannot yield any feasible solution. In the model, the EPEI will regulate the available production time for each line and the demand to be fulfilled during this interval.

5.4.1 Assumptions

Several assumptions have been made regarding the development of the optimization model.

The container size will constrain the EPEI values, as the demand values need to be evenly divisible by the container size and the EPEI. Initial runs without the container size constraint will be conducted to determine the lowest possible EPEI. If the container size highly conflicts with the lowest achievable EPEI, adjustments to the container size may be considered in the future.

Additionally, to address concerns about stability in the early stages of the implementation, the Assembly lines will initially be able to pull the parts from the FIFO lanes only after both PA lines have completed the entirety of the demand for the specific product. Once ABC has gained proficiency with the new system, this constraint can be relaxed through adjustments to the precedence requirements.

5.4.2 Sets, parameters and variables

To start modeling the optimization problem, we will first determine the sets of our model. The first set is K, representing the number of Assembly lines that must respect the given demand.

Similarly, another set, L, will represent the two PA lines. Finally, we have the set I, which contains the nine products that must be produced during the interval. An artificial product has been added to the index I to facilitate the development of the optimization model. The artificial product will serve as a starting and ending point for the constraints based on the Vehicle Routing Problem.

Sets:

K k Є K index for the Assembly lines K = {1, 2}

L l Є L index for the preAssembly lines L = {1, 2}

I i Є I & j Є I indexes for the products I = {1, …10}

After defining the sets to depict the manufacturing environment we are improving, we need to define the model's parameters. The first parameter, b_i, represents the C/Ts of the products i at the Assembly lines. We then need to define the weekly demand for each product i by using the parameter d_i. The last parameter concerning the products will be a_{ijk}, defining the C/O time from product i to product j at Assembly line k. Although the C/O times are the same on both Assembly lines, some products cannot be produced on both Assembly lines. We can see in Table 11 that some cells contain M, indicating the unavailable products for the represented Assembly line.

Table 11: Changeover matrix for Assembly line A in the optimization model

Products	Art	1	2	3	4	5	6	7	8	9
Art	M	900	900	M	M	600	M	1200	1500	1500
1	0	M	1500	M	M	1500	1500	1500	1500	2625
2	0	900	M	M	M	1500	1500	1500	1500	2625
3	M	M	M	M	M	M	M	M	M	M
4	M	M	M	M	M	M	M	M	M	M
5	0	900	900	M	M	M	600	1200	1500	1500
6	0	900	900	M	M	600	M	1200	1500	1500
7	0	900	900	M	M	1200	1200	M	1500	1500
8	0	900	900	M	M	900	900	900	M	1500
9	0	1575	1575	M	M	900	900	900	900	M

Since the PA has been improved, all the products will be produced at T/T, represented by the parameter R. The remaining parameters are constants, used throughout the model in several instances. Parameter T represents the available time per line in a week, 270,000 seconds. Parameter B represents the container size at which we will release production orders to the shopfloor, 12 parts. Additionally, the EPEI is represented by parameter V defined as a fraction/multiple of base period length e.g. 1 week. Finally, parameter M is a high-value parameter used in the sub-route elimination constraints.

Parameters:

b_i : Cycle times

d_i : Weekly demand

a_{ijk} : Changeover time from product i to product j in line k

T : Available time in a week

V : Chosen EPEI (ratio based on 1 Week, ex.: V=0.5 means half a week)

R : T/T of the pre Assembly lines

M : High number (9 999 999)

B: Container Size

The final step before defining the constraints is to define the decision variables (DVAR). The DVAR x_{ik} and q_{ik} will define how much of the product I will be produced on Assembly line k and PA line l. Both DVARs will later be multiplied by B, the container size. To allocate the C/O processes to the different lines, we will use the binary DVAR w_{ijk} and c_{ijl}, taking the value 1 if a C/O has to be performed from product i to product j on Assembly line k or PA line l. Because we want to create a schedule for the PA and the Assembly, we need to model the starting times at the PA lines l and the Assembly lines k using s_{ik} and z_{il}. These two DVARs will also be helpful to link the Assembly and PA schedules with the precedence constraints.

Lastly, *Cmax* is defined as the highest completion time of both Assembly lines k, enabling the model to minimize the delay between the PA and the Assembly while finding the optimal sequence for both Assembly lines.

Decision variables:

x_{ik} : Decision to produce an amount x of product i at Assembly line k

w_{ijk} : $\begin{cases} 1, & \text{if a C/O from product i to product j at assembly line k is performed} \\ 0, & \text{Otherwise} \end{cases}$

s_{ik} : Starting time of product i at Assembly line k

q_{il} : Decision to produce an amount q of product i at Assembly line l

c_{ijl} : $\begin{cases} 1, & \text{if a C/O from product i to product j at PA line l is performed} \\ 0, & \text{Otherwise} \end{cases}$

z_{il} : Starting time of product i at pre Assembly line l

Cmax: Maximum completion time of both Assembly lines

5.4.3 Model

The next step is to define the objective function of the optimization model. The objective is to minimize the latest completion time *Cmax*. This serves multiple purposes: reducing the available time for the PA and Assembly lines, ensuring an optimal allocation of production quantities to the processes. Simultaneously, the objective function will also minimize the necessary WIP between the PA and Assembly processes.

In a traditional Lean Manufacturing framework, the EPEI of the system is defined by the processes that cannot meet T/T and have high C/O times. By reducing the EPEI, the average demand to be fulfilled during this time interval decreases proportionally. With the total C/O time remaining constant, the EPEI can be determined as the lowest time interval in which the average demand of all the products can be followed, while being able to perform all the necessary changeovers. Since reducing C/O times results in a lower achievable EPEI for the system, minimizing the total C/O time of the Assembly would, therefore, appear to be the best option to achieve the lowest EPEI. However, simply minimizing the total C/O time at the Assembly would not consider the PA lines nor would it consider the WIP between the two processes.

As both schedules are linked through precedence constraints, the latest completion time of the Assembly lines impacts the starting and completion times of the PA lines. Consequently, using *Cmax* as the objective function minimizes the total time available to fulfill the demand at both the PA and Assembly lines, thereby reducing the delay between these processes. With less time available for each process, the model is forced to find a better sequence and production allocation. Since the schedules of the Assembly lines and the PA lines are linked through precedence constraints, a longer delay between the two processes would result in an increased latest completion time for the Assembly process. Minimizing *Cmax* would therefore simultaneously minimize the delay (or WIP) between the two processes.

Finally, with *Cmax* being minimized, the total C/O time of the Assembly process might not be minimal. However, the sequences of both PA lines and Assembly lines are optimized to fulfill the demand within the lowest possible EPEI and the WIP between both processes optimized to supply the Assembly with the parts just-in-time.

Minimize $Cmax$

Subject to :

$Cmax \geq s_{ik} + x_{ik} * b_i * B$ ∀i∈I, k∈K (1)

$\sum_{k \in K} x_{ik} * B \geq V * d_i$ ∀i∈I (2)

$x_{jk} \leq \sum_{i \in I: i \neq j} d_j * w_{ijk}$ ∀j∈I, k∈K (3)

$x_{jk} \leq \sum_{i \in I: i \neq j} d_j * w_{jik}$ ∀j∈I, k∈K (4)

$\sum_{i \in I} x_{ik} * B * b_i + \sum_{i \in \mathrm{I}} \sum_{j \in \mathrm{I}} w_{ijk} * a_{ijk} \leq V * T$ ∀k∈K (5)

$s_{jk} \geq s_{ik} + x_{ik} * B * b_i + a_{ijk} - M * (1 - w_{ijk})$ ∀i∈I, j∈I, k∈K : i≠j & j>=2 (6)

$\sum_{i \in \mathrm{I}} w_{1ik} = 1$ ∀k∈K (7)

$\sum_{i \in \mathrm{I}} w_{i1k} = 1$ ∀k∈K (8)

$\sum_{l \in L} q_{il} * B \geq V * d_i$ ∀i∈I (9)

$q_{jl} \leq \sum_{i \in I: i \neq j} d_j * c_{ijl}$ ∀i∈I, l∈L (10)

$q_{jl} \leq \sum_{i \in I: i \neq j} d_j * c_{jil}$ ∀i∈I, l∈L (11)

$\sum_{i \in I} q_{il} * B * R \leq V * T$ ∀l∈L (12)

$z_{jl} \geq z_{il} + q_{il} * B * R - M * (1 - c_{ijl})$ ∀i∈I, j∈I, l∈L : i≠j & j>=2 (13)

$\sum_{i \in \mathrm{I}} c_{1jl} = 1$ ∀l∈L (14)

$\sum_{i \in \mathrm{I}} c_{i1l} = 1$ ∀l∈L (15)

$z_{i1} + q_{i1} * B * R \leq s_{i1} + M * (1 - \sum_{j \in I} w_{ij1})$	∀i∈I	(16)
$z_{i2} + q_{i2} * B * R \leq s_{i1} + M * (1 - \sum_{j \in I} w_{ij1})$	∀i∈I	(17)
$z_{i1} + q_{i1} * B * R \leq s_{i2} + M * (1 - \sum_{j \in I} w_{ij2})$	∀i∈I	(18)
$z_{i2} + q_{i2} * B * R \leq s_{i2} + M * (1 - \sum_{j \in I} w_{ij2})$	∀i∈I	(19)
$\sum_{j \in I} c_{ijl} \leq 1$	∀i∈I, l∈L: i≠1	(20)
$\sum_{j \in I} c_{jil} \leq 1$	∀i∈I, l∈L: i≠1	(21)
$\sum_{j \in I} w_{ijk} \leq x_{ik}$	∀i∈I, k∈K: i≠1	(22)
$\sum_{j \in I} w_{jik} \leq x_{ik}$	i∈I, k∈K: i≠1	(23)
$\sum_{j \in I} c_{ijl} \leq q_{il}$	∀i∈I, j∈I: i≠1	(24)
$\sum_{j \in I} c_{jil} \leq q_{il}$	∀i∈I, j∈I: i≠1	(25)
$x_{ik} \geq 0, int$	∀i∈I, k∈K	
$w_{ijk} \in \{0,1\}, int$	∀i∈I, j∈I, k∈K	
$s_{ik} \geq 0, float$	∀i∈I, k∈K	
$q_{il} \geq 0, int$	∀i∈I, l∈L	
$c_{ijl} \in \{0,1\}, int$	∀i∈I, j∈I, l∈L	
$z_{il} \geq 0, float$	∀i∈I, l∈L	

$D_k \geq 0, float$ $\forall k \in K$

$Cmax \geq 0, float$

The first constraint defines *Cmax* as the highest completion time by adding up the production time to the starting time of each product at each Assembly line. As the value of *Cmax* is minimized in the objective function, it ensures that it will never exceed the latest completion time of both Assembly lines.

The second constraint ensures that each product's demand is fulfilled by adding up the production quantities from both Assembly lines. The weekly demand for each product is multiplied by V, which accounts for the proportionality between the EPEI and the average weekly demand.

Constraints (3) and (4) are introduced to prevent the model from allocating a product to an Assembly line without performing a C/O from and to this product. These constraints also ensure that a product is only assigned to an Assembly line if a corresponding C/O precedes it at the same Assembly line.

Constraint (5) limits the production capacity of each Assembly line. The sum of the production and C/O times cannot exceed the available time within the defined EPEI (V). The available time T, the amount of time (in seconds) available in one week, is multiplied by V to account for the proportional relationship between the EPEI and the available time.

Constraint (6) serves multiple purposes. Inspired by the Vehicle Routing Problem, the initial goal is to create a sequence of parts for each Assembly line, while considering the sequence-dependent changeovers. Based on the Miller-Tucker-Zemlin (MTZ) constraint, it also prevents creating subtours, ensuring the creation of a single sequence of products per Assembly line. Additionally, following Wei and Ching (2022) the ranks typically used for the MTZ constraint have been replaced by starting times. This allows us to later link the PA lines and the Assembly lines with precedence constraints. The index j is defined to be greater than or equal to 2, ensuring that the artificial product is always selected as the sequence's starting point.

Constraints (7) and (8) will ensure that the sequences of both Assembly lines start with the artificial product. This prevents the model from starting with a product without accounting for the necessary C/O time to set it up at the Assembly line.

With most of the constraints being established for the Assembly lines, we can move on to the constraints for the PA lines. Constraints (9) to (15) fulfill the same role for the PA lines as constraints (2) to (8) do for the Assembly lines, with the distinction that no C/O times are considered for the PA lines.

Additionally, the four precedence constraints (16) to (19) link the Assembly's starting times with the PA's completion times. They ensure that the PA lines complete the required production quantities before the Assembly lines require them. Specifically, the latest completion time of product i from both PA lines l must be lower than the earliest starting time of product i at both Assembly lines k.

In cases where some products are not produced in either Assembly line, they will get a starting time of 0. It is, therefore, necessary to add an additional term to the right-hand side of the constraints (16) to (19), ensuring that the precedence constraints do not consider the unselected products.

Because no C/O time has been defined at the PA lines, there is no "cost" for changing from one product to another. To prevent the model from selecting unnecessary C/O and providing wrong results (e.g., having a C/O from product 1 to 3 and 1 to 7 at the same line), we need to limit the number of C/O per product and PA line to a maximum of 1 with constraints (20) and (21).

Finally, constraints (22) to (25) ensure that C/O are only performed at Assembly or PA lines where the corresponding products are produced. These constraints are necessary since the sequences of the Assembly lines and the PA lines are connected through the precedence constraints. Without these restrictions, the model could unrealistically plan unnecessary C/O to modify the starting times of the products in a way to develop seemingly optimal results, which, however, would be infeasible in practice.

5.4.4 Results of the optimization and implications for the system

As previously noted, the EPEI will be determined by experimentation with the optimization model results. A simplified optimization model is first used to identify the lowest achievable EPEI for the Assembly process without being constrained by external factors like the batch size and the PA lines. This value obtained by the simplified model will then be utilized in the complete model, facilitating the determination of the lowest possible EPEI for ABC's system. A comparison of the two EPEIs provides insight into the potential effect of further reducing the container size.

The simplified optimization model and the results can be found in Appendix D and E.

Beginning with an EPEI of 1 week (V = 1), the value was incrementally decreased until reaching an unfeasible solution, which corresponds to the minimum achievable EPEI.. Multiplying the demand by a decimal value invariably leads to relaxations as the model cannot allocate fractional quantities of a certain product. In this case, the model was run until CPLEX provided a solution without any relaxation.

Ultimately, the model achieved a minimal EPEI of 0.48 weeks. However, this value is inapplicable to the complete model as it would lead to uneven demand values.

With the EPEI value of 0.48 being determined, it is now possible to run the model including the PA lines and the batch size. Given that an EPEI of 0.48 would lead to relaxations, as the demand would not be divisible by 12 (the Batch size) anymore, we will first run the model with an EPEI of 0.5 weeks.

The model converged to the optimal solution after 1h12min with an optimality gap of 0.28%. Table 12 presents the results for the production quantities at the PA lines (q_{il}) and the Assembly lines (x_{ik}), as well as the starting times at the PA lines (z_{il}) and the Assembly lines (s_{ik}).

Table 12: Results optimization model

q_il			z_il			x_ik			s_ik		
	l			l			k			k	
i	1	2	i	1	2	i	1	2	i	1	2
1	0	0	1	0	0	1	0	0	1	0	0
2	34	4	2	80998.2	128644.2	2	0	38	2	0	134997
3	8	30	3	68292.6	39705	3	0	38	3	0	87630.6
4	8	1	4	31764	17470.2	4	0	9	4	0	47218.2
5	0	8	5	0	4764.6	5	0	8	5	0	74375.4
6	14	0	6	9529.2	0	6	6	8	6	31764	61717.8
7	4	3	7	44469.6	19058.4	7	7	0	7	50822.4	0
8	1	26	8	66704.4	87351	8	27	0	8	134191.8	0
9	10	3	9	50822.4	1	9	13	0	9	108222.6	0
10	6	10	10	1	23823	10	16	0	10	62872.8	0

The absence of any constraint enforcing an equal start time for both Assembly lines results in the model scheduling the Assembly lines' start times as soon as the parts become available from the PA lines. This leads to a delay between the starting times of Assembly lines 1 and 2.

However, given the variability of the mix will from week to week, it cannot be guaranteed that, for instance, Assembly line 1 will consistently be able to start earlier than Assembly 2. If the mix of the subsequent cycle requires Assembly 2 to start before Assembly 1, it would become impossible to meet the demand on time. For the example of Table 12, Assembly line 1 would start later than given by the optimization model. Therefore, the necessary delay to be kept between the Assembly and the PA equals to the highest of both starting times, here 47218.2s (13.12h).

In the Gantt chart illustrating the schedules for each PA and Assembly line (Appendix C), we can observe the delays between the production of products 5 and 6 and between products 9 and 8 at Assembly line 1. These periods of inactivity stem from the discrepancy in starting times of both Assembly lines and the constraint about the total available time for the Assembly lines.

Specifically, Assembly line 1 starts earlier than Assembly line 2 because the parts for Assembly line 1 would be ready earlier than the parts for Assembly line 2, but Assembly 2 defines the latest completion time. The difference in starting times artificially extends the time theoretically available for Assembly 1 to meet the demand. For the FSM, both Assembly lines will start the production cycle simultaneously, eliminating the idle times observed in Appendix C. The capacity constraint (5) prevents the model from overloading the lines and ensures that even if Assembly 1 starts later than the model suggests, it will still meet the demand on time.

Since the Assembly lines pull from the PA station through the FIFO lanes, only the necessary quantities and sequences of product types will be transferred from one process to the other. The precedence constraints ensure that the necessary parts arrive in the FIFO lanes just-in-time while the short management time frame given by the pitch ensures a leveled production volume.

The optimized subpart containing the Assembly lines and the PA lines will be incorporated into the FSM as shown in Figure 13:

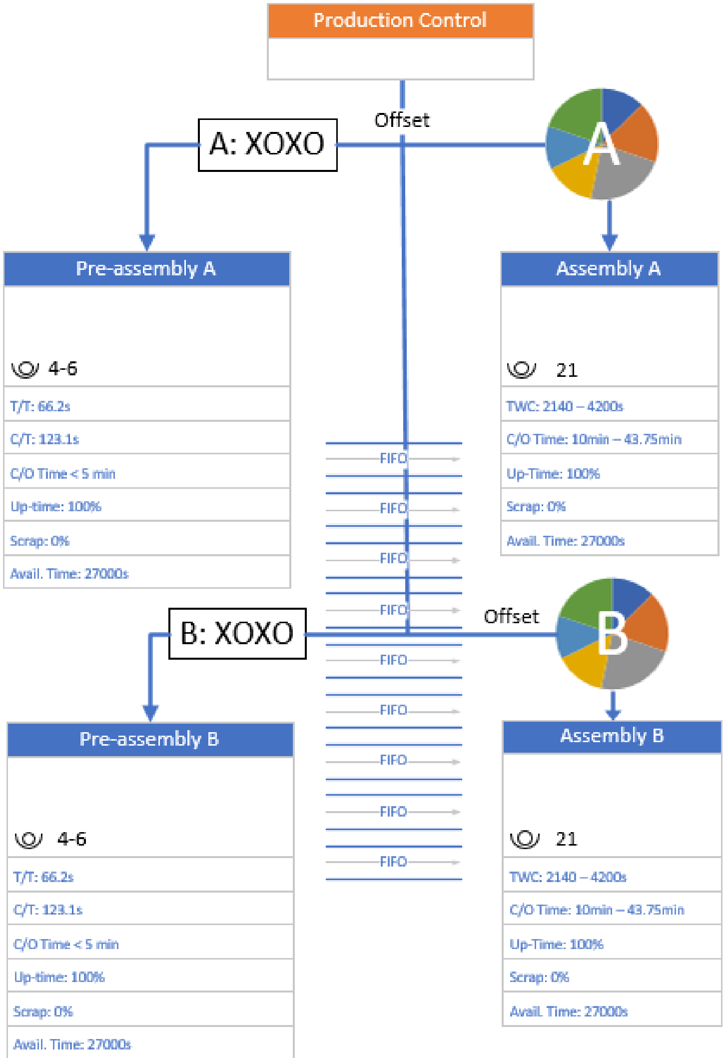

Figure 13: Revised Pull system between the Assembly and the Pre-assembly lines

The schedules and production wheels generated by the optimization model are updated and transferred every 0.5 weeks to the PA lines and Assembly lines, respectively. The starting time of the wheels is offset by 13.1 hours from the schedules, ensuring the PA lines supply the FIFO lanes adequately to prevent idling in the Assembly lines. This delay is maintained by sustaining a consistent level of WIP within the FIFO lanes. Upon receiving the wheels, the Assembly lines follow the specified sequences and quantities, pulling from the FIFO lanes as needed. Simultaneously, the PA lines follow their schedules to deliver the correct parts to the FIFO lanes on time for the Assembly.

5.5 Quantitative definition of the necessary WIP with the calculated EPEI

With the optimization model defining the minimum EPEI, it is now possible to quantitatively define the necessary WIP levels to keep between the other processes (to serve as SS), as well as the SMs within the value stream.

Assembly/ Testing

The maximum demand based on targeted fill-rate will define the required WIP (in units) between the Assembly and the Testing stations, as explained in Section 5.3.2. Assuming the demand follows a normal distribution and selecting a service level of 99.4%, we multiply this by the C/T differences between the Assembly and the Testing process, as shown in the equation below. This aims to prevent the Testing process from becoming idle in the worst-case scenario of producing products 7, 8, and 9 at the beginning of the EPEI cycle.

$$WIP_{A-T} = \sum_{i=7}^{9} (C/T_i - T/T_i) * \left(\mu_{EPEI} + \sqrt{EPEI} * k * \sigma_i\right)/(T/T)$$

The individual WIP levels to cope with the C/T differences of products 7, 8, and 9 are represented in Table 13:

Table 13: WIP for the C/T differences between the Assembly and the Testing station

	Products		
	7	8	9
Weekly STDEV	72	15	19
Demand (over EPEI)	324	156	192
C/T Assembly	145.90	160.70	200.00
T/T	132.5	132.5	132.5
Necessary WIP (s)	6046.97	5132.04	15168.32
Necessary WIP (units)	91,34	77,53	229,12

The highest combined C/O time for this group of products is 5025s (83.75 min), which is achieved by following the sequence of products 9 →7 → 8. Adding this to the previous WIP components results in a total WIP of 31372.3s (8.7h) or 474 units for the SS between the Assembly and the Testing stations.

Testing/ Finishing

The normal distribution assumption of demand will also be used to define the SS between the Testing and the finishing processes. With a service level of 99.4% and an EPEI of 0.5 weeks, the values for the maximum demand of products 1 and 2 are represented in Table 14:

Table 14: Maximum demand for products 1 and 2

Products	Avg. Demand over EPEI	STDEV	Max. demand	Proportion
1	456	64	569,55	28%
2	456	42	530,29	26%

In the worst case, the Assembly will have to produce products 1 and 2 in parallel at the beginning of the EPEI cycle. This scenario represents the maximum duration in which Testing process would not supply any parts to the Finishing process. The necessary WIP to cope with this is equal to 1100 parts or 20.23h.

To define what parts will be kept in the SS and in what quantities, we fist need to consider the average demand of products 3 to 9. The sum of the average demand from products 3 to 9 is equal to 1128 parts. To keep only what is necessary in the SS, we will therefore keep 4 parts less than the average demand for each product. The exact amount of each product in the SS is shown in Table 15.

Table 15: Safety stock Testing/ Finishing

Testing/ Finishing	
Necessary SS Assembly/Testing	1100
SS Product 3	104
SS Product 4	92
SS Product 5	164
SS Product 6	80
SS Product 7	320
SS Product 8	152
SS Product 9	188

Finished goods supermarket

The finished goods SM will comprise three components: the CS, which is equal to the average demand; the BS, which accounts for the variability in demand; and the SS, which accounts for production losses like defects or downtimes. Similarly to the WIP of the FIFO lanes, the BS will be determined by the normal distribution of the demand and a service level of 99.4% for each product.

When summing up the defined WIP levels together, it becomes evident that the LT between the pacemaker and the finished goods SM will be longer than the duration of the EPEI cycle. This results in the parts being pulled at time T will be entirely replenished later than the next pull signal at T+1. The parameter J will represent the LT between the pacemaker process and the finished-goods SM. Although the CS remains based on the EPEI, the BS must be adapted to address the difference between J and EPEI. Rather than using the EPEI as the interval to define the BS, we will use J for the calculations of the BS. Consequently, the SS, being proportional to the CS and the BS, will also be influenced by the changes in the calculations of the BS.

For each product, the three components of the finished goods SM are defined as follows:

$$Cycle\ Stock\ (CS) = \mu_{EPEI}$$

$$Buffer\ Stock\ (BS) = \sigma_i * k * \sqrt{EPEI + J}$$

$$Safety\ Stock\ (SS) = (CS + BS)/(1 - production\ losses)$$

Given that the available standard deviation is based on the weekly demand, the LT between the pacemaker and the finished goods SM (J) must also be expressed in weeks. The LT between the pacemaker and the finished goods SM is 42.1h, corresponding to 0.56 weeks.

Based on the previously defined equations, the size of the SM for each product is represented in Table 16:

Table 16: Finished-goods supermarket size

Products	CS	BS	SS	Total	Adapted to container size
1	456	165	13	634	636
2	456	108	12	576	576
3	108	99	11	218	228
4	96	68	9	173	180
5	168	180	18	366	372
6	84	48	7	139	144
7	324	185	26	536	540
8	156	38	10	204	204
9	192	48	12	252	264
			Total (pcs)	**3097**	**3144**
			Total (h)	**56,93**	**57,8**

The total values are rounded up to align with the container size to ensure compatibility with the system's production pitch and transportation system.

Additionally, the used scrap rate varies across products. Products 1 and 2 do not require to be processed by finishing, whereas the other parts still need to undergo finishing. Consequently, a combined scrap rate of 5% has been used for products 3 to 9, requiring both finishing and Testing processes. The parameters used to calculate the size of the SM are represented in Table 17.

Table 17: Parameters to define the finished-goods supermarket

Scrap Testing	3%
Scrap Finishing	2%
Combined scrap	5%
k	2,5
EPEI+J	1,06
EPEI	0,5

Raw materials supermarket

The raw materials SM, linking the supplier to ABC's factory, is designed using the same principle as the finished goods SM. However, since there is no discrepancy between the suppliers LT and the EPEI, the EPEI can be directly used to determine the BS.

Furthermore, as the supplier is an internal company structure located near the factory, it is assumed that the parts will be delivered on time and of the required quality. This reliability eliminates the necessity of maintaining an SS. Thus, the lack of an SS for the raw material SM calculation in Table 18.

Table 18: Raw materials supermarket size

Products	CS	BS	Total	Adapted to container size
1	456	114	570	576
2	456	74	530	540
3	108	68	176	180
4	96	47	143	144
5	168	124	292	300
6	84	33	117	120
7	324	127	451	456
8	156	26	182	192
9	192	33	225	228
		Total (pcs)	**2685**	**2736**
		Total (h)	**49,36**	**50,29**

To keep consistency with the system's production pitch and transportation system, the total values of WIP also need to be rounded up and aligned with the container size.

5.6 Leveling the volume

The optimization model has determined the lowest possible EPEI and the appropriate schedules for the PA and Assembly processes. ABC has leveled its production mix by reducing the EPEI to a minimum. The low EPEI increases the production frequency, enabling the company to meet customer demand without overproduction, significantly decreasing the LT over the entire value stream and increasing the responsiveness of the system to customer demand changes.

Leveling the volume is essential to enhance the factory's responsiveness to potential disruptions and provide ABC with a clear management time frame. This process involves reducing the increment of work sent to the pacemaker by defining a pitch. The pitch is a time interval during which a specific number of parts must be produced, typically a multiple of the container size. Any deviation from the pitch will send a signal to the production control department, requiring immediate investigation of the root causes and action to solve the problem.

This approach standardizes the release of production information, ensuring consistency and predictability. Furthermore, by only releasing a fraction of the demand during each interval, the impact of schedule modifications on the system is minimized, preventing unnecessary transportation and potential waste associated with schedule modifications.

With the T/T being 66.2s and a container size of 12 units, the pitch would be 13.2 min. However, implementing such a short pitch would require ABC to address issues within this narrow time frame. Since we doubt that the company will be able to address all the potential problems in less than 15 minutes, we will adopt a pitch of 24 parts.

Under this revised pitch, the information about the following parts to be produced will be released every 26.4 min. At the end of each interval, the factory will have a clear overview of whether the system is functioning as it should.

Demand information will be communicated using a Heijunka box, which will be filled with production kanbans. The internal transporters will pull the kanbans at the beginning of the pitch interval and send them to the pacemaker to define the following products to be produced. Additionally, the pitch will be used to manage transportation between the SMs and the various processes. For this purpose, we will refer to Smalley's (2009) work on synchronizing the transporters with the system.

Finally, we cannot use a Heijunka box to schedule the Assembly due to its variable C/T's. The pitch gives a fixed number of parts to be produced during each interval; following a pitch with this process would not be possible as the output would necessarily vary over time. Instead, product wheels will be implemented to communicate the appropriate sequences and quantities of products to the Assembly lines. These wheels will trigger the pull mechanism between the PA and Assembly lines. Similarly to Wilson and Nazma's (2013) findings, the types and quantities of products will differ from one production cycle to the other. However, the product sequences will also be adapted to the specific mix of products assigned to each Assembly line, resulting in different sequences for each EPEI cycle.

5.7 List of improvements

Several improvements must be implemented throughout the value stream to achieve the desired future state of the production system. These improvements are prerequisites for the successful implementation of the new system and will be summarized as follows:

- The TWC of the PA lines must be improved (up to 17% for product 8).
- The PA lines must be adapted to T/T, and the operators must be trained to work on all the products, following Rother and Harris' (2001) guidelines to create a continuous flow.
- The TWC of the Testing stations must be improved by 2.3%.
- The TWC of the finishing stations must be improved by 7.3%.
- The company's internal supplier must increase its shipping interval and become able to follow the EPEI cycle.
- The production planning department must be trained to effectively utilize the SM to address demand variability. They will also need to be trained to use the optimization model to define the schedules for the pacemaker and the Assembly process.
- Following Shingo's (1985) SMED methodology, the Testing stations' C/O time must be reduced to less than 5 minutes.
- The transportation system must be synchronized with the production system to follow the pitch as delivery intervals, deliver the appropriate parts on time, and inform the pacemaker about the subsequent parts.
- ABC's customer must be included in the new system and be able to pull from the finished goods SM at a standardized interval, the EPEI.
- Implementing preventive maintenance programs must improve the uptime of the Assembly lines from 98% to 100%. If this requirement cannot be met, the SS of the finished goods SM will have to be increased.

The FSM will visually represent these improvements using Kaizen burst icons to highlight their significance and necessity before implementation of the new system.

5.7.1 Future-state map

With the future state for each component of the value stream being defined, the findings can finally be summarized into a single FSM depicted in Figure 14. This visualization simplifies understanding of the new system and directs improvement efforts toward the most critical areas.

The FSM outlines how ABC’s future production system will operate and serves as a guideline for its management. The system begins with the customer placing orders every 0.5 weeks. The Shipping department receives these orders, which pulls the necessary parts from the finished goods SM and releases withdrawal kanbans for the production control department.

The production control department will evaluate the capacity requirements for the pacemaker and the Assembly process by analyzing the required mix of products. The total demand will be pulled from the finished goods SM. One part of this demand will be fulfilled by pulling from the CS, and is going to be sent to production through kanbans. The part of the demand exceeding the average demand will be fulfilled by pulling from the BS, which will be replenished during later EPEI cycles, in which the observed demand is below average. The optimization model will generate the schedules for the PA lines and the product wheels for the Assembly lines. The optimization model will also provide feedback on the feasibility of the required mix.

At this stage, the heijunka boxes are filled with production kanbans while the production wheels are prepared. However, they are not released simultaneously as a delay offsets the wheels with the PA schedules. At the same time, production control will also send information about the upcoming quantities and sequences of the products to the Testing and Finishing processes, enabling them to pull from the SS when necessary.

When the production kanbans are released, the internal transporters collect them during each pitch interval. These transporters deliver the required materials to the different processes of the value stream and communicate the required production quantities to the PA lines. The PA lines, in turn, supply the FIFO lanes with the appropriate parts, enabling the Assembly lines to pull the parts following the sequences given by the product wheels. The precedence constraints ensure that the correct parts are always available in the FIFO lanes, allowing the Assembly to follow the production wheels' instructions. The limited information given during a single Pitch interval makes it impossible for the PA lines to overproduce.

While executing the kanban instructions, the PA lines will pull from the raw materials SM, which will release production kanbans. These kanbans will be collected in a kanban post, forming replenishment orders for the supplier to refill the raw materials SM during each EPEI interval.

The Assembly lines will begin pulling from the FIFO lanes upon receiving the production wheels. The wheels' limited time horizon ensures that overproduction is avoided. Even if disruptions occur at the PA lines, the sequences and interdependence of the processes will be maintained, preventing the Assembly lines from producing further.

Once assembled, the products are transferred to the Testing FIFO lanes. Following the information given by the Production control department, Testing will either pull the parts from the FIFO lane or pull from the SS. After Testing, the products are transferred to the finishing FIFO lane or directly to the finished goods SM, depending on the product type. Similarly to the Testing process, the Assembly will either produce the parts in the FIFO lane or pull from the SS, depending on the information given by the Production control department. Both processes will receive information about the entire demand over an EPEI cycle. This will enable them to know when to pull parts from the SS and when to pull parts from the FIFO lanes.

Finally, the T/T provides a “pulse” for the entire production system, establishing a rhythm for the operations to follow and enabling the creation of a narrow management time frame, the Pitch, to respond to disruptions promptly and effectively. Any problem in the value stream will become apparent within a Pitch interval, necessitating immediate intervention to preserve system stability. This structured approach promotes continuous improvement and drives ABC’s factory toward operational excellence.

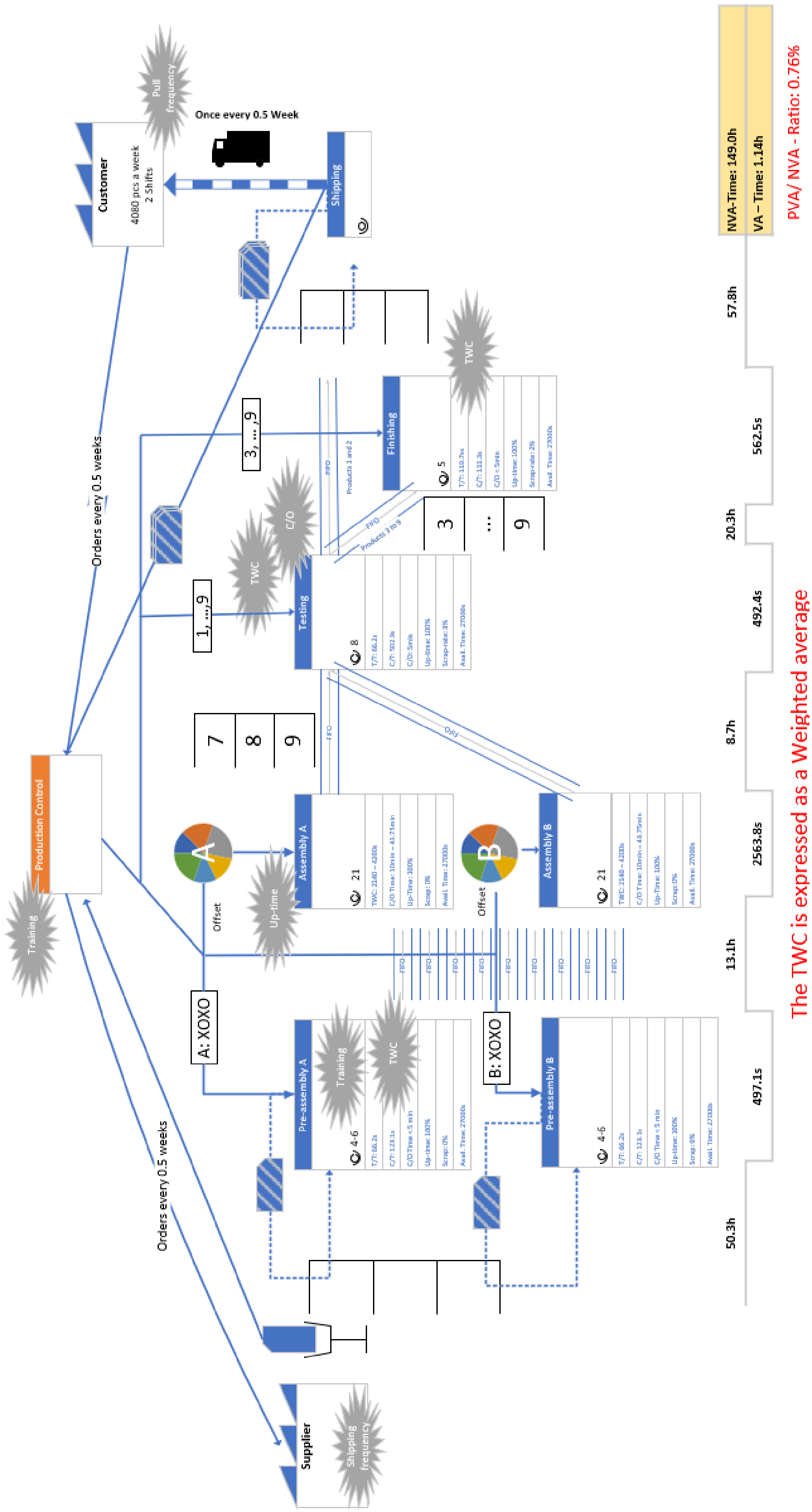

Figure 14: Future-state-map

With the FSM of ABC's factory now established, a comparative analysis with the CSM allows for the evaluation of the system's improvements. The primary metrics used in the comparison are LT, the number of operators, VA time, and VA/ NVA-ratio. Table 19 summarizes the differences between the two systems:

Table 19: Metrics comparison between CSM and FSM

	CSM	FSM
Lead time (h)	358.9	150.14
VA-Time (h)	1.17	1.14
NVA-Time (h)	358.8	149
VA/ NVA	0.32%	0.76%
# of operators*	67.5	65

*per shift

The critical finding in implementing the future state is the reduction of the total production LT by 58.2%, from 358.9h to 150.14h. This LT reduction is mainly due to the WIP reduction throughout the value stream and the low EPEI enabled by the FSM. Although the system VA/ NVA-ratio remains below 1%, it has more than doubled, rising from 0.32% to 0.76%. The VA time is slightly reduced, reflecting the results of the process improvements necessary to adhere to T/T and create a continuous flow within the processes. The same improvements also reduced the number of operators required per shift by 2.5. These resources will be reallocated to other departments, necessitating an additional workforce, preferably to production line support departments.

Beyond measurable metrics, the FSM also offers qualitative improvements. The reduced EPEI increases scheduling flexibility and responsiveness to customer demand variations, leading to higher customer satisfaction.

Establishing a T/T also provides ABC with a single production rhythm, improving the predictability of system and process performances as well as facilitating the management of the system. This T/T is utilized to define a management time frame, the pitch, enabling faster reactions to disruptions, promoting continuous improvement, and ultimately leading to higher process performances.

Additionally, the pitch is also utilized to synchronize the transportation system with the production system, standardize the logistics processes, and thus reduce waste associated with the previous PUSH system (unnecessary transportation, confusion, non-standardized transportation routes…, etc.).

Furthermore, the reduction in C/T and C/O times necessitates standardization, benefiting the learning processes for new and current employees. The standardized operations will also lay a foundation for further attempts to reduce the C/T or C/O times.

Finally, the FSM provides a standardized process for the production control department. The EPEI cycles dictate the department's operations and require a systematic approach to managing the finished goods SM quantities and scheduling the processes. Similarly, communication with the supplier becomes standardized through the raw materials SM, improving delivery predictability and variability between the two factories.

Moreover, most WIP reductions are concentrated in the finished goods and raw materials inventories. This high concentration in WIP reduction is primarily attributed to the low EPEI enabled by the development of continuous flow at the different processes, the concurrent scheduling system and the specifically calibrated inventory levels between the processes. Although reductions in other WIP levels are less significant, their quantities are now controlled through FIFO lanes. The FIFO lanes ensure that the WIP levels do not exceed a certain threshold and prevents the processes from overproduction. The standardized WIP levels also enable ABC to support the low EPEI, ensuring the system's reliability without risk of failure.

Ultimately, this Lean FSM provides the foundations for implementing the new system and designing solutions to achieve the desired improvements. In Womack, Jones, and Roos's (1991) words, the processes within the value stream will operate as an integrated "machine," producing products at a defined frequency and interacting through standardized procedures. This cohesive framework will drive operational excellence and support ABC in achieving its performance objectives.

6 Conclusion, contributions, recommendations, and future

This thesis aims to develop a future state for ABC company to enhance operational efficiency and transition to a LMS while contributing to the literature about the implementation of Lean systems. With the FSM being designed and its functioning thoroughly explained, this chapter summarizes the key findings, provides recommendations for further improvements, and identifies areas for future research.

6.1 Conclusion

The comparison between the CSM and the FSM demonstrates that the proposed system could reduce the total LT of ABC company's facility by 58.2% and double the overall system's VA/NVA-ratio. These improvements are primarily due to the achievement of a short EPEI value of 0.5 weeks, which leads to a significant reduction in WIP across the entire value stream. Achieving and maintaining this low EPEI required the development and implementation of a new scheduling method, concurrent scheduling.

Following Rother and Shook (1999), a T/T is defined for all the processes to follow. The processes are then adapted to achieve OPF and the TWC reduced to meet the T/T. This could be achieved for all the processes besides the Assembly, which couldn't be modified due to financial constraints. The Assembly process operates with two parallel lines, has variable C/T and sequence-dependent C/O times. These particularities make it difficult to implement the Assembly process into an LMS following the guidelines published in literature.

To address this challenge, a new concurrent scheduling method was developed to simultaneously control the pacemaker and the Assembly process. Although the approach deviates from traditional Lean guidelines, concurrent scheduling involves sending distinct schedules to the pacemaker and the Assembly process simultaneously. The processes are then connected through multiple FIFO lanes, storing the necessary quantities of products to achieve an optimal production sequence at the Assembly process. This method allows ABC to link the two processes without using a SM, minimizing the required WIP.

An optimization model is used to find the best sequence and production quantities for the PA and Assembly processes. The Assembly being the constraining factor to lower the EPEI of the system, an optimal sequence is also leading to the determination of the lowest possible EPEI for the system. As the optimization model considers both PA and Assembly processes, the WIP level between the two processes is also being minimized. For the concurrent scheduling method, the PA, which is the pacemaker of the system, will send parts to multiple FIFO lanes while the Assembly will pull the parts from the same FIFO lanes. The FIFO lanes will be constantly holding a certain amount of WIP and serving as a buffer to avoid the Assembly lines becoming idle. The schedules of both processes are linked through precedence constraints, which, together with the EPEI that limit the information being sent to the processes, eliminate the risk of overproduction and maintain an interdependence of the processes.

After developing the concurrent scheduling method, the remaining processes are connected through FIFO lanes holding a certain level of WIP to avoid the processes becoming idle. The finished-goods are stored within a SM from which the customer is pulling from at a constant interval, the EPEI. The released kanban cards are then sent to the production control department, which defines the necessary production mix for the subsequent EPEO cycle.

The low EPEI of 0.5 weeks levels the facility’s production mix and thereby improves the company’s flexibility in responding to customer demand variations and increase customer satisfaction in the long term. A defined pace, the Pitch, levels the production quantities released within the system and increases the factory’s responsiveness to issues such as delivery delays or breakdowns.

Furthermore, a list of necessary improvements has been developed to guide ABC in implementing the FSM. Once achieved, the FSM will serve as a standardized foundation for continuous improvement and operational excellence. Given that both the factory's customer and supplier are internal to the company, the proposed system could also serve as a benchmark for Lean practices across the company.

Finally, the FSM introduces a standardized process to manage the new production system, which reduces variability over the entire supply chain by including the factory's supplier and customer. In comparison to the CSM, the facility also gains total control over the WIP levels through the FIFO lanes and the SM.

In summary, the analysis of the CSM and the design of the FSM have identified ABC’s main operational challenges, provided a tailored solution to these challenges, and established a framework to guide their improvement efforts.

6.2 Contributions

While other companies will not face the exact conditions in which the provided solution has been designed, multiple aspects of the solution can serve as a valuable resource to implement Lean into various production environments, reducing WIP levels and LT in traditional manufacturing systems.

The concurrent scheduling method and the optimization model could be used to concurrently schedule more complex systems, involving more than 2 processes and more parallel lines. Also, for single processes in Lean production environments with sequence-dependent C/O times and/or variable routings, parts of the optimization model could be used to schedule the said process and minimize the EPEI.

Finally, concurrently scheduling the pacemaker and another process while using multiple FIFO lanes could also be used without the optimization model within a Lean value stream. This eliminates the necessity of a SM when connecting the pacemaker with another process that could not achieve T/T or has high C/O times.

6.3 Recommendations for future improvements

Although the future state already proposes substantial improvements over the current state, there are additional opportunities for improvement once the system reaches a stable state.

First, the SS before and after the Testing process has been defined based on worst-case scenarios. While these scenarios are theoretically possible, ABC will determine if such an inventory is necessary. Monitoring these inventory levels will enable the company to determine if the scenarios are realistic and, if appropriate, gradually reduce the required inventory.

Second, the delay between the Assembly and PA lines could be further reduced by adapting the optimization model and modifying the precedence constraints. Rather than waiting for the PA lines to complete the orders before starting them at the Assembly lines, the delay could be minimized by enabling the Assembly to pull from the FIFO lanes while the PA lines are processing the same products. However, the early stages of the system would benefit from the higher delay to accommodate potential instabilities. Therefore, we recommend implementing this solution only once a stable future state has been achieved.

Furthermore, the development of the FSM has been conducted around specific constraints given by the company. Although these constraints were necessary to be respected during the study, we will provide further recommendations to improve the system's efficiency should these constraints be relaxed in the future.

The core challenge lies in the Assembly's characteristics. The inability to perform any modifications to the process resulted in the necessity of higher WIP throughout the value stream. Achieving a consistent C/O time for each product sequence would provide greater flexibility for the scheduling process and could potentially reduce the EPEI. Moreover, the system may not need concurrent scheduling if the C/O could be reduced beneath a certain threshold. In such a case, the Assembly lines could be connected to the PA lines through a simple FIFO lane. A delay would still need to be maintained between both processes because of the C/T discrepancy, but smaller than the currently held delay. The Assembly can be included in the system through one of the four methods provided by Duggan (2013) and presented in chapter 5.3.1.

Finally, an additional area of improvement involves the WIP between the Testing and finishing processes. Since products 1 and 2 do not require the finishing process, a delay between the two processes is necessary to avoid idle time at the finishing process. Merging the finishing WC with the Testing process without significantly increasing the TWC would further reduce the delay.

6.4 Future research

The study raised broader questions about Lean systems design, especially with high LT, creating opportunities for future research.

The development of the FSM and the associated solutions are tailored to ABC's specific case and may serve as a reference for similar cases in the industry. This study suggests that the applicability of Lean systems should be extended to various environments and settings.

First, the design of the finished goods SM's buffer stock is typically determined by the system's EPEI. Using the EPEI as the replenishment interval is valid only if the LT between the pacemaker and the SM is lower than the EPEI, as the BS would then account for variability in demand over the EPEI cycle and be replenished during the same interval.

In the case of ABC, the proposed future state could not sufficiently reduce the LT to meet this condition. Consequently, the quantities produced during a certain EPEI cycle correspond to the demand of a previous cycle. The variability in demand could therefore exceed the variability over a single EPEI cycle. The duration of the LT between the pacemaker and the finished goods SM has been added to the EPEI to define a higher BS and address this issue. However, because the LT of a single product depends on the sequence in which it will be sent into the system, further research could be conducted to determine the LT of each single product depending on the production mix.

Second, for this case study, customer demand is assumed to be unknown until the start of the EPEI cycle. Some industries may have the possibility to know the demand in advance and set up a frozen zone. In such cases, a different optimization model would be required. With a LT greater than the EPEI, information about the demand of the upcoming cycle would be available while the parts from the previous cycle are still being processed. The parts that have not been produced from the previous cycle could be added to the schedule of the new cycle, and the schedules adapted to this new information to improve the C/O times.

Both areas require further investigation, particularly the implementation of pull systems characterized by high LTs and low EPEIs.

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Appendix A: Opl coded CPLEX mod file for the optimization model

```
int m=...; // Number of products
int n=...;// number of lines
int p=...;
range L =1..p;
range K =1..n;/*range of assembly lines*/
range I =1..m;/*range of products*/
float b[I] =...; // Cycle times
float V =...; // chosen production interval (in Weeks)
int d[I] =...; // Weekly demand
float T =...; // Available time per Week
float M = 9999999;
float R=...;
int B=...;

float Two_Dim_a[1..m*n][I] = ...;/*Necessary to have a three dim param.*/
float a[k in K][i in I][j in I] = Two_Dim_a[(k-1)*m + i, j]; /*from class*/

dvar int+ x[I][K]; // Production of i at line k
dvar boolean w[I][I][K]; // Changeover from i to j
dvar float+ s[I][K]; // starting time of i at k

dvar float+ z[I][L];//starting time of i at l
dvar int+ q[I][L];// Prod of i at line l
dvar boolean c[I][I][L]; //1 if c/o from i to j at l

dvar float+ Cmax;

execute{
  cplex.tilim = 600;
}

minimize Cmax;//sum(i in I, j in I, k in K) w[i][j][k]*a[k][i][j];

subject to{

 forall(i in I, k in K){
   Cmax>= s[i][k] + x[i][k]*b[i]*B;
 }

 forall(i in I){
    c1: sum(k in K)x[i][k]*B >= V*d[i];
    //Production of i must exceed demand
  }

  forall(k in K, j in I){
    c2: x[j][k]*B<=sum(i in I: i!=j)d[j]*w[i][j][k];
    c21: x[j][k]*B<=sum(i in I: i!=j)d[j]*w[j][i][k];
    //If we produce i at k then we need a changeover from j to i at k
  }

  forall(i in I, k in K: i!=1){
    sum(j in I)w[i][j][k]<=x[i][k];
    sum(j in I)w[j][i][k]<=x[i][k];
  }

  forall(k in K){
    c3: sum(i in I)x[i][k]*B*b[i] + sum(i in I, j in I)w[i][j][k]*a[k][i][j] <= V*T;
    //Total time must be less than available time
   }

  forall(i in I, j in I, k in K: i!=j && j>=2){
    c6: s[j][k] >= s[i][k] + x[i][k]*B*b[i] + a[k][i][j] - M*(1 - w[i][j][k]);
  }// subtour elimination and time allocation
```

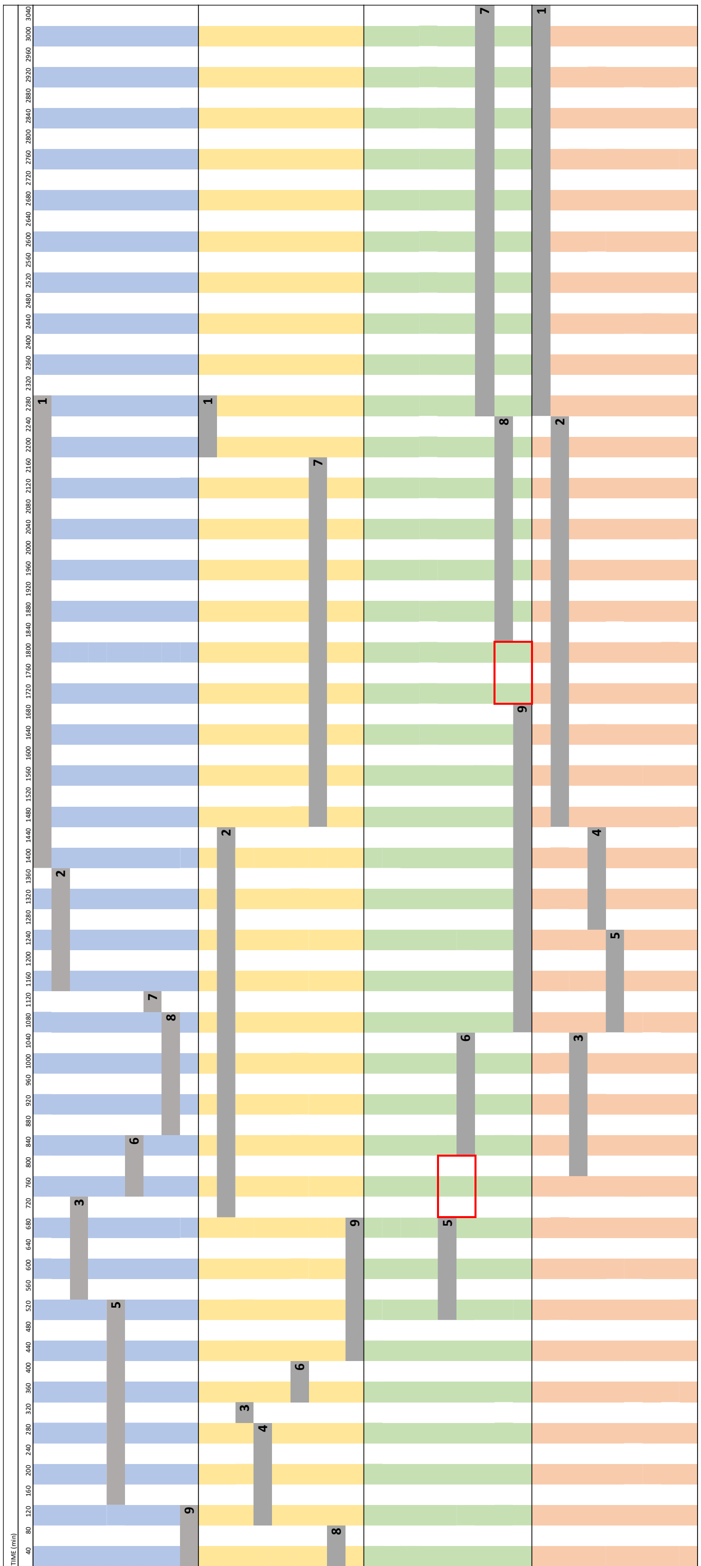
```
forall(k in K){
  c9: sum(j in I)w[1][j][k]==1;
  c10: sum(i in I)w[i][1][k]==1;
}// both sequences must visit the dummy once


  forall(i in I){
  c11: sum(l in L)B*q[i][l] >= V*d[i];
  //Production of i must exceed demand
}

forall(l in L, j in I){
  c12: q[j][l]<=sum(i in I: i!=j)d[j]*c[i][j][l];
  c121:q[j][l]<=sum(i in I: i!=j)d[j]*c[j][i][l];
  //If we produce i at l then we need a changeover from somewh
}

forall(l in L){
  c13: sum(i in I)q[i][l]*B*R<= V*T;
  //Total time must be less than available time
 }

forall(i in I, l in L: i!=1){
  sum(j in I)c[i][j][l] <=1;
  sum(j in I)c[j][i][l] <=1;

  sum(j in I)c[i][j][l] <=q[i][l];
  sum(j in I)c[j][i][l] <=q[i][l];
}

forall(i in I, j in I, l in L: i!=j && j>=2){
  c14: z[j][l] >= z[i][l] + q[i][l]*B*R - M*(1 - c[i][j][l]);
}// subtour elimination and time allocation
```

```
forall(l in L){
  c15: sum(j in I: j!=1)c[1][j][l]==1;
  c151: sum(i in I: i!=1)c[i][1][l]==1;
}// both sequences must visit the dummy once

forall (i in I){
  z[i][1] + q[i][1]*B*R <= s[i][1] + M*(1-sum(j in I)w[i][j][1]);
  z[i][2] + q[i][2]*B*R <= s[i][1] + M*(1-sum(j in I)w[i][j][1]);
  z[i][1] + q[i][1]*B*R <= s[i][2] + M*(1-sum(j in I)w[i][j][2]);
  z[i][2] + q[i][2]*B*R <= s[i][2] + M*(1-sum(j in I)w[i][j][2]);
}  // for every model, the end time of Pre assy must be before st
```

Appendix B: Opl coded CPLEX dat file for the optimization model

```
n = 2;
m = 10; //9+ 1 dummy
V = 0.5; // min value for the EPEI is 0.5
T = 270000;
SheetConnection ExcelFile("Data_Opti_Wheel_Assy.xlsx");
b from SheetRead(ExcelFile,"Cycle_Time_Matrix!C2:C11");
d from SheetRead(ExcelFile,"Demand_Matrix!B2:B11");
Two_Dim_a from SheetRead(ExcelFile,"Arc_Set_A!C2:L21");

B = 12;
p = 2; //number of pre assembly lines
R = 132.35; //TT
```

Appendix C: Results of the optimization model (Gantt-Chart)



Process	Product	Plan start (min)	Duration (min)	Plan End (min)	C/T (s)	Number of Batches
PA 1	1	1350,0	900,0	2249,9	132,4	34
	2	1138,2	211,8	1350,0	132,4	8
	3	529,4	211,8	741,2	132,4	8
	4				132,4	0
	5	158,8	370,6	529,4	132,4	14
	6	741,2	105,9	847,0	132,4	4
	7	1111,7	26,5	1138,2	132,4	1
	8	847,0	264,7	1111,7	132,4	10
	9	0,0	158,8	158,8	132,4	6
PA 2	1	2144,1	105,9	2249,9	132,4	4
	2	661,7	794,1	1455,8	132,4	30
	3	291,2	26,5	317,6	132,4	1
	4	79,4	211,8	291,2	132,4	8
	5				132,4	0
	6	317,6	79,4	397,0	132,4	3
	7	1455,8	688,2	2144,1	132,4	26
	8	0,0	79,4	79,4	132,4	3
	9	397,0	264,7	661,7	132,4	10
Assembly 1	1				101,9	0
	2				101,9	0
	3				128,7	0
	4				128,7	0
	5	529,4	150,7	680,1	125,6	6
	6	847,0	175,8	1022,9	125,6	7
	7	2236,5	787,9	3024,4	145,9	27
	8	1803,7	417,8	2221,5	160,7	13
	9	1047,9	640,0	1687,9	200,0	16
Assembly 2	1	2249,9	774,4	3024,4	101,9	38
	2	1460,5	774,4	2234,9	101,9	38
	3	787,0	231,7	1018,6	128,7	9
	4	1239,6	205,9	1445,5	128,7	8
	5	1028,6	201,0	1229,6	125,6	8
	6				125,6	0
	7				145,9	0
	8				160,7	0
	9				200,0	0

Appendix D: Simplified Optimization model

K k Є K index for the Assembly lines K = {1, 2}

I i Є I & j Є I indexes for the products I = {1, …10}

b_i : Cycle times

d_i : Weekly demand

a_{ijk} : Sequence dependent changeover times

T : Available time in a week

V : Chosen EPEI (ratio based on 1 Week, ex.: V=0.5 means half a week)

M : High number (9 999 999)

x_{ik} : Decision to produce an amount x of product i at Assembly line k

w_{ijk} : $\begin{cases} 1, & \text{if we decide to perform a C/O from product i to product j at assembly line k} \\ 0, & \text{Otherwise} \end{cases}$

s_{ik} : Best starting time of product i at Assembly line k

Cmax: Maximum completion time of both Assembly lines

Minimize $Cmax$

Subject to:

$Cmax \geq s_{ik} + x_{ik} * b_i * B$	i∈I, k∈K
$\sum_{k \in K} x_{ik} \geq V * d_i$	i∈I
$x_{jk} \leq \sum_{i \in I: i \neq j} d_j * w_{ijk}$	i∈I, k∈K
$x_{jk} \leq \sum_{i \in I: i \neq j} d_j * w_{jik}$	i∈I, k∈K
$\sum_{i \in I} x_{ik} * b_i + \sum_{i \in I} \sum_{j \in I} w_{ijk} * a_{ijk} \leq V * T$	k∈K
$s_{jk} \geq s_{ik} + x_{ik} * b_i + a_{ijk} - M * (1 - w_{ijk})$	i∈I, j∈I, k∈K : i≠j & j>=2
$\sum_{i \in I} w_{1jk} = 1$	k∈K
$\sum_{i \in I} w_{i1k} = 1$	k∈K
$x_{ik} \geq 0, int$	i∈I, k∈K
$w_{ijk} \in \{0,1\}, int$	i∈I, j∈I, k∈K
$s_{ik} \geq 0, float$	i∈I, k∈K

Appendix E: Results of the simplified optimization model

Production quantities x_ik			
		Assembly k	
		1	2
Products i	1	0	438
	2	0	438
	3	0	104
	4	0	92
	5	70	91
	6	81	0
	7	311	0
	8	149	0
	9	184	0

Start times s_ik			
		Assembly k	
		1	2
Products i	1	0	84887
	2	0	39355
	3	0	600
	4	0	14585
	5	600	27025
	6	9992	0
	7	84210	0
	8	59366	0
	9	21666	0

We can see that the first products to be produced are products 5 at line 1 and product 3 at line 2. Their start time are not 0 because we first need to perform a C/O from the model being previously produced.

Relaxations			
	Demand	from	to
Products i	1	437.76	437.76
	2	437.76	437.76
	3	103.68	103.68
	4	92.16	92
	5	161.28	161
	6	80.64	80.64
	7	311.04	311
	8	149.76	149
	9	184.32	184

Appendix F: Explanation of the BS formula

The aim of the BS is to cope with the variations in demand of the individual products. Assuming the demand follows a normal distribution, we need to define a confidence-level (or service-level) and calculate the threshold (the BS) which the demand should not exceed.

With a service level of approximately 99.4% and k being the number of standard deviations corresponding to the service level , we obtain the following:

The probability of the demand not exceeding the CS and the BS equals to:

$$P(d_i \leq CS + BS) = 0.99379$$

$$P\left(\frac{d_i - \mu}{\sigma} \leq \frac{CS + BS - \mu}{\sigma}\right) = P\left(\frac{d_i - \mu}{\sigma} \leq k\right) = 0.99379$$

After setting this equation, we can solve it to find the BS:

$$\frac{CS + BS - \mu}{\sigma} = k$$

$$CS + BS = \mu + k * \sigma$$

However, the standard deviation as well as the demand being based on a week, we need to adapt the formulas to the EPEI (expressed in weeks).

With:

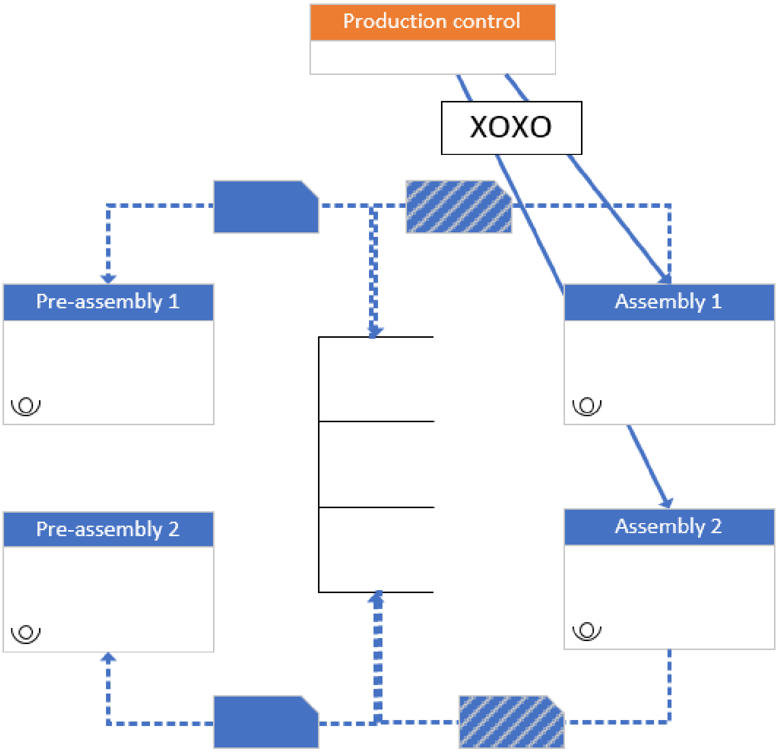
$$\mu_{EPEI} = EPEI * \mu_{week}$$

$$\sigma^2{}_{EPEI} = EPEI * \sigma^2{}_{week}$$

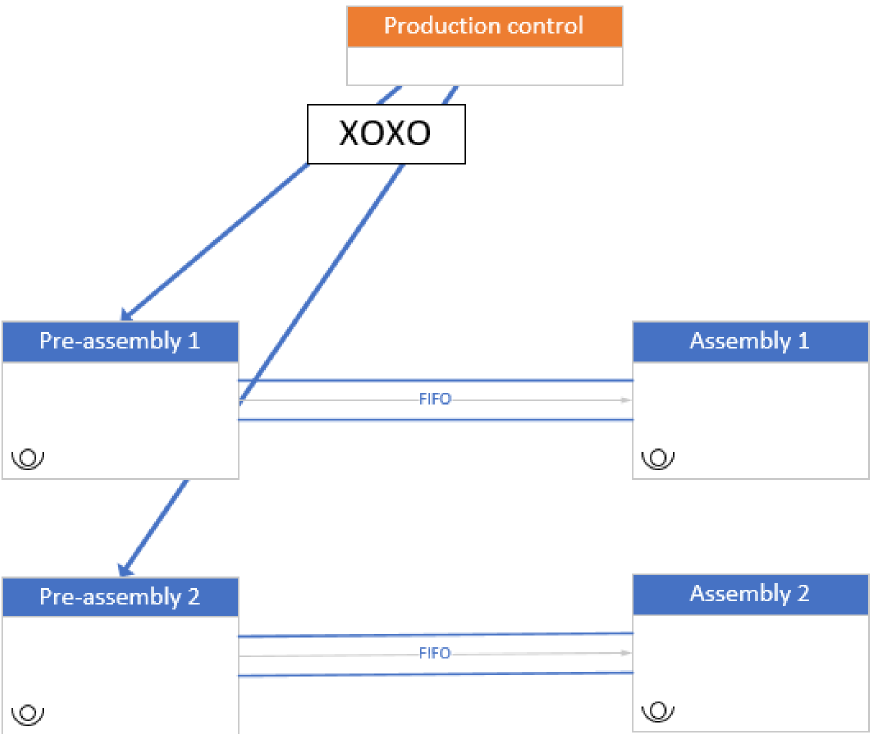
We obtain:

$$CS_{EPEI} + BS_{EPEI} = EPEI * \mu_{week} + k * \sqrt{EPEI} * \sigma_{week}$$

Appendix G: Using a Supermarket



Appendix H: Dedicating the Pre-assembly lines to one Assembly line



Appendix I: Flexible allocation of Pre-assembly lines