POLITECNICO DI TORINO

Collegio di Ingegneria Gestionale e della Produzione
Corso di Laurea Magistrale in Management Engineering

Evaluating the Limitations and Adaptability of Value Stream Mapping in High-Mix Low-Volume (HMLV) Manufacturing

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A.A 2024/2025

Index

Figures

Abstract

This thesis evaluates the limitations and adaptability of Value Stream Mapping (VSM) when applied in high-mix, low-volume (HMLV) manufacturing environments. While VSM has proven highly effective in repetitive, high-volume settings, its applicability in complex and customized contexts remains uncertain. The research addresses this gap by conducting a case study in a small metal-mechanic enterprise specializing in diamond wheel production, where product variety, fluctuating demand, and non-linear process flows complicate traditional lean implementations.

The methodology combined a literature review with a practical application of VSM, supported by process mapping, on-site observation, and data collection. The current state analysis revealed challenges such as long lead times, inconsistent maintenance practices, excessive work-in-process, and fragmented information flow. A tailored future state map was proposed, integrating preventive maintenance scheduling, improved visual management, and adjustments in process sequencing. These interventions demonstrated the potential to reduce non-value-added time and stabilize operations, even in a highly variable production context.

The study consolidates and applies adaptations of VSM already developed in the literature, testing their effectiveness in a small HMLV enterprise. The contribution lies in demonstrating the feasibility, challenges, and outcomes of these adaptations in practice.

1. Introduction

Globalization has brought along the widening of the market with huge growth potential for companies. Nonetheless, competition has also become a greater challenge, requiring more investment in sectors such as R&D.

As resources are scarce, companies started strengthening their efforts to seek saving opportunities to redirect this money to where is most needed.

One of the philosophies that emerged and became very popular some decades ago is Lean Manufacturing, targeting waste and inefficiencies in manufacturing settings, achieving incredible results after its application.

In the very competitive and ever evolving manufacturing industry, companies incessantly look for ways to improve and optimize their processes, with the ultimate goal of remaining competitive in the market.

In this context, methodologies and tools were in place, and one of the most famous ones was Lean Manufacturing. The methodology comprises many interesting tools, but undoubtedly one of the most valuable ones is Value Stream Mapping (VSM). The tool became very successful and popular, especially in low-mix/high-volume environments where it showed significant impact on the reduction of waste and performance overall improvement. Nonetheless, because of the gained popularity, small and medium size companies started to get interested in the tool, and the limitations started to emerge.

This study aims to explore these limitations analyzing how the utilization of the tool can be adjusted according to the complexity and particularities of the environment, and how these adjustments can be replicated to other similar settings. More specifically, assess how well traditional VSM can be applied within a real HMLV metalworking environment, and to develop methodological adaptations when necessary.

The second chapter will display how the Lean methodology started and evolved to finally be translated into usable tools that would help companies gain competitiveness in the market. It summarizes the main concepts pertaining to the scope of this study, helping to understand the particular scenario faced during the development of this work.

The third chapter is focused on the analysis of the state of the art. Given that the environment to be studied is closer to be a high-mix/low-volume setting, the research aims to analyze first the challenges faced by this kind of environments, then to follow up with the usage of the tool in the industry, to finally merge both contexts and visualize the work that has been done, the challenges that have been encountered, and the gaps left by the previous studies that found themselves in the same scenario.

The fourth chapter is where an adequate but generalized elaboration of the proposed method will be explained. The reader will be able to grasp the idea of basic context in terminologies associated with an HMLV company, as well as the challenges they face when trying to apply VSM tools.

In chapter five, the study case will basically initiate with the analysis of the characteristics of the HMLV environment in the selected company, to later implement the conventional VSM approach and document its practical limitations. Afterwards, changes will be proposed displayed in a future VSM, that will ultimately lead to a final execution phase where the results will be shown and analyzed.

Finally, chapter six will show the main findings of the thesis and will highlight the key challenges that remain for VSM in HMLV settings. It will also point out promising avenues for future research that could lead the industry toward a more optimized, data-driven decision processes.

The aim of this work is to apply existing adaptations discussed in the to the case of a small HMLV manufacturer. In doing so, it seeks to validate their applicability and highlight practical challenges when moving from theory to execution.

2. Theoretical background

2.1 Introduction

This chapter presents the foundational concepts of Lean Manufacturing, with a particular emphasis on Value Stream Mapping (VSM), a tool widely adopted to diagnose and improve operational performance. Lean Manufacturing emerged as a paradigm shift in industrial production, addressing the limitations of traditional systems full of excessive inventory, long lead times, fragmented workflows, and underutilized human potential. At its core, Lean focuses on three main pillars: waste elimination, continuous improvement, and a relentless focus on customer-defined value (Womack J. P., 1996).

While Lean principles were initially developed in the context of high-volume, low-mix automotive manufacturing (Womack et al., 1990), their application has expanded significantly into more complex production environments. The case study analyzed in this thesis focuses on a small-scale metal-mechanic company operating under a mixed-model production regime, where approximately two-thirds of the output is standardized, while the remainder exhibits a High-Mix/Low-Volume (HMLV) configuration. Additionally, certain customized products follow an Engineer-to-Order (ETO) logic, introducing a level of variability that challenges traditional Lean tools and routines. To address such complexity, this chapter not only retraces the historical and philosophical foundations of Lean but also explores the conceptual adaptations required for its application in high-variability settings. Specifically, technical constructs such as takt time, pacemaker processes, Little's Law, and Overall Throughput Effectiveness (OTE) will be introduced to support the methodological approach adopted in the subsequent analysis (Thomassen, Alfnes, & Gran, 2015; Rossini, et al., 2019; Cannas & Gosling, 2021).

2.2 From Craft Production to Lean Thinking

The historical development of manufacturing systems is often framed as a progression from craft production to mass production, and finally to lean production. Each stage reflects evolving responses to societal needs, technological capabilities, and economic pressures.

In the era of craft production, products were made one at a time by highly skilled artisans. This method allowed for extensive customization and high-quality workmanship, but it was inherently slow, costly, and difficult to scale. As demand for standardized goods rose in the early 20th century, a more efficient system was needed.

Mass production, pioneered by Henry Ford, revolutionized manufacturing by introducing the moving assembly line in 1913. This approach decomposed complex assembly tasks into simple, repeatable actions performed by semi-skilled workers. The use of single-purpose machines and conveyor belts allowed Ford to achieve unprecedented levels of output and cost efficiency. However, the gains in productivity came at a cost. Mass production relied heavily on buffer stocks to prevent disruptions, used rigid machinery that was hard to reconfigure, and fostered a work environment that alienated labor through monotonous and repetitive tasks (Womack J. J., 1990).

By the mid-20th century, the limitations of the mass production model had become increasingly apparent. Market demands were shifting toward greater product variety and higher quality, while the inefficiencies inherent in overproduction, excessive inventories, and rigid systems grew more costly. In post-war Japan, Toyota engineers Eiji Toyoda and Taiichi Ohno concluded that directly imitating the American mass production model would be unfeasible given Japan's scarce resources, spatial limitations, and the need for a more integrated and engaged workforce. In response, they developed the Toyota Production System (TPS), a holistic manufacturing philosophy grounded in the elimination of waste, the pursuit of continuous flow, and a deep respect for people (Liker, 2004; Ohno, 1988).

As documented by Womack, Jones, and Roos (1990), Toyota's system offered a third way between craft and mass production. It combined the flexibility and quality of the former with the scale and efficiency of the latter, without inheriting their respective inefficiencies. Lean production was thus conceptualized as a superior model capable of delivering high-variety, high-quality products at scale, with minimal waste and enhanced responsiveness.

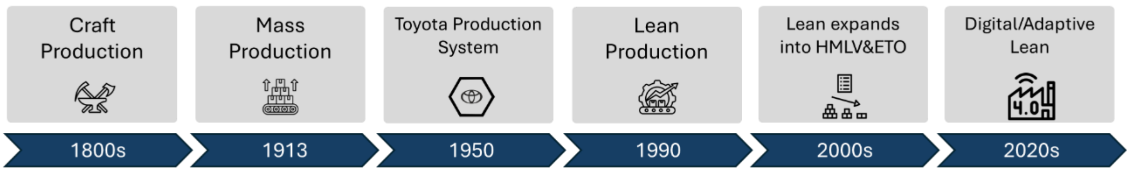

Figure 1- Production evolution timeline

2.3 Principles and Cultural Foundations of Lean

The Toyota Production System is often represented as a house (Figure 2), where each part of the house represents an important aspect of the whole system. This visualization emphasizes that Lean is not merely a set of tools; it is an integrated system of principles, practices, and cultural norms that collectively drive improvement. Among its most prominent principles are *continuous improvement (kaizen), respect for people, flow*, and *pull*.

Continuous improvement is both a mindset and a systematic approach to identifying and eliminating sources of waste. It involves empowering workers to observe problems in real time and propose solutions. At Toyota, for instance, line workers are trained and authorized to stop the production line using an andon cord whenever a quality issue arises. This reflects a deep commitment to "building quality in" rather than inspecting it later (Liker, 2004). The kaizen approach is incremental yet relentless, it assumes that every process can be improved, and that the pursuit of perfection is asymptotic but essential.

Respect for people supports the social architecture of Lean. Workers are not treated as passive executors of standardized tasks, but as knowledgeable contributors to system improvement. Toyota's decision to offer job stability and organize shopfloor workers into autonomous teams was critical in building a culture of trust and shared accountability. This principle extends to suppliers as well, who are seen not as adversaries to be pressured for cost reductions, but as long-term partners in mutual development (Liker, 2004; Ohno, 1988).

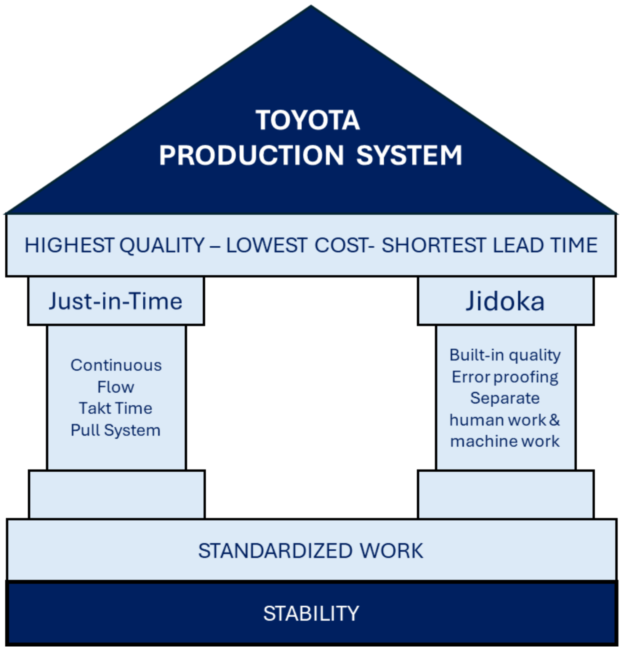

Figure 2- Toyota Production System House

Flow refers to the uninterrupted movement of products or information through a system. In Lean environments, the goal is to eliminate any barrier, be it excess inventory, long setups, or poor layout, that impedes smooth transitions between process steps. This concept is particularly powerful because it reveals hidden forms of waste, such as overproduction or waiting, that traditional performance metrics may overlook (Womack J. P., 1996; Rother & Shook, 2003).

Pull systems are the opposite of traditional push scheduling. Instead of forecasting demand and producing in anticipation, Lean systems use tools like kanban cards to signal downstream demand upstream, triggering production only when needed. This minimizes inventory, reduces lead times, and exposes problems in real-time. Pull systems are inherently more responsive but require stable processes and reliable information flow (Rother & Shook, 2003).

Together, these principles support an organization-wide operating philosophy that aims not only for efficiency but also for agility, quality, and engagement.

2.4 Relevance in High Mix Low-Volume (HMLV) and Engineer-to-order (ETO) Contexts

Despite its origins in repetitive production environments, Lean thinking has been increasingly adopted in settings where variability, customization, and engineering complexity are the norm. High-Mix, Low-Volume (HMLV) and Engineer-to-Order (ETO) systems exemplify such environments.

HMLV refers to manufacturing settings where a broad range of products is made in small quantities. Changeovers are frequent, demand is often unpredictable, and process standardization is difficult. Traditional Lean tools such as takt time, standard work, or flow lines must be adapted or reinterpreted. In these contexts, variability is not a defect to be eliminated, but a design condition to be managed (Rossini, et al., 2019).

Engineer-to-order (ETO) denotes a fulfilment strategy where substantial engineering begins after the customer order. While many ETO operations are HMLV, HMLV does not imply ETO; they address different dimensions (variety/volume vs. order fulfilment).

ETO systems take variability further. In such systems, customer orders trigger not only production but also engineering and design activities. This shifts the Customer Order Decoupling Point (CODP) upstream, often into design or prototyping. The CODP marks the boundary between forecast-driven and order-driven operations, and its position fundamentally shapes how Lean tools can be applied (Cannas & Gosling, 2021).

To navigate this complexity, practitioners introduce the concept of a pacemaker process, a point in the value stream that sets the rhythm for upstream and downstream activities. In ETO or HMLV environments, pacemakers are not always physical machines but may include planning milestones, engineering approvals, or batch release protocols (Thomassen, Alfnes, & Gran, 2015).

Takt time, in its standard definition, loses relevance when product volumes and mix fluctuate. Instead, an indicative average takt, calculated across a representative family or product cluster, can be used to guide workload balancing and detect overburdened resources (Thomassen, Alfnes, & Gran, 2015). This form of takt is less rigid but provides essential structure in environments where complete standardization is unfeasible.

Little's Law, which links lead time (L), work-in-progress (WIP), and throughput (T) through the formula $L = WIP / T$, remains valid even in high-variability systems. It enables managers to reason about performance bottlenecks, set realistic delivery expectations, and evaluate the impact of WIP reduction efforts (Rossini, et al., 2019).

Overall Throughput Effectiveness (OTE) is another relevant metric in such settings. OTE generalizes the concept of OEE beyond individual machines to assess the effectiveness of entire value streams. It captures not only availability, performance, and quality losses but also delays from setups, rework, and engineering changes. In job-shops or small batch manufacturing, OTE offers a systemic view of operational health (Rossini, et al., 2019).

In summary, while Lean principles remain powerful, their application in HMLV and ETO settings require nuanced interpretation and tailored implementation. These adaptations will serve as the foundation for the analytical framework employed in the rest of this thesis.

2.5 Value Stream Mapping (VSM)

Value Stream Mapping (VSM) is a core diagnostic and design tool within the Lean Manufacturing framework. It enables organizations to visualize, analyze, and improve the flow of materials and information required to deliver a product or service to the customer. Unlike traditional process mapping tools that often focus on isolated operations or solely on activities, VSM provides a systemic overview that highlights both value-adding and non-value-adding steps across the entire value stream (Rother & Shook, 2003; Bicheno & Holweg, 2016).

The value stream represents the complete set of actions, both those that add value and those that do not, required to bring a product from raw material to the customer, or a service from request to delivery. Mapping this stream creates visibility into how value flows through the organization and how delays, handoffs, or overprocessing may hinder performance. It supports the transition from a fragmented, siloed process view to a holistic understanding of operations, thereby enabling data-driven and team-based problem-solving (Rother & Shook, 2003; Ohno, 1988).

VSM is typically structured in two main stages. The **Current State Map** captures the existing process as it operates, documenting each step, inventory levels, information flow, and time data such as cycle time and lead time. This allows organizations to identify inefficiencies including bottlenecks, excess inventory, rework, and long changeover times (Womack & Jones, 1996; Rother & Shook, 2003). Following this, the **Future State Map** envisions a redesigned process that improves flow, reduces waste, and aligns more closely with Lean principles such as pull production, leveled scheduling, and reduced work-in-progress (WIP). The gap between the current and future states defines the roadmap for Lean transformation initiatives (Liker, 2004; Womack J. P., 1996).

What makes VSM particularly effective is its dual focus on material flow and information flow. While conventional improvement efforts often emphasize physical production, VSM explicitly visualizes how information travels across departments and triggers production activity. This comprehensive perspective allows decision-makers to uncover inefficiencies not only in manufacturing but also in scheduling, planning, and administrative workflows (Rother & Shook, 2003).

VSM is widely used in Lean initiatives as a baseline diagnostic tool, but it also supports continuous improvement over time. It can be revisited and adapted periodically to reflect changes in demand, system constraints, or process improvements. Its simplicity, visual format, and collaborative nature make it highly effective for facilitating cross-functional understanding among operators, engineers, managers, and support staff (Liker, 2004).

A major strength of VSM is its capacity to integrate key performance indicators (KPIs) into the visual representation. Commonly included metrics are cycle time, lead time, takt time, and percentage of value-added time. These KPIs help identify where value is created, where resources are wasted, and where process intervention is most needed (Rother & Shook, 2003).

Cycle time refers to the time required to complete a specific task or operation under standard conditions. It includes only the time during which active work is performed, excluding idle or waiting time. In HMLV and ETO systems, where tasks vary across products, average or representative cycle times are often used for analysis (Rother & Shook, 2003; Rossini, et al., 2019).

Lead time is the total elapsed time from the moment a product enters the value stream to when it is completed and delivered. Unlike cycle time, lead time includes all waiting periods between steps and serves as a comprehensive indicator of responsiveness and efficiency. A high proportion of non-value-adding lead time signals the need for better flow and waste elimination (Liker, 2004; Womack J. P., 1996).

Takt time is derived from the German word "Taktzeit" and represents the rhythm of customer demand. It is calculated by dividing available production time by customer demand in a given period. Takt time sets the ideal pace for production to meet demand without overproduction or shortages. If any process step exceeds takt time, it indicates a bottleneck (Bicheno & Holweg, 2016).

Value-added (VA) and non-value-added (NVA) time help distinguish between activities that directly contribute to the final product and those that do not. While some NVA activities are necessary (e.g., compliance), many are considered waste. Figure 3 shows a decision map that helps identify what to do if a process falls under each quadrant, according to how it is labeled. Identifying and minimizing NVA time is essential for Lean effectiveness (Ohno, 1988).

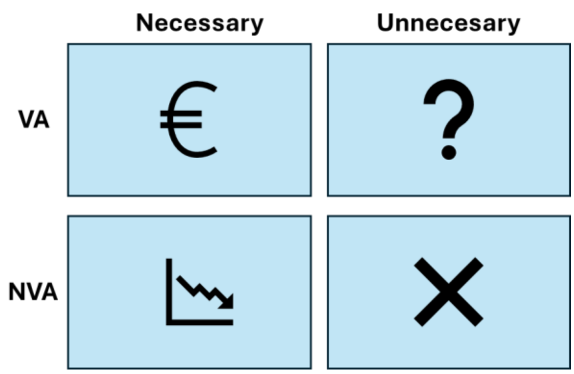

Figure 3- Decision map for VA-NVA analysis

The visual language of VSM also plays a crucial role. It uses standardized symbols to represent process steps, inventory, data flows, suppliers, customers, and transport. Arrows distinguish between material and information flow, and data boxes contain quantitative inputs such as cycle time, uptime, and batch size. These symbols support communication and allow teams to quickly interpret the map (Rother & Shook, 2003).

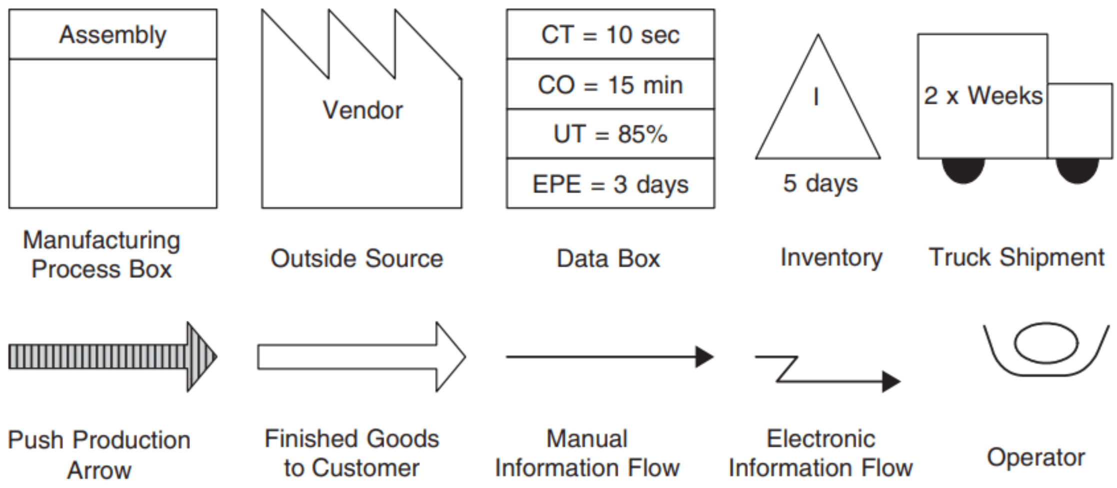

Figure 4- Common VSM symbols

In complex environments such as HMLV or ETO, the application of VSM becomes more challenging. Traditional VSM assumes stable routings and demand, with a dominant flow path. However, in HMLV systems, routing divergence, variable setup times, and customer-driven production orders disrupt this structure. Thomassen et al. (2015) suggest adapting VSM by selecting representative product families, focusing on shared resources, and using aggregated data to reflect generalized flow behaviors. In ETO contexts, VSM must also extend upstream to incorporate design, engineering, and planning, especially when the Customer Order Decoupling Point (CODP) occurs before fabrication.

In these high-variability settings, data collection may require custom time studies or expert estimations instead of real-time system data. Future State Maps may need to incorporate flexible scheduling and dynamic prioritization, and often rely on indicative rather than strict takt times. Nevertheless, even in these complex scenarios, VSM clarifies underlying process logic, reveals inefficiencies, and supports alignment among stakeholders (Romero & Arce, 2017; Thomassen, Alfnes, & Gran, 2015).

In the context of this thesis, VSM will be employed both to document the existing production process at Diamant SRL and to identify targeted areas for Lean improvement. The methodology will be adapted to reflect the operational reality of a mixed-model, high-variability environment and to propose a configuration that better synchronizes resources with demand while minimizing inefficiencies and redundancies.

2.6 Key metrics and Elements in VSM

Beyond its visual clarity, VSM derives much of its power from integrating key performance metrics directly into the process representation. These metrics make waste visible and quantifiable, allowing teams to prioritize interventions based on real impact.

Cycle time refers to the time required to complete a specific task or operation under normal working conditions. In HMLV and ETO systems, cycle times often vary considerably across products, so VSM may report average or representative cycle times for analysis (Rother & Shook, 2003; Rossini, et al., 2019).

Lead time, by contrast, measures the total elapsed time from the entry of raw material to the delivery of the final product. In job-shop and mixed-model environments, lead times may span days or weeks due to queueing, changeovers, or waiting for customer approvals. Mapping lead time across stages allows companies to identify where delays accumulate and which steps require more flow efficiency (Bicheno & Holweg, 2016).

Takt time is traditionally calculated as available working time divided by customer demand, providing a rhythm to pace production. In repetitive systems, this serves as a heartbeat to synchronize processes. However, in HMLV contexts, applying a fixed takt is unrealistic. Instead, an indicative average takt time can be used as a benchmark for line balancing, capacity planning, and pacing pacemaker processes (Thomassen, Alfnes, & Gran, 2015).

VSM also distinguishes between **value-added (VA)** and **non-value-added (NVA)** time. VA activities directly transform the product in ways the customer is willing to pay for, while NVA activities consume time and resources without adding value. Often, a surprisingly small percentage of lead time is VA. Quantifying this ratio in VSM helps focus improvement efforts where they yield the highest returns (Rother & Shook, 2003).

To deepen the analysis, VSM can incorporate **Little's Law**, which relates lead time (L), work-in-process (WIP), and throughput (T):

$$\mathbf{L = WIP / T}$$

This formula enables simple yet powerful diagnostics. For example, high WIP and low throughput indicate flow inefficiency. In HMLV environments, it helps estimate realistic lead times under fluctuating workloads (Rossini, et al., 2019).

In non-repetitive or multi-product systems, VSM can also integrate **Overall Throughput Effectiveness (OTE)**, a KPI derived from Overall Equipment Effectiveness (OEE). OTE expands the analysis from individual machines to entire value streams, capturing availability losses, performance gaps, and quality rework holistically. It is especially relevant when flow is discontinuous, or resources are shared across products (Rossini, et al., 2019).

VSM's use of standard visual symbols for operators, processes, inventory, and information flow enhances communication and cross-functional collaboration. Arrows denote material or data movement; process boxes house metrics like cycle time, changeover, uptime, and batch size; and data boxes support side-by-side comparison across variants (Rother & Shook, 2003). These symbols ensure that even complex systems can be quickly understood by multidisciplinary teams.

Key metric	Formula	Unit	Definition
CODP	-	Position in process flow	Location where the process shifts from forecast-driven to order-driven
CT	$CT = \frac{total\ processing\ time}{Nro.of\ units\ produced}$	Min/unit	Time to complete one unit at each process
L	$LT = Queue\ time + Proce.time + Transport + Waiting$	Days/hours	Total time from order to delivery
WIP	$WIP = L \times Throughput$		Average pieces in progress between processes
TAKT TIME	$TaktTime = \frac{Avail.Prod.Time}{Cust.Demand}$	min/unit	Available time ÷ customer demand

Table 1- Key Metrics

2.7 The Eight Wastes of Lean

A fundamental concept in Lean Manufacturing is the identification and elimination of waste, known in Japanese as *muda*. Waste refers to any activity or process that consumes resources but does not add value from the perspective of the customer. While traditional production systems often treated such inefficiencies as inevitable, Lean explicitly targets them for reduction or elimination to improve overall efficiency, reduce costs, and enhance responsiveness.

Originally, the Toyota Production System identified seven types of waste, but over time, Lean practitioners recognized an eighth form, underutilized talent, as equally detrimental. These eight wastes serve as a diagnostic lens through which organizations can analyze their processes and identify areas for improvement (Liker, 2004; Rother & Shook, 2003).

The first and somewhat easiest identifiable waste is **overproduction**, which occurs when products are made in greater quantity or earlier than needed. This kind of waste leads to excessive inventory, higher storage costs, and increased risk of obsolescence or defects. It also masks other inefficiencies within the process. Lean views overproduction as the root cause of many other wastes, and its elimination is central to the implementation of pull systems and Just-in-Time production (Liker, 2004).

Waiting refers to any idle time when materials, information, people, or equipment are not in motion or not being used productively. This can result from imbalanced workloads, equipment downtime, delays in approvals, or process bottlenecks. Waiting time adds no value and often leads to increased lead times and decreased throughput (Rother & Shook, 2003).

The third type of waste is **transportation**, which involves the unnecessary movement of materials, products, or information between processes. While some transportation is inevitable in manufacturing environments, excessive or unoptimized movement increases the risk of damage, adds to lead times, and does not contribute to value creation. Lean encourages streamlined layouts to minimize this form of waste (Womack J. P., 1996).

Overprocessing refers to performing more work or using more components, materials, or steps than are required by the customer. This can come from poorly designed processes, lack of standardization, or an overemphasis on quality checks without understanding where true value is. For instance, using precision equipment for tasks that do not require high precision is a form of overprocessing (Womack J. P., 1996).

The fifth waste is **inventory**, which includes raw materials, work-in-progress (WIP), and finished goods that are not actively being processed or sold. Excess inventory consumes space, increases handling costs, traps capital, and may hide underlying problems in the production process. Lean promotes inventory reduction through pull systems and demand-based production to maintain optimal flow (Liker, 2004; Ohno, 1988).

Motion refers specifically to unnecessary movement by people. This includes walking, reaching, bending, or searching for tools, parts, or documents. Poor workstation design and lack of standard operating procedures often contribute to excessive motion, leading to fatigue, reduced productivity, and even injuries (Ohno, 1988).

Defects are perhaps the most visible form of waste. They include errors in products or services that require rework, repair, or result in scrap. Beyond the immediate cost of correction, defects can damage customer satisfaction, increase inspection requirements, and disrupt flow. Lean emphasizes building quality into the process, root cause analysis, and continuous improvement to minimize defects (Liker, 2004).

The **eighth waste**, added later by Lean practitioners, is **underutilized talent**. It refers to the failure to leverage the full capabilities, skills, and ideas of employees. Traditional hierarchies often limit frontline workers' participation in problem-solving, even though they are closest to the process. Lean organizations seek to empower employees through training, suggestion systems, and team-based problem-solving, recognizing that people are central to continuous improvement (Bicheno & Holweg, 2016).

By systematically identifying and targeting these eight forms of waste, Lean organizations are better equipped to streamline operations, enhance value delivery, and foster a culture of operational excellence. These categories are not mutually exclusive and often overlap, for example, overproduction can lead to excess inventory and increased transportation. Therefore, waste analysis should be approached holistically and iteratively as part of the broader Lean transformation process.

Figure 5- Eight wastes of Lean

2.8 Other strategic Lean Tools

One of the most popular tools found in the Lean toolkit to address manufacturing problems is 5S. It is, in fact, one of the most widely recognized Lean practices and typically serves as the entry point for organizations embarking on a Lean transformation. The 5S methodology aims to create and maintain a clean, organized, and efficient workplace through a structured five-step process: **Sort**, **Set in Order**, **Shine**, **Standardize**, and **Sustain**.

The first step, **Sort (Seiri)**, involves removing all unnecessary items from the workplace, tools, materials, or equipment that are not essential to current operations. This step eliminates clutter and enables smoother workflows. Next, **Set in Order (Seiton)** ensures that the remaining items are organized so that they are easy to access, reducing time wasted searching for tools or materials. **Shine (Seiso)** refers to regular cleaning and inspection of the workplace, which not only improves aesthetics but also helps identify equipment issues early.

The fourth step, **Standardize (Seiketsu)**, focuses on developing visual cues, standard operating procedures, and routines that maintain the first three S's consistently. This standardization enables uniformity across workstations and promotes accountability. Finally, **Sustain (Shitsuke)** emphasizes discipline and habit formation to ensure long-term adherence to the 5S system. It often requires cultural reinforcement through training, leadership modeling, and regular audits.

5S is more than a housekeeping initiative, it plays a strategic role in establishing the foundation for other Lean tools. A well-organized workspace improves safety, reduces motion waste, enhances productivity, and facilitates faster problem detection. In environments like HMLV or ETO, where variability is inherent, 5S contributes to operational stability by improving visual control and freeing up space previously occupied by excess materials or outdated equipment.

In the context of this thesis, 5S is considered a baseline enabler of Lean success. Its implementation at the company supports not only the reduction of workplace waste but also the cultural shift required to sustain continuous improvement initiatives.

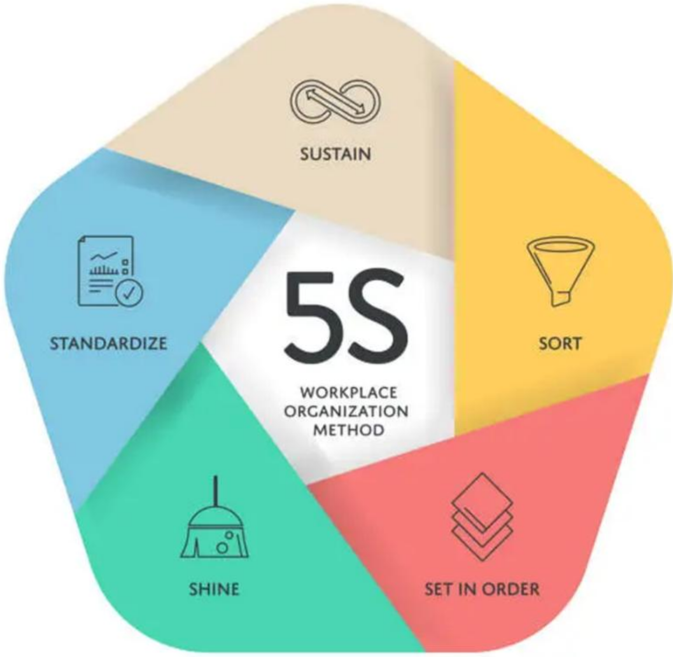

Figure 6- 5S Diagram

In Lean Manufacturing, effective problem-solving requires more than identifying symptoms, it demands uncovering and addressing root causes. Two foundational tools in this regard are the 5 Whys technique and the Ishikawa Diagram, also known as the Fishbone Diagram. These methods are frequently used in tandem to systematically diagnose the sources of inefficiencies, defects, or recurring issues within a production process.

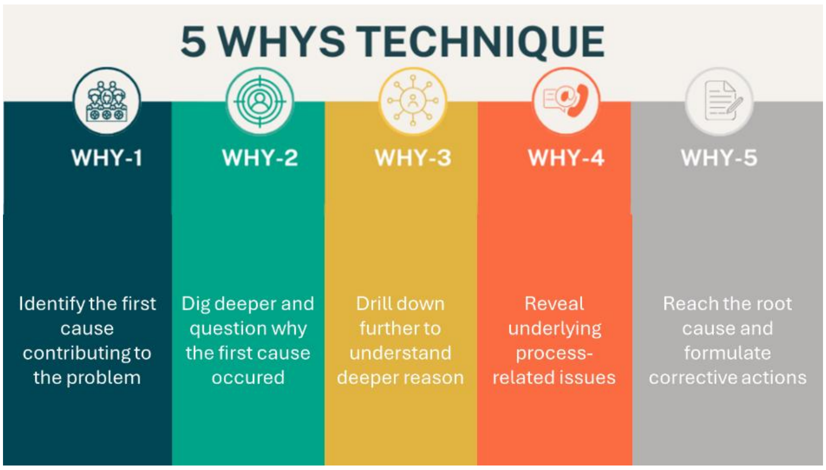

Figure 7- 5Whys Technique

The 5 Whys method is a simple but powerful tool developed by Sakichi Toyoda and adopted as part of the Toyota Production System. It involves asking “why?” repeatedly, typically five times, in response to a problem, with each question probing deeper into the underlying cause. The goal is to move beyond surface-level explanations (e.g., "the machine stopped") to uncover systemic issues (e.g., "maintenance schedules were skipped due to understaffing"). This technique is particularly valuable because it promotes critical thinking without requiring complex data analysis. It encourages frontline workers and supervisors to engage directly with problems, making it ideal for Lean environments that prioritize employee involvement in continuous improvement (Ohno, 1988).

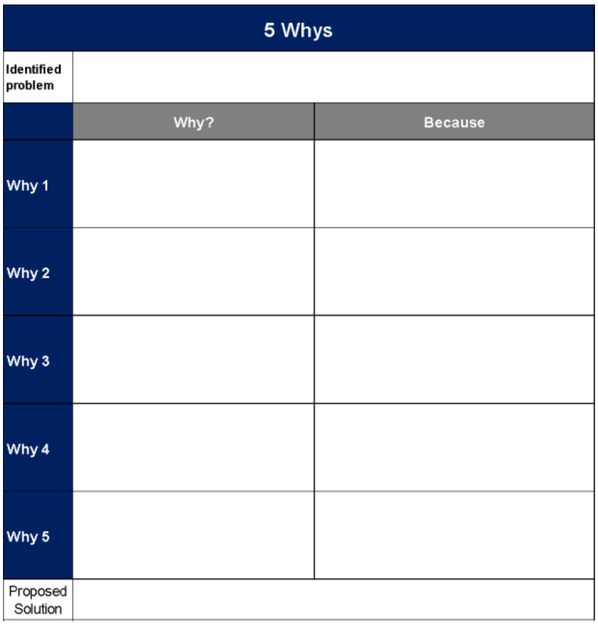

Figure 8- 5 Whys template

While the 5 Whys is linear, the Fishbone Diagram provides a visual structure for categorizing potential root causes. Introduced by Kaoru Ishikawa, this diagram resembles a fish skeleton: the problem is placed at the “head,” and the “bones” branching off represent major categories of influence, typically including Methods, Machines, Materials, Manpower, Measurement, and Environment (the 6 Ms). Under each category, contributing factors are listed and explored collaboratively. This method is especially useful for complex problems with multiple interacting causes, as it helps teams visualize connections, brainstorm comprehensively, and prioritize areas for deeper investigation.

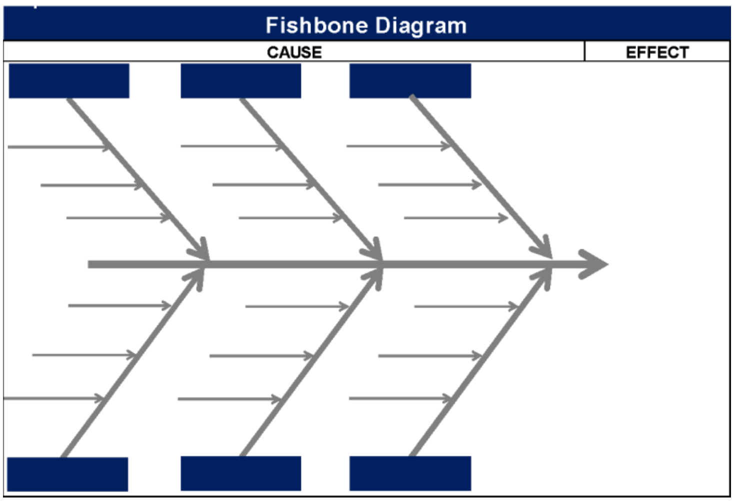

Figure 9- Fishbone diagram template

Both tools align with Lean principles by fostering team-based problem-solving, exposing hidden inefficiencies, and enabling targeted countermeasures. In the context of this thesis, the 5 Whys and Fishbone Diagram are used to analyze root causes behind specific wastes or performance issues revealed by the Value Stream Mapping exercise. Their use supports a structured approach to continuous improvement, ensuring that corrective actions address the true drivers of inefficiency rather than superficial symptoms.

2.9 Limitations of Lean and VSM in Complex Environments

Like any methodology, Lean Manufacturing and its tools must be adapted to the context. Particularly, when applied in complex or dynamic environments, they have limitations, and they must be acknowledged and addressed accordingly.

A significant limitation is data availability and accuracy. VSM relies heavily on accurate measurements of times, quantities, and flows. In many organizations, particularly small or less digitized firms, detailed operational data may be missing, inconsistent, or outdated. Without reliable data, maps may misrepresent the current state, leading to incorrect conclusions and misguided improvement efforts. This is especially problematic in administrative or service processes, where tasks are less visible and more variable than in traditional manufacturing settings (Womack J. P., 1996).

Cultural and organizational resistance also poses a substantial barrier to Lean implementation. Lean thinking requires a deep shift in mindset, especially for organizations accustomed to top-down management styles and rigid functional silos. Empowering frontline workers, flattening hierarchies, and promoting transparency often face pushbacks from both management and employees. Resistance may stem from fear of change, lack of trust, or skepticism about the benefits of Lean. Without strong leadership commitment and a supportive culture, Lean initiatives risk being superficial or short-lived (Liker, 2004; Bicheno & Holweg, 2016).

Moreover, Lean and VSM do not inherently address digital integration, which is increasingly important in modern production environments. While VSM provides a powerful visualization of processes, it is traditionally paper-based and does not automatically capture real-time data or system-level dynamics. As manufacturing environments become more digitized through Industry 4.0 technologies, such as IoT sensors, MES platforms, and digital twins, VSM must be adapted or supplemented to stay relevant. The integration of digital tools is still an evolving field, and many companies struggle with bridging traditional Lean methods with data-driven approaches (Bicheno & Holweg, 2016).

Another limitation lies in the focus on internal processes. VSM typically maps activities within the boundaries of a single organization or production line. However, in today's interconnected supply chains, many forms of waste originate upstream or downstream, from unreliable suppliers, poor demand forecasts, or inefficient distribution systems. While advanced applications of VSM can extend across organizational boundaries, doing so requires strong collaboration, data sharing, and mutual trust among partners, conditions that may not always be present (Ohno, 1988).

While Lean Manufacturing emerged as a flexible and efficient alternative to traditional mass production, particularly addressing its rigidity and over-reliance on large batch processing, the application of certain Lean tools can become challenging in complex production environments. Value Stream Mapping (VSM), for instance, is most effective in stable, repetitive processes where product flows can be standardized and easily visualized.

Although a limited number of products represent the majority of the company's sales volume, the presence of multiple customized items and Engineer-to-Order (ETO) projects introduces a significant degree of variability in the production process. This justifies the classification of the company as a High-Mix Low-Volume (HMLV) environment, particularly from the perspective of Lean implementation and Value Stream Mapping complexity.

Nevertheless, the company to be addressed later in this work, like many others, deals with high-mix, low-volume (HMLV) production systems. This kind of company, characterized by frequent product changes, customized outputs, and variable demand, poses specific challenges to the use of VSM. Attempting to capture the flow of every product variant on a single map can lead to oversimplification or, conversely, to a level of complexity that turns the tool impractical. As a result, while Lean philosophy remains highly relevant in such settings, VSM in its traditional form may not provide sufficient clarity or actionable insights.

To address these challenges, the tools are often adapted by grouping similar products into families for separate VSMs, using layered or digital mapping solutions, or combining VSM with other Lean tools such as spaghetti diagrams, process flow charts, or takt-based planning. These adaptations help preserve the Lean objective of waste elimination and continuous improvement while accommodating the variability inherent in HMLV operations. Lean must be applied with a balance between standardization and adaptability, recognizing the trade-offs inherent in each process decision (Liker, 2004; Rother & Shook, 2003).

In summary, while Lean Manufacturing and VSM offer powerful methodologies for process improvement, their limitations must be carefully considered. Factors such as product complexity, cultural readiness, data maturity, supply chain integration, and environmental volatility all influence the success of Lean transformations.

3. State of the art

3.1 Introduction

This chapter dives in the literature review of the topic being addressed in this work, aiming to classify recent scientific contributions related to lean Manufacturing and Value Stream Mapping (VSM) applied to process improvement.

The databases used for the extraction of the related documents were SCOPUS, Science Direct, IEEE and Research Gate.

3.2 Research Methodology

The structure of this chapter follows applicable guidelines set in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Statement. Studies were identified by searching Scopus, Science Direct, Research Gate, and IEEE databases from 2015 to 2025. This period was selected in order to focus on the latest updates of the tool in the field.

The search targeted articles written in English, Spanish, and Portuguese, and was not only limited to studies published in indexed Journals. Considering the characteristics of the business to be studied in this work, the search syntax used included the following search terms referring to Value Stream Mapping, Lean manufacturing, High-Mix-Low-Volume, HMLV, and Low-volume production. Thus, the general query used to retrieve information from different sources was:

(ALL ("Value Stream Mapping" OR "Lean Manufacturing") AND ALL ("High Mix Low Volume" OR hmlv OR "low-volume production")) AND PUBYEAR > 2014 AND PUBYEAR < 2026

Within articles, conference papers and reviews, **153** documents were retrieved from Scopus, **54** from ScienceDirect, and **5** from IEEE. As a complementary source of information, with the same query, ResearchGate was also used although it does not specify the number of papers retrieved. Nonetheless, **6** potentially relevant documents were selected, chosen by the affinity of their titles with the topic of this work.

After removing duplicates and other out of scope or irrelevant documents based on the titles, **39** documents were selected from Scopus, **8** from Science Direct, **5** from IEEE, and all **6** from ResearchGate.

The second screening was assessed based on the analysis on the abstracts and keywords, getting **11** relevant documents in total.

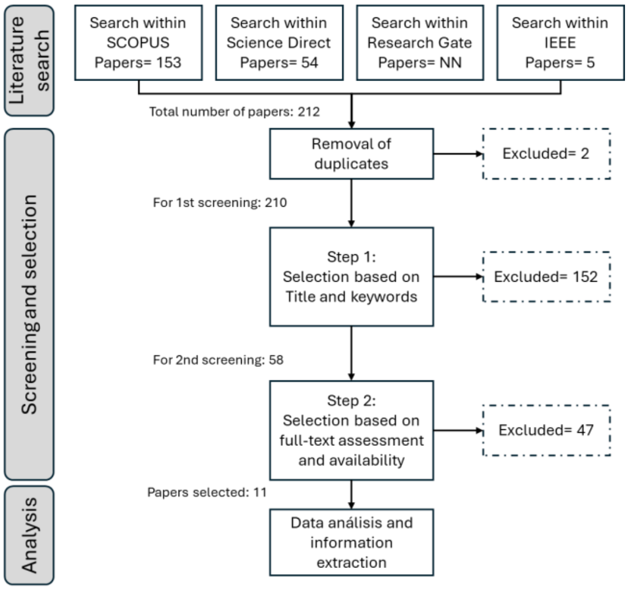

Figure 10- Literature review methodology

3.3 Categorization and summary of literature

After reviewing the documents previously retrieved, we can categorize them in three main groups:

- Reviews and Frameworks

These papers take a broad, synthesizing view, mapping what's known about Lean (LM), High-Mix/Low-Volume (HMLV), Engineer-to-Order (ETO), and the role of VSM, often proposing organizing frameworks or research agendas. A major HMLV review consolidates 2000–2022 work and shows production planning dominates prior research while other parts of the value chain remain underexplored. It also highlights a shift toward decision-support and Industry 4.0 technologies in HMLV settings. Recent work on lean techniques for discrete manufacturers proposes a 5P framework (Philosophy–Process–People–Problem-solving–Product), forecasting tighter integration with digital and SME-friendly strategies. For ETO specifically, a decade review formalizes two-dimensional decoupling concepts and clarifies where and how lean bundles fit, while calling for comparative and prescriptive studies. Finally, small-batch/high-cost contexts get their own lean-indicator landscape, arguing that generic lean bundles apply but require context-specific adaptation and KPI realignment. Included papers in this category are:

- A Review of the High-Mix, Low-Volume Manufacturing Industry (Gan, Musa, & Yap, 2023)
- Recent Advances in Lean Techniques for Discrete Manufacturing Companies: A Comprehensive Review (Yang, Fu, Zhu, & Lv, 2025).
- A decade of engineering-to-order (2010–2020): Progress and emerging themes. (Cannas & Gosling, 2021).
- Lean indicators for small batch-size manufacturers in high-cost countries (Adlin, Nylund, Lanz, Lehtonen, & Juut, 2020)
- Overall Task Effectiveness: a new Lean performance indicator in ETO environment. (Braglia, Gabbrielli, & Marrazzini, 2019)

- Process improvement in complex manufacturing environments

This group reports hands-on interventions (kaizen, pull, line redesign) in HMLV/MTO/ETO-like settings, quantifying lead-time, WIP, and efficiency gains when lean tools are tailored to complexity. An integrated VSM case on a complex automotive assembly line (low product similarity) shows measurable cuts in cycle time/WIP and higher line efficiency after current/future-state mapping and layout changes. A kaizen framework customized for Italian MTO demonstrates >10% cost reduction and a jump in on-time delivery (70→95%), emphasizing A3 and RACI-driven results. Metallurgical and SME settings also show practical gains from VSM-guided roadmaps, illustrating feasibility outside automotive. Included papers in this category are:

- Leanness assessment of a complex assembly line using integrated VSM: a case study (Sangwa & Sangwan, 2023)
- Extending lean frontiers: a kaizen case study in an Italian MTO manufacturing company (Rossini, et al., 2019).
- Value stream mapping applied on a metallurgical industry with a mix of products with a wide range of parts (Rosa, 2021)
- Implementation of Lean Manufacturing in a Small and Medium Enterprise using Value Stream Mapping (Shravan, Dharmanand, Krishnaunni, Vyshnav, & Kiron, 2024).
- Quick Response Manufacturing for High-Mix, Low-Volume, High-Complexity Manufacturers (Duda, Markiewicz, & Lis, 2021)

- Value Stream Mapping: Evolution and applications

These papers center on the application and evolution of Value Stream Mapping as a tool for identifying inefficiencies and driving process improvements. Traditional VSM is modified and expanded through digital integration and adaptations for ETO and small batch production. These papers show that VSM remains a powerful diagnostic tool, that for instance, in one highlighted case, its integration with process planning resulted in 15–20% reduction in waste and idle times. Digitalized VSM further enhances visibility and communication, a finding reflected in the current study's interest in digital twin tools. Still, there are still challenges in standardizing digital VSM practices, especially regarding data capture, real-time updating, and visual consistency. Additionally, many implementations remain static and disconnected from ongoing decision-making, indicating the need for dynamic, interoperable VSM systems that continuously evolve with production realities. Included papers in this category are:

- A New Value Stream Mapping Approach for Engineer-to-Order Production Systems (Thomassen, Alfnes, & Gran, 2015).
- Extending Value Stream Mapping for Lean Production Planning and Control (Van Landeghem & Cottyn, 2022).
- Applying Value Stream Mapping in Manufacturing: A Systematic Literature Review (Romero & Arce, 2017).

This categorization shows how the conversation has moved from generic lean recommendations to a more context-specific toolkit for each case. It also lets in evidence the gaps and challenges faced by the tools when the environment becomes ever more complex, and the digital world develops further. With this perspective in mind, the following table summarizes the key publications referred to in the categories previously mentioned.

1. Xinyan Yang, Lei Fu, Ling Zhu, Jiufang Lv (2025). Recent Advances in Lean Techniques for Discrete Manufacturing Companies: A Comprehensive Review
   It proposed a 5P lean-technology framework (Philosophy, Process, People, Problem-solving, Product) integrating product-centric methodologies (e.g., QFD, FIFO, cellular manufacturing) to enable end-to-end value stream coverage. It analyzed 369 papers and outlined six future lean-tech strategy directions for SMEs in discrete manufacturing, Dynamic lean management mechanisms, New lean paradigms (e.g., Lean 4.0), Sustainable lean integration, Endogenous technological innovation, Human-centered value activation, and Business model restructuring.

2. Shravan E R; Sourav Dharmanand; Krishnaunni V; Vyshnav S; Kiron K R (2024). Implementation of Lean Manufacturing in a Small and Medium Enterprise using Value Stream Mapping
   This paper demonstrated the application of VSM within an Indian SME, achieving important improvements in lead time, and value-added ratio. Key improvements included standardizing raw material input and redistributing labor for simultaneous operations. The study highlighted the feasibility of significant lean gains in SMEs with minimal investment, proposing future automation for further gains.

3. Gan, Z.L.; Musa, S.N.; Yap, H.J. (2023). A Review of the High-Mix, Low-Volume Manufacturing Industry
   It revealed that 71% of HMLV studies (2000–2022) focused on non-industry-specific production planning, with gaps in logistics, maintenance, and sustainability. Mapped the shift from theoretical scheduling (2000s) to Industry 4.0-driven solutions, highlighting rising interest in big data and human-robot collaboration. Exposed that only 40% of models were industrially validated, predominantly in semiconductors/electronics, urging real-world testing in diverse sectors.

4. Sangwa, N.R.; Sangwan, K.S. (2023). Leanness assessment of a complex assembly line using integrated value stream mapping
   The authors introduced an Integrated VSM framework for complex assembly lines producing products with low similarity (59%). By redefining work cells as Multi-Machine Activities (MMAs) operated by single workers, they unified material/information flows, wastes, and metrics for multiple products on a single map. In an automotive case study, they reduced cycle times, cut WIP inventory, and improved line efficiency, proving VSM’s adaptability to low-similarity contexts. The study also highlighted layout redesign and phased kaizen implementation as critical enablers, addressing gaps in traditional VSM’s handling of merging flows and parallel processes.

5. Hendrik Van Landeghem (2022). Extending Value Stream Mapping for Lean Production Planning and Control

This paper enriched classic VSM with a 5-level PPC hierarchy, new symbols and 13 redesign questions that integrate material- and information-flow planning, supporting gradual evolution from push-MRP to pull systems.

6. Cannas, V.G.; Gosling, J. (2021). A decade of engineering-to-order (2010-2020): progress and emerging themes.

   A systematic review of 151 ETO studies was conducted, identifying three core research avenues, refined ETO definitions via 2D decoupling points and archetypes, emerging strategy topics, and context-adapted lean bundles for ETO. It also quantified lean's impact and proposed four future challenges, multidisciplinary integration, technology evaluation, configuration transitions and servitization models.

7. Jerzy Duda (2021). Quick Response Manufacturing for High-Mix, Low-Volume, High-Complexity Manufacturers

   The study developed a hybrid QRM cell-formation method for contract manufacturers operating under ETO / HMLVHC conditions. It showed that combining traditional tech-cells with QRM flow reduces response time without full re-cellularization.

8. Rosa, A.F.P.; Royer, R.; Ávila, V.R. (2021). Implementation of Lean Manufacturing in a Small and Medium Enterprise using Value Stream Mapping

   The study bridges a gap in VSM literature by tackling high-variability, low-volume production systems, proving VSM's adaptability beyond sequential manufacturing. The key contributions that the paper gave were regarding the methodology for complex VSM, the quantification of improvements when eliminating non-adding-value activities, and the demonstration of cross-functional action plans for implementing Lean tools.

9. Adlin, N.; Nylund, H.; Lanz, M.; Lehtonen, T.; Juuti, T. (2020). Lean Indicators for Small Batch-Size Manufacturers in High-Cost Countries

   Through a systematic review of 20 empirical studies (2010–2019), it developed a Lean Manufacturing Reference Framework (LMRF) tailored to SBSM, high-cost-country producers and mapped it to sustainability & KPI landscapes, stressing integrated product-production development and context-contingent metrics. The framework uniquely integrates product development with production processes and validates findings via a Sustainability-KPI Landscape, highlighting context-specific adaptations for lean success.

10. Rossini, M.; Audino, F.; Costa, F.; Cifone, F.D.; Kundu, K.; Portioli-Staudacher, A. (2019). Extending lean frontiers: a kaizen case study in an Italian MTO company

   It developed and validated a structured kaizen framework for HMLV and MTO manufacturing. The framework integrates A3 problem-solving with a RACI matrix to define roles and phases. Key innovations include a scenario-based mixed-model line design for HMLV flexibility and the use of "Managing for Daily Improvement" boards to sustain gains. The study underscores cross-functional team organization as critical for kaizen success in non-traditional lean environments.

11. Marcello Braglia (2019). Overall Task Effectiveness: a new Lean performance indicator in ETO environment

    It introduced OTE, an "OEE-like" KPI that separates losses external to the project order from task-related inefficiencies, offering simultaneous standard-time setting and hidden-loss diagnosis for manual assembly in ETO plants.

12. Romero, L.F.; Arce A. (2017). Applying Value Stream Mapping in Manufacturing: A Systematic Literature Review

    It demonstrated VSM's applicability beyond automotive and quantified its impact, noting *lead time reduction* across 120 studies. It identified *waiting time*, *excess inventory*, and *overproduction* as the most targeted waste, with over-processing being neglected. It also revealed that 62.5% of studies combined VSM with non-lean tools (e.g., discrete-event simulation), enhancing dynamic workflow analysis. It finally highlighted the need for *future-state mapping* to avoid incomplete lean transitions.

13. Thomassen, M.K.; Alfnes, E.; Gran, E.(2015). A New Value Stream Mapping Approach for Engineer-to-Order Production Systems.

    The paper addressed the limitations of traditional VSM in ETO systems, where high customization, non-repetitive processes, and complex product structures hinder lean implementation. It proposed an 11-step adapted VSM framework specifically for ETO environments. Key contributions include Integrating Customer Order Decoupling Point (CODP) analysis into both current and future-state mapping to optimize lead times, introducing temporized Bill of Materials (BOM) to identify critical paths and shared resources, advising average takt time over rigid takt, within others.

3.4 Description of Selected Works

Recent Advances in Lean Techniques for Discrete Manufacturing Companies by Yang et al. (2025):

This paper conducts a systematic literature review over 369 journal articles to address lean technology applications and implementation strategies within discrete manufacturing companies. Its aims to summarize existing lean manufacturing technologies and methods, propose a revised theoretical framework covering VSM in discrete manufacturing, and predict future trends for SMEs.

It proposes a *5P* meta-framework, Philosophy, Process, People, Problem-Solving and Product to integrate lean tools with Industry 4.0 in discrete-item factories. A multi-stage data-analytics pipeline (bibliometric search, keyword co-occurrence, cluster analysis) results in nine technology clusters going from AI-enabled JIT to AR-supported training. The authors distil six strategic recommendations for small and medium-sized enterprises (SMEs) including lean management mechanisms and sustainable lean paradigms. While the company considered for the case study is not a pure discrete manufacturer, the *5P* canvas offers an umbrella under which we can position a mixed-portfolio strategy.

Implementation of Lean Manufacturing in a Small and Medium Enterprise using Value Stream Mapping (2024)

This study aims to demonstrate the application of VSM to reduce waste and improve efficiency in an SME manufacturing thermos-mechanically-treated steel bars. The primary goal is to minimize lead time by eliminating NVA activities through a structured VSM approach.

The methodology initially develops a current state VSM using data collected via site visits and document analysis. KPIs include cycle time, changeover time, inventory levels, and takt time. The future state VSM proposes exclusive raw material usage to reduce furnace lead time, and worker redistribution for simultaneous operations. As a result, it was obtained a significant reduction in total lead time, and a marginal decrease in processing time.
This paper strongly aligns with the scope of this thesis, as it prioritizes low-cost organizational changes over technological upgrades, which in this work will not be the focus but rather a second level suggestion for improvement.

A Review of the High-Mix-Low-Volume Manufacturing Industry by Gan et al. (2023)

Surveying 152 publications from 2000-2022, the authors map research trends in High-Mix/Low-Volume (HMLV) manufacturing. A structured methodology of six-step is employed, including database searches, co-citation clustering, and keyword co-occurrence analysis. The study categorizes works by industrial sectors, research focus, and validation methods.

The results show that most academic work gravitates toward production-planning algorithms and digital decision support in electronics and semiconductor sectors, though it is evolving to Industry 4.0-driven decision support systems. An identifiable gap was that, while most of the study addressed semiconductors, electronics and other non-industry-specific challenges, downstream processes were underexplored. Also, only 40% of proposed models underwent industrial testing, leaving opportunity for further exploration. This review is valuable because it frames research opportunity for hybrid plants where standard product lines coexist with smaller engineered orders.

Leanness Assessment of a Complex Assembly Line Using Integrated VSM by Sangwa & Sangwan (2023):

Combining Gemba walks, classical process mapping and an integrated VSM, the authors tackle an assembly line with only 59 % product similarity. The objective was to overcome traditional VSM limitation in complex environments (merging flows, multiple products, low similarity), simultaneously map material/information flows, wastes and performance metrics for products on a single VSM, and reduce cycle time, non-value-added (NVA) activities, as well as WIP inventory while improving efficiency.

The methodology consisted of a case study carried out in an Indian automotive components plant. The team involved executed Gemba walks and 5W analysis to identify problems. The process can be summarized in four steps, current state VSM development, weaknesses analysis, future state VSM design, and layout redesign.
The case is a compelling proof that VSM can succeed when product variety is high, very much the scenario this study is going to face. The methodology offers a repeatable roadmap for handling low-similarity flows, though it concentrates on assembly rather than machining. The outcome resulted in cycle time reduction, WIP inventory reduction, increase in line efficiency, distance travelled reduction, and customer demand met.

Even though the case study is confined to a single complex assembly line within the automotive industry, its core contribution (the Integrated VSM framework) is directly relevant for addressing the challenge of mapping and improving lines with multiple, low-similarity products, a common scenario in modern manufacturing.

A Decade of Engineering-to-Order (2010-2020): Progress and Emerging Themes by Cannas & Gosling (2021):

This systematic literature review (SLR) aims to synthesize and evaluate progress in Engineer-to-Order (ETO) supply chain management research between 2010 and 2020. It looks for the identification of emerging themes, major advances, and methodological changes within the ETO environment, thus, establishing a structured agenda for future research.

The paper examinations focused on supply-chain structures, the maturing two-dimensional customer-order decoupling point (CODP), and digital-lean synergy. As a result, the paper shows that progress was made in conceptualizing engineering flows, decoupling points and ETO archetypes. Also, the emergence of new themes was noted, such as risk management, industry 4.0, design automation, and others.

Regarding Lean/Agile in ETO settings, the focus leaned towards defining and applying lean tools tailored for each ETO complexity. Little connection was made between lean practices and specific ETO decoupling configurations. Future research agenda in this frontier could continue looking for a more flexible adaptation of lean tools as generic and useful as possible.

VSM in a Metallurgical Job-Shop with Wide Part Range by Ariane Ferreira Porto Rosa et al. (2021)

This paper analyzes the production system of a metallurgical industry from a Lean Manufacturing perspective to identify and eliminate waste. It addresses the challenge of applying VSM to complex product families with a wide range of parts manufactured in parallel. The main goal was to develop a methodology integrating Process Mapping (PM) and VSM to visualize, analyze and improve such systems, proposing future improvements. The study proposed a four-stage methodology consisting of exploratory visit, literature review, case study (executed via an 8-step roadmap) and the analysis of the results.

In the end, the integrated PM and VSM approach successfully identified significant wastes across the complex production flow. The future state VSM proposed key lean transformations were translated into three main action plans, product redesign, kanban system implementation, and FIFO system implementation. Moreover, the paper demonstrated the feasibility and effectiveness of combining PM and grouping parts into logical sets for VSM application in high-variety, parallel-process environments, overcoming a key limitation of traditional VSM.

Lean Indicators for Small-Batch-Size Manufacturers in High-Cost Countries by Adlin et al. (2020):

Responding to the scarcity of performance measurements and the lack of tailored frameworks for small batch size manufacturing (SBSM) firms in high-cost countries, the authors construct a Lean Manufacturing Reference Framework (LMRF) that integrates product and production development. While Lean Manufacturing (LM) principles are well established for mass production, SBSM contexts face unique challenges that represent an obstacle for the success of lean implementation.

A SLR was carried out using a generic LM framework with four domains, Continuous Learning, Development Process, Principles, and Practices. As a result, it was found that all generic LM bundles apply to SBSMs but require significant adaptation. Regarding the specific steps of the framework, customize improvement routines are needed, policy deployment must integrate product/production development, value includes value creation alongside value capture, and LM practices must be combined with non-LM methods.

Extending Lean Frontiers: A Kaizen Case in an Italian MTO Company by **Rossini et al. (2019):**

This research project demonstrates how an A3-driven Kaizen framework paired with a RACI matrix yielded a 10% production cost reduction and on-time delivery's significant improvement. The contribution lies in formalizing a rapid improvement event specifically suited to MTO complexity.

Its primary goal is to propose and validate a novel, structured framework for guiding kaizen events in such complex settings and demonstrate its effectiveness through a real-world case study. For this, the research adopts a single case study methodology, conducted at the Italian plant of Ingersoll rand. The core methodology implies the application of a newly developed kaizen framework. It defines four macro-phases (planning, pre-event work, event, post-event work), assigning specific roles and responsibilities using a RACI matrix (Responsible, Accountable, Consulted, Informed).

An important feature of this study is the combination of several Lean tools such as the A3 Problem-solving report, VSM, SIPOC analysis, Ishikawa diagrams, cycle time analysis, and others.

Given the depth of the analysis and the work done, the project yielded significant operational and financial improvements for the company. A 10% reduction in assembly hours for the targeted product family, plan attainment improvement from 70% to 95%, and the lowering of WIP were just some of the most important gains.

The utility of this study relies on the experience acquired while adapting lean/kaizen principles to complex, non-mass-production environments.

Applying Value Stream Mapping in Manufacturing: A Systematic Literature Review by L. F. Romero & A. Arce (2017):

Targeting the evolution of Value Stream Mapping (VSM) from 1990 to approximately 2016, the authors classified 155 articles by scope, map-granularity and digital enhancement. Using PRISMA filtering plus qualitative content analysis, the study classifies papers by methodology and industry context, emphasizing practical implementation challenges.

As a result, it was found that Europe led the research output (45%), while Asia showed recent growth. Over 60% of studies applied VSM in medium-automation environments. Also, the most targeted wastes were waiting time, excess inventory and overproduction respectively, while lead time reduction averaged 52.3% across cases. Moreover, 44% of the cases combined VSM with other lean tools, while 62.5% used non-lean tools like discrete-event simulation. This review strengthens the methodological base for this thesis by confirming that multi-product and digitally aided VSM, are legitimate yet still under-explored research options.

A New VSM Approach for Engineer-to-Order Production Systems by Thomassen et al. (2015):

This paper addresses the significant challenges faced by ETO manufacturers when implementing lean principles, especially due to high product customization, non-repetitive processes, and complex value streams. The goal is to develop an adapted VSM methodology specifically tailored for ETO environments, focusing on three core limitations, its inability to handle intertwined routings and complex product structures, its lack of adequate techniques for customization, and its insufficient treatment of the Customer Order Decoupling Point (CODP) positioning.

The methodology consists in the combination of literature reviews of existing lean adaptations for HMLV and MTO environments with iterative case study validation. The insights from the analysis were synthesized and refined over two years through interactive discussions and testing within a Norwegian manufacturer of heavy ship equipment. Data collection included quantitative operational metrics, process routings, bill of materials (BOM) analysis, and lead time measurements, supported by active engagement with company representatives.

This work aligns almost perfectly with the thesis's focus on adapting lean methodologies for complex settings. Nevertheless, the thesis scenario is a mixed scenario of ETO with a good proportion of standard product streams.

3.5 Discussion and Research Gap

Recent reviews converge on a clear view: Value Stream Mapping (VSM) is the dominant first-step diagnostic for visualizing material and information flow, exposing queues and inventories, and structuring lean improvements across industries (Romero & Arce, 2017). In HMLV settings, a comprehensive survey of the field shows research concentrating on production-planning and decision-support topics, often with limited industrial validation outside electronics/semiconductors, while downstream operations receive comparatively less attention (Gan, Musa, & Yap, 2023). Measurement also remains a pain point; small-batch/high-variety contexts frequently require tailored indicators to track the impact of lean changes over time, a gap addressed by proposals for context-specific "lean indicators" for small-batch manufacturers (Adlin, Nylund, Lanz, Lehtonen, & Juut, 2020).

Thus, there is a growing push toward a digital/hybrid VSM, some papers even emphasizing digital twins, discrete-event simulation and VR-supported VSM (Romero & Arce, 2017; Yang, Fu, Zhu, & Lv, 2025).

While works for ETO, MTO and HMLV contexts are still new, rigorously measured data is still needed (Thomassen, Alfnes, & Gran, 2015; Cannas & Gosling, 2021).

As of the gaps left by the literature, although traditional VSM is a mature visual technique, executable maps are still rare, especially for high-mix settings. Also, researchers almost never use simulation models that link the map to lead-time, WIP or other KPIs before any physical change is made, the issue being more significant the more complex the environment gets. Finally, given the budget constraint that most SMEs face, managers tend to be reluctant to invest time implementing changes because of the lack of data-driven tools to support their decisions.

Thus, the present thesis is designed to address some of these gaps, especially testing until what point the classical method can work inside an HMLV metal-working environment. A priori, a full current-state map will be drawn on the shop floor, and the data will be collected manually, highlighting every difficulty faced during this process. A software for simulation will allow us to visualize how the future VSM will look like, and the outcome will be a step-by-step recommendation that other researchers or practitioners of lean tools in similar HMLV contexts can follow before investing in any other more experimental-approach project.

To recapitulate, there is a strong consensus of VSM as a visualization and diagnostic tool, and this work will help in the development of a simulated adaptation to a specific HMLV environment to study its impact on the improvement of the process performance.

4. Methodological framework

Building on prior studies, this thesis consolidates existing VSM adaptations into a structured five-phase process. This framework is not presented as a new methodology, but as an operationalization of approaches already tested in other contexts. The originality lies in their application to a small HMLV enterprise.

As for the scope of this work, in the focal company the ETO share is minor and is not analyzed. Accordingly, this thesis concentrates on the dominant non-ETO HMLV flows and references ETO only to clarify boundaries. Decoupling-point and design-engineering issues are therefore out of scope as well.

4.1 Introduction to the Adaptive VSM methodology

Value Stream Mapping is a critical tool within the lean manufacturing approach, used to identify and eliminate non-value-added activities and waste in a production process, and to this end, it aims to increase the understanding of the workflow (Romero & Arce, 2017).

It is also well established that while VSM is highly effective in high-volume, low-mix production, traditional VSM still struggles in more complex settings due to non-repetitive processes and intertwined routings. HMLV environments are characterized by high degree of customization, small batch sizes, varied product routings, and cycle time variability.

Even though there have been case studies exploring specific scenarios to bridge the gap identified, providing a structured, adaptable approach to VSM for HMLV environments help to enrich this amalgama of cases to the point that future literature reviews can better characterize the tools and methodologies, pointing to a somehow more standardized yet flexible way of developing VSMs for companies with similar scenarios. Thus, this study is structured into five phases, reflecting adaptations reported in the literature.

Figure 11- Framework Overview

4.2 Phase I: Preliminary Scoping and Product Family Grouping

As has been seen by Thomassen et al., product family definition is very important to narrow down the scope of the VSM. In order to better understand the market's behavior, it is important to understand the historical behavior of orders arrived, for which information from the previous year selling data will be used.

If available, an important aspect to consider will be the relationship between high volume and high revenue, since this will determine the prioritization of the VSM to be developed.

As the following step, a process map for each type of product will be developed. This will be done using a simple flow chart scheme since it is just to help us understand the complexity of each product. Nonetheless, it will further allow us to rethink some aspects of the production in terms of the organization of the layout or even question the steps of the process itself.

After understanding the extent to which the proportion of each type of product impacts the production planning, the development of a product-process matrix will be elaborated, so to understand the commonalities that products share with each other. It is expected that after this step, items with similar paths will be grouped together to be treated similarly, though the level of process commonalities required will be assessed later in the specific scenario.

Thus, the deliverables for this phase will be the production proportion for each kind of model, which will be closely related to the demand of each product, and a process matrix to show commonalities between models in terms of the steps to be produced.

Process / Product	Process 1	Process 2	Process 3	Process 4
Product a	X	X	X	X
Product b	X		X	X
Product c		X	X	X
Product d	X	X		X
Product e	X	X	X	X

Figure 12- Process matrix example

4.3 Phase II: Current State Value Stream Mapp

This phase focuses on visually representing the current state of operations to identify inefficiencies. The current state map depicts how value is created and identifies all activities needed to transform raw materials into final goods.

The mapping will account for parallel and merging flows, which often characterize complex assembly lines. The need to highlight the push systems employment is also mentioned in the literature, since it can lead to losses.

Multi-machine activities operated by a single operator will be considered a work cell to simplify complex material/information flow, given that the number of operators is less than the number of processes. It is important to note that Value Stream Mapping does not prescribe an ideal number of operators; rather, operator allocation is determined by the relationship between takt time and process cycle times (Rother & Shook, 1999; Liker, 2004). In high-mix, low-volume environments, operators frequently perform multiple-machine activities, a strategy highlighted by Thomassen et al. (2015) and Sangwa and Sangwan (2023) as a means of increasing flexibility and balancing workloads. Accordingly, the decision to structure the VSM with eight operators is not presented as a universal staffing rule but as a reasonable adaptation to the company's current resources, consistent with lean theory that prioritizes alignment with takt time and flexible work distribution

The next step will consist in the collection of data, which is a fundamental aspect of the work for an effective VSM. To execute it, different mechanisms can be put in place, such as observations, interview with operators, current documentation analysis, etc. For this study in particular, *gemba walks* will be conducted as the main mechanism to identify problems from the shop floor perspective. It will also pave the way for future work to be executed by the company, as a result of this study, so that operators will be already familiar with the analysis that is being done. As for the kind of data to be collected, it has to be the ones needed to elaborate a well detailed value stream map, so cycle time, number of workers, available time, up time, etc.

Assumptions and approximations will be made to simplify the representation of complex activities or the lack of accuracy of specific information.

The deliverables for this phase will be a demand curve throughout a twelve-month period, the spaghetti maps for the most important models to be analyzed, the flowchart of the process for the chosen model with the corresponding motivations, and finally, the current state map of it.

4.4 Phase III: Waste Identification and Analysis

The first part of this phase focuses on the identification of what is considered waste in the process, also known as "muda". The term usually refers to activities that do not add value to the product, or ultimately, to the customer.

The main expected waste already addressed in the theoretical background of this thesis is related to transportation waste, large inventory, motion waste due to poor workstation design, waiting due to unbalanced lines, and defect waste due to rejections within others.

Once the wastes and problems associated with them are identified, the solutions are next in line to be addressed. For this step, it is essential to carry out root cause analysis activities.

Root cause investigations are usually performed with the help of skilled operators in order to gain internal perspective on what is not being done correctly, and the events that could eventually interfere with the development of the new solution. Sometimes, external consultants can also be of great help observing non-value-adding activities and solving problems overall, since they usually have a broader view of the business and are exposed and familiar with many different scenarios in the industry. A tool commonly used for this phase is the 5W form, a simple 5-step-question form that guides the person doing the analysis to the root cause of the problem.

Another way of approaching root cause analysis is by grouping team members and having brainstorming sessions where they can express themselves, discuss the issue and even come up with the potential solutions to the problem.

This root cause analysis approach is meant to help eliminate problems from the source of its generation, and also build solutions that are actually effective, not just based on suppositions.

All in all, this phase is expected to deliver on the identification of waste analyzed in each workstation, and the corresponding analysis related to the cause of these problems.

4.5 Phase IV: Future State Design

In this phase, solutions are proposed and validated virtually before implementation. The future state VSM is developed by removing non-value-added activities from the current VSM to create a more continuous flow. This could involve designing mixed-model assembly lines to handle different types or configuration of products, reducing waiting times caused by production in big batches, and making the system more responsive to customer demand for different products.

Different lean tools will be evaluated to use, like Just-in-Time approaches, Kanban systems for pull-based production, and establishing standard work instructions, etc.

Another important assessment to be considered will be product design alteration, which can eliminate unnecessary processes, reduce material waste, and decrease cycle time.

Layout modification through the rearranging of machines is also a popular way of reducing waste related to transportation, minimizing cross-movements.

The deliverable expected in this phase is the future state map plus the action log to implemented, as well as the newly calculated KPIs.

4.6 Phase V: Execution

Even though once the opportunities in the current VSM can be implemented with not much bureaucracy, it is recommended to use alongside some other lean tools to optimize the outcomes. Tools like 5S, kaizen events, problem-solving, and other tools must be considered to maximize the benefits of the improvement process. Another very important aspect is the involvement of operators and other stakeholders, as part of a broader cultural shift toward a continuous improvement mindset.

Improvements are usually divided into short-term (0-3 months) and long-term (up to 1 year) phases. Short-term improvements usually focus on quick-wins and local or individual workstations, while long-term improvements go for more structural aspects and can also include cultural/mindset change.

At the beginning, it is very important that all stakeholders are trained in lean concepts so that everybody understands the process that the company is going to go through. Kaizen events are a very useful tool, especially at the beginning of the lean transformation process.

Kaizen event is a short-term, focused improvement effort to rapidly improve a specific process or area. It consists of several steps that are sequentially executed and last a couple of days. Generally, the steps include training to learn about lean principles, going to the actual place of work to observe the process (Gemba walks), mapping the current process, identifying the waste, analyzing the root cause of the problems, proposing and executing the solutions along with the standardization of the process. It is expected that the action plan will be updated after this event.

The long-term phase is actually the next step of the Kaizen activity, which implies a follow-up of the action plan and the planification of other Kaizen events if the company sees it necessary. Also, continuous monitoring of key performance indicators (KPI) is critical for sustaining improvements. These KPI can be the standard ones like cycle time reduction, decrease in WIP inventory, or others that are used in particular in the process.

The deliverable for this phase consists in the measurement of WIP and takt time on the shop floor.

5. Results/Case study

This chapter will initiate with the introduction of the chosen business where the studied tool was implemented, a summary of how the business started and what it does. Afterwards, a detailed description of the implementation of the tool will be explained, following the steps laid out in the previous chapter.

5.1 The Company

This work was developed in a small metal-mechanic business whose name will be kept anonymous by the choice of the owner. The main activity performed is the manufacturing of diamond tools, specifically grinding wheels, specializing in both the glass and ceramics sectors.

Founded in 1975, the business was already an expanding company, navigating between the avant-garde of the time and the work of human hands. Now as ever, the company is committed to creating unique, tailor-made products.

The use of the latest technologies, essential for the manufacturing process, is perfectly combined with human action and supervision to obtain an optimal final product that meets the clients' needs.

Piece by piece, wheel by wheel, the company strengthens its business and its foundation for a better future, focused on expansion and continuous improvement.

It offers a varied production of diamond wheels for use in the glass and ceramic industries. It currently has approximately five standard models of wheels, with their respective variations in diameter and specifications tailored upon customer request. In addition to standardized products, orders can be placed for custom models, and existing models can even be adapted to suit the customer’s specific needs.

The company has eight operators distributed across approximately seventeen tasks. In addition to producing wheels, the company also acts as an intermediary for the sale of other products.

Figure 13- Grinding wheels

5.2 Phase I: Preliminary Scoping and Product Family Grouping

Diving deeper into the process from the customer’s request to the expedition of the product, the company offers a set of five families of products that are standard for the market, and account for more than 95% of the yearly production, while the other 5% represents engineer-to-order products that are required by customers with very specific characteristics. Even though the model is standard, in many cases the client specifies their needs, which in case does not comply with the standard product expected performance, is adjusted accordingly to perform optimally as the client expects it.

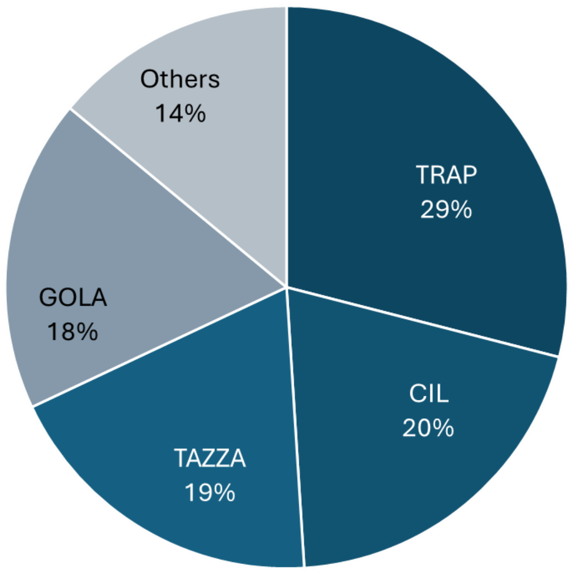

Figure 14- Proportion of production for each model

The products are grouped in five families: TRAP, CIL, TAZZA, GOLA, and Others. In "Others" are included some models with very few orders per year and also engineered-to-order kind of products. Apart from those, each of these products has their own path through the production process.

If the one-year period of sales behavior is considered in the Figure 14 and Figure 15, it can be seen that there are three product families that are sold almost in the same proportion, the TRAP, CIL and TAZZA models, and a little less but still important number of golas, with the blue columns showing the confirmed orders, and the light blue columns showing the orders that were already delivered. It can also be noticed that the biggest gap between both columns happens in the TRAP family, which already flags an issue to be considered later in the analysis.

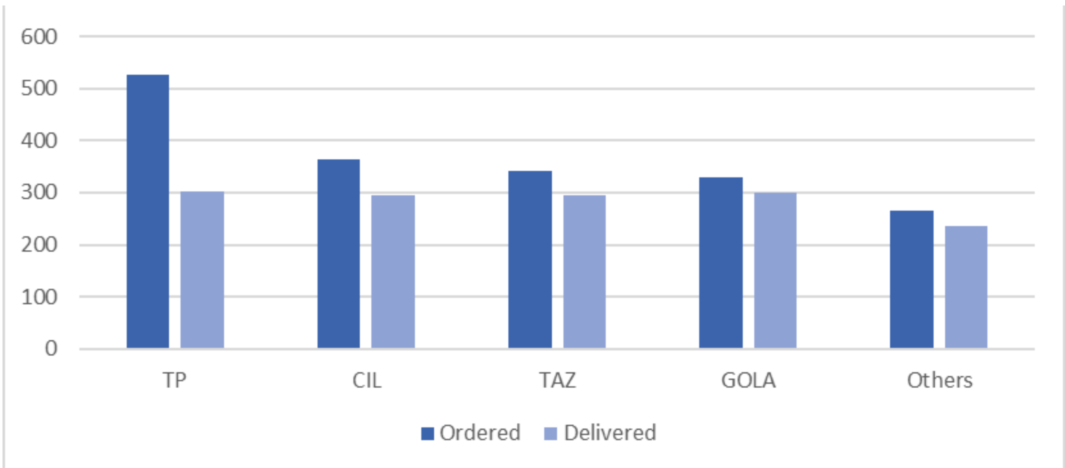

Figure 15- Demand per model

The production process contains many steps that are not always included in the production of each grinding wheel. In total, there are eighteen steps, from the stamping of the diamond ring to the delivery process.

It is important to notice that the families are named after the functionality of the diamond rings that are being manufactured. Another aspect to take into account is that the process path for some models changes after a certain diameter, for example, in the CIL family, diameters between 100 and 150 have a common path, while bigger diameters have another different path. Therefore, rather than limiting the analysis to four main groups, we will expand it to eight.

In the matrix presented in Figure 16, it will be displayed what processes are involved in the production flow of each product. Besides the TAZZA family, the rest share most of the steps. What is invisible in the matrix is the way the product goes back and forth in the process, causing a lot of inefficiencies in waiting time.

	Operations / **Products**	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Step 10	Step 11	Step 12	Step 13	Step 14	Step 15	Step 16	Sep 17	Step 18
Families	Diameter																		
TRAP	100-150	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X
	200	X	X	X	X		X		X	X			X	X	X	X	X	X	X
CIL	100-150	X	X	X	X			X	X		X	X		X	X	X	X	X	X
	200	X	X	X	X			X	X					X	X	X	X	X	X
TAZZA	-	X	X	X	X	X	X		X					X	X	X			X
GOLA	60-80	X		X	X				X					X	X	X	X	X	X
	100-175	X	X	X	X		X		X			X		X	X	X	X	X	X
	200	X	X	X	X		X		X					X	X	X	X	X	X

Figure 16- Process matrix

5.3 Phase II: Current State Value Stream Mapp

The layout shown in Figure 17 approximates the actual layout of the workshop, and as such it helps to depict a general idea of how the product flows physically. The process analysis of each product will be done considering that no big error was made so that the product must go back and be fixed (whenever fixable) in the previous processes.

Figure 17- Production process layout

The value stream map confection will be done with just a set of products that comply with certain criteria. The consideration will be based on the impact in Figure 14, the demand in Figure 15, the complexity of the process in terms of transportation, cycle time, and how it integrates some parts of the process of the other products.

With all the previous considerations, the TRAP family seems to be the most relevant in this case study. It concentrates the biggest production share, it has the most steps in the process, it is also the one that shares the highest affinity with the other processes.

Product	Steps	Affinity
TRAP100-150	16	-
TRAP200	14	88%
CIL100-150	12	75%
CIL200	11	69%
TAZZA	10	63%
G60-80	10	63%
G100-175	13	81%
G200	12	75%

Table 2- Affinity table for the TRAP 100-150

Thus, TRAP with its two different diameters remains the product family selected for the analysis. However, since the smaller-diameter model includes more steps and encompasses all the steps of the larger-diameter model, the analysis will focus on the TRAP 100–150 variant.

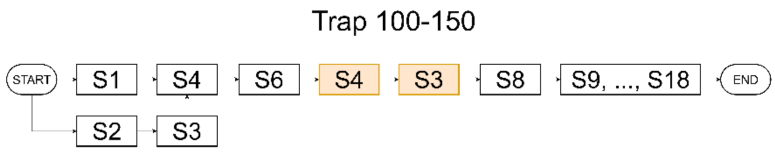

Figure 18- Flow chart of the process for model Trap 100-150

Figure 18 shows the flowchart of the product type TRAP 100-150, highlighting S4 and S3 as concurring processes where the product has to return. This back-and-forth movement can be better seen in the spaghetti diagram, and it becomes an issue as it implies waste of time, motion, it gets mixed up with the same products but in different stages, and all this considering it is just one product type.

It is important to notice that several Gemba walks were performed throughout the process as they were very helpful to identify waste in situ, hold conversations with operators and understand how the processes could be improved, and most importantly, reveal multiple back-and-forth flows that contribute to transportation waste. All these movements are illustrated in the spaghetti diagrams in Figure 19, 20, 21 and 22 for each family respectively, which overlays product travel paths onto the same layout.

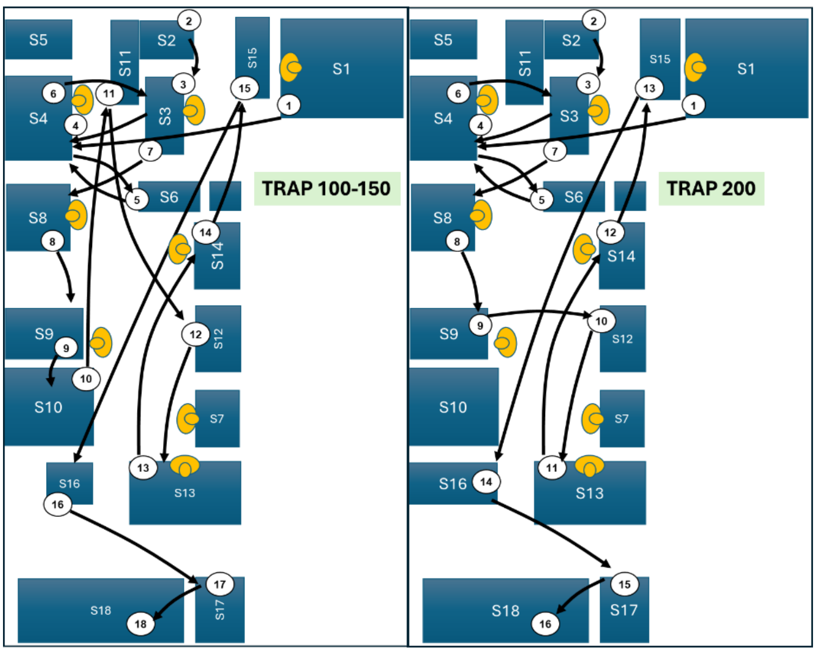

Figure 19- Spaghetti map for the Trap family

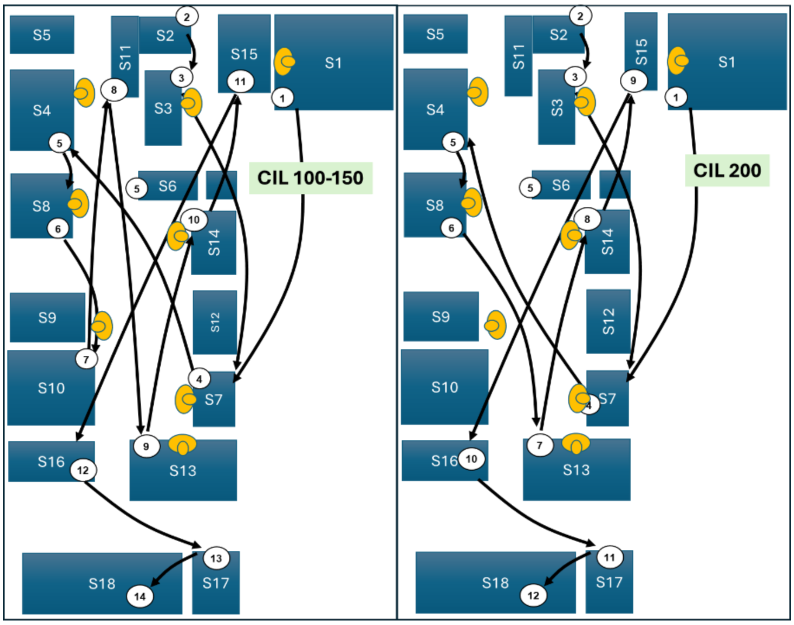

Figure 20- Spaghetti map for the CIL family

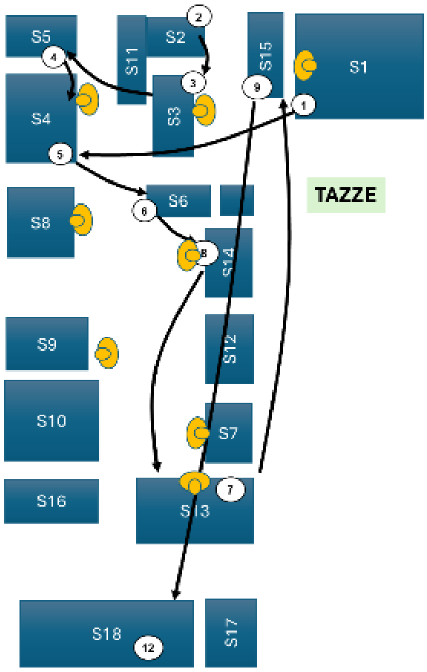

Figure 21- Spaghetti map for the Tazza family

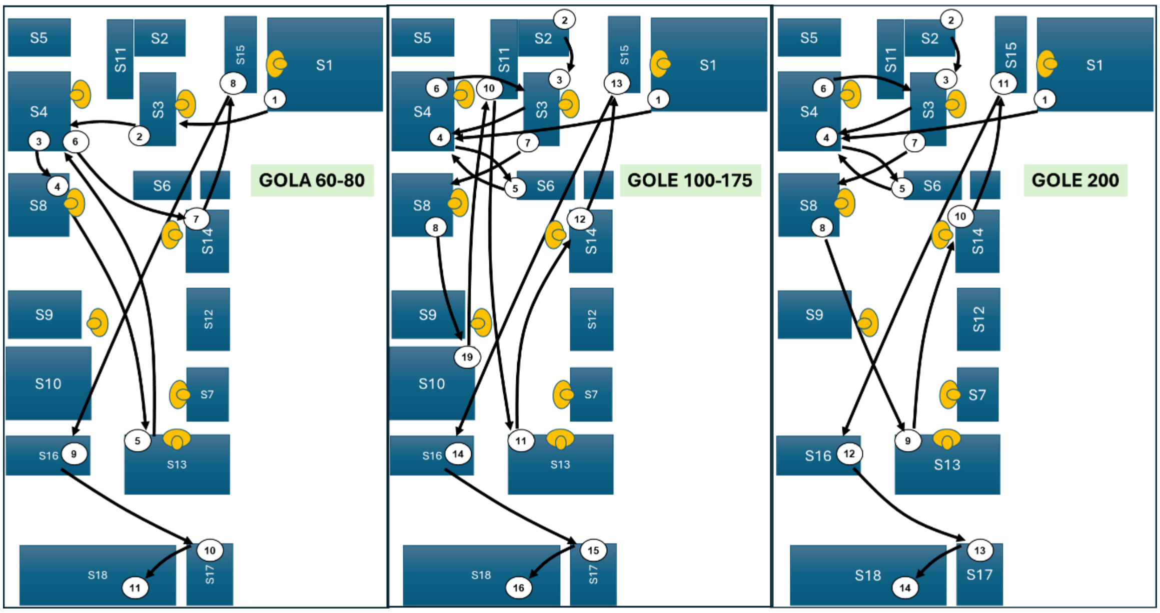

Figure 22- Spaghetti map for the Gola family

Additionally, since orders vary in the number of units requested, an average number of units per order will be used as a reference. For simplification purposes, this analysis will therefore be based on batches of six units each.

The most addressed performance indicators in the VSM are takt time and WIP. This last indicator was observed in the shop floor in several occasions, having approximately a mean of 7 batches in the whole process. The main processes beholding waiting batches were process 4, overloaded with other products going back and forth, as can be seen in the spaghetti map of the other family products, and process 12, which is the bottle neck of the process as will be seen later in the VSM.

In terms of the takt time, the demand curve in Figure 23 shows that in certain months the requests were higher than in others. Thus, it was better to consider the month with the higher demand as the one to determine the current takt time.

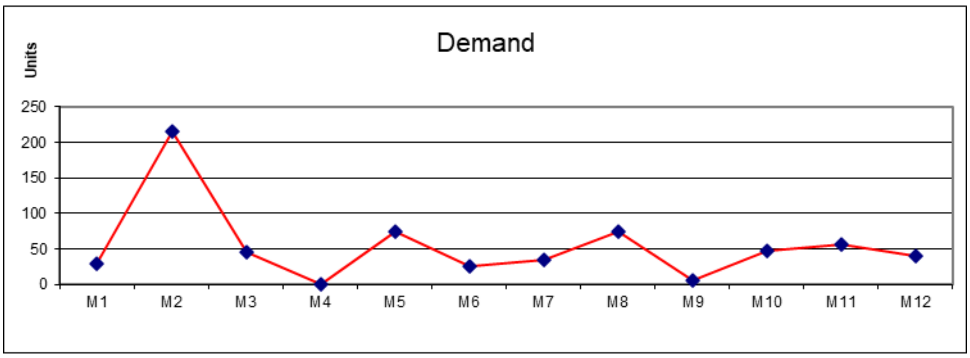

Figure 23- Demand curve over a 12-month period

Initially, the takt time for the TRAP product family was calculated following the conventional approach: dividing the net available production time by the average daily demand, as obtained from historical data. The demand curve showed that in certain months the requests were higher than in others, and as the difference between the high-demand month and the low-demand month was important, the high-demand month determined the monthly demand to calculate the takt time. This calculation resulted in a takt time of *1045* min per batch.

If the takt time were to be adjusted according to the month with the highest demand, its target value would be *263* min per batch. The problem that arises with this number has to do with the limitations given by the cycle time the processes.

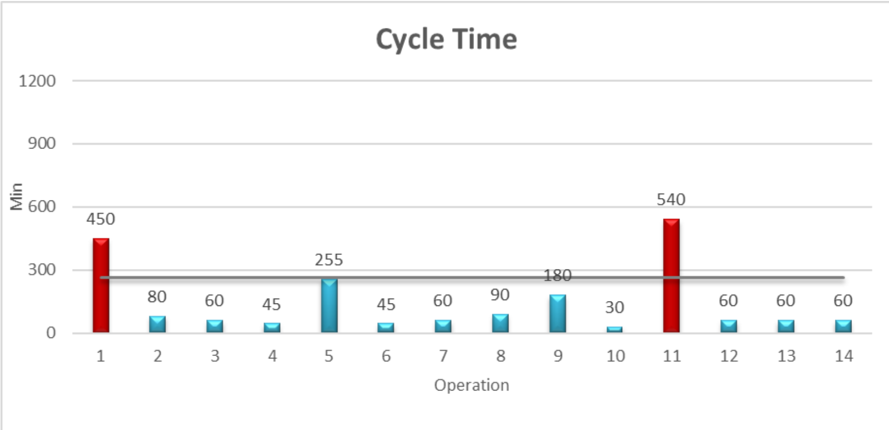

Figure 24- Cycle Time per Operation

Both processes in red in the Figure 24 are related to machine limitations to comply with the given target takt time.

However, discussing this indicator, it became evident that the company's strategic priority was not merely to meet historical demand, but to reduce lead times significantly in order to enhance responsiveness. In other words, the operational objective was to produce at a pace that would enable faster-than-expected delivery to customers, thus creating a competitive advantage.

To align the takt time with this goal, the decision was made to base the calculation on a target demand scenario rather than the historical demand. Specifically, a representative demand level was chosen, reflecting a higher throughput rate that the company aims to sustain in order to fulfil orders more quickly. This approach effectively sets a more demanding takt time, challenging the process design to support a faster production rhythm, but at the same time, complying with the current bottlenecks that solely depend on machine capacities.

This adjustment shifts takt time from a reactive metric to a proactive tool for driving process improvement. By attaching takt time to an aspirational demand level, the company ensures that improvement initiatives, such as layout optimization, waste elimination, and equipment upgrades, are guided by the need to achieve a lead time reduction beyond current customer expectations.

The representative demand was 17 batches per month, which represented a takt time value of 563 min per batch, practically half of what was initially calculated. This number was constraint by the process bottleneck, which is the located in the step 12, and its given by the machine's capacity.

It is worth mentioning that the company is foreseen to acquire a higher-capacity machine for process 12, which would eliminate the limitation for that step, becoming process 1 the new bottleneck of the process.

Finally, integrating process sequence, timing, WIP, and information flow, the current state value stream map (Figure 25) serves as the baseline for waste identification and improvement planning.

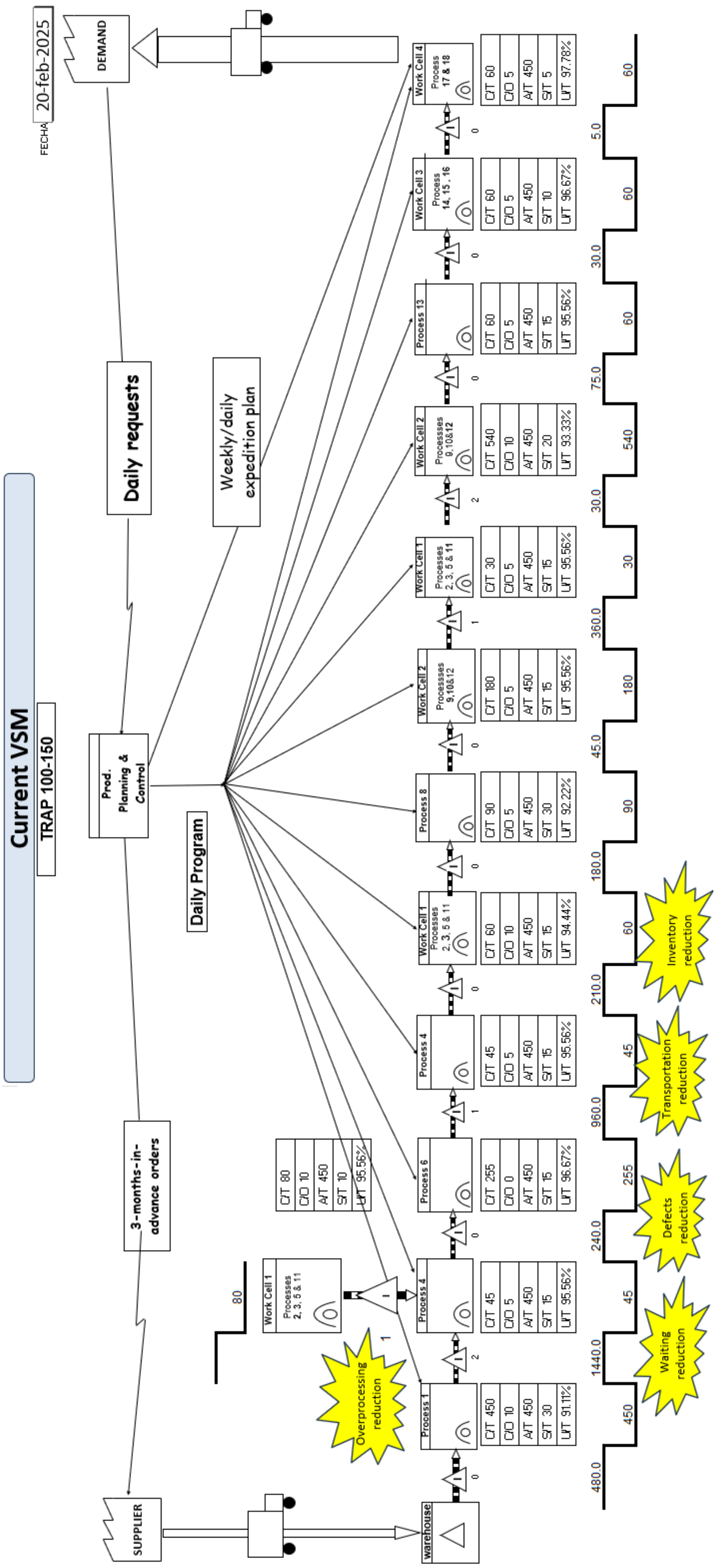

Figure 25– Current VSM

5.4 Phase III: Waste Identification and Analysis

Having the spaghetti map in mind (Figure 19), one of the first things to question was the constraints to rearrange the machines in order to have a layout that reflected the actual way the products flow and avoid moving products back and forth.

At the very beginning of the process, there is the warehouse that stores the raw materials, tools to adjust the machines, and other elements useful for the workshop. If the operator needed something from the warehouse, the time to get to the warehouse was negligible, but the time invested to search for tools or raw materials was significant, which led to the conclusion that standardizing the warehouse was an activity to be included in the to-do list of the improvement process.

In Process 1, the communication of the order plus the availability of the raw materials was observed to be somewhat adequate, however, there was an opportunity for better order and standardization, which was indeed confirmed by the engineering office as an issue causing further quality complaints upstream and even from customers. Thus, the main waste observed in process 1 was defects.

In the work cell 1, where processes 2 and 3 are performed, there was some level of inventory observed, although not much about the current product being studied. Also, an important waiting time was observed.

Process 4 was the step with the biggest inventory, accumulating many products in the workstation, many of them with an excessive waiting time, but ultimately this was subject to the priority put by the office in the daily program. It was also discussed that the work done in the machine of process 4 was feasible to be done in another equipment used in process 11, but the operator was not trained to that adaptation and was even reluctant to learn it. Here the eighth type of waste, underutilized talent can be observed.

Further analysis of the workstation and daily operation revealed that the delays were caused by products returning to the station after being processed in subsequent steps. In addition, the workstation was frequently burdened with “extra work” assigned by the office, such as tasks related to the design of other projected products and similar activities.

In process 6, much of the listed types of waste was not observed, but comments about customer complaints related to the performance of the work done in this step was made.

After process 6, there is a return to process 4 and then back to process 3 before moving to process 8. This path shows transportation waste and implies waiting time that was already seen at the moment of analyzing each workstation.

A potential future inefficiency was observed in process 8. Though the machine was performing normally, lately it has been facing mechanical problems that were addressed by the technician during weekends, but not having a maintenance schedule, it could potentially fail on weekdays and delay the production by a couple of days, considering the technicians availability is scarce.

In processes 9 and 10 much waste was not observed, but the return to work-cell 1 for process 11 seemed to add up to the waiting time of products in the work cell.

Process 12 is regarded as one of the most critical stages for the type of grinding wheel under analysis. It involves creating the profile of the diamond wheel which directly determines the final shape imparted to the glass. Here it was observed inventory waste, and important waiting time caused by different reasons, high cycle time, defects caused by errors during the machine setting, and the profile regeneration of the graphite electrode, which is used to grind the profile on the diamond wheel.

Moreover, a certain level of variability was identified regarding the output of the process in terms of the position of the profile in the grinding wheel. A difficulty pointed out by the operator was that, having two similar wheels, and doing the setting similar for both products, the outcome would be slightly different, sometimes impacting as a defect on the product that most of the time cannot be solved any further, the product being necessarily discarded. Comments from the operator and the supervisor pointed to a reliability problem with the machine itself.

For the rest of the steps, there was an opportunity to rearrange the machines so that the process could follow the natural process flow.

Overall, it was noticed a lot of disorder, with products of different characteristics mixed with one another, having the risk of confusing them and ultimately sending the client the wrong wheel. Tools were disorganized, causing search time and inefficiency. There was not either a routine to clean and organize the place, which was performed very occasionally, leaving room for accumulation of dust and all kinds of dirt in the workstations. Also, based on a scaled version of the workshop layout (Figure 19), the current flow requires the product to travel approximately 170 m from stamping to shipment, reflecting multiple back-and-forth transfers across workstations.

To summarize, with all the information gathered during the gemba walk, a fishbone diagram was built to display the main problem and the possible causes related to each aspect of the analysis. Circled in red are the most important causes to address according to the team.

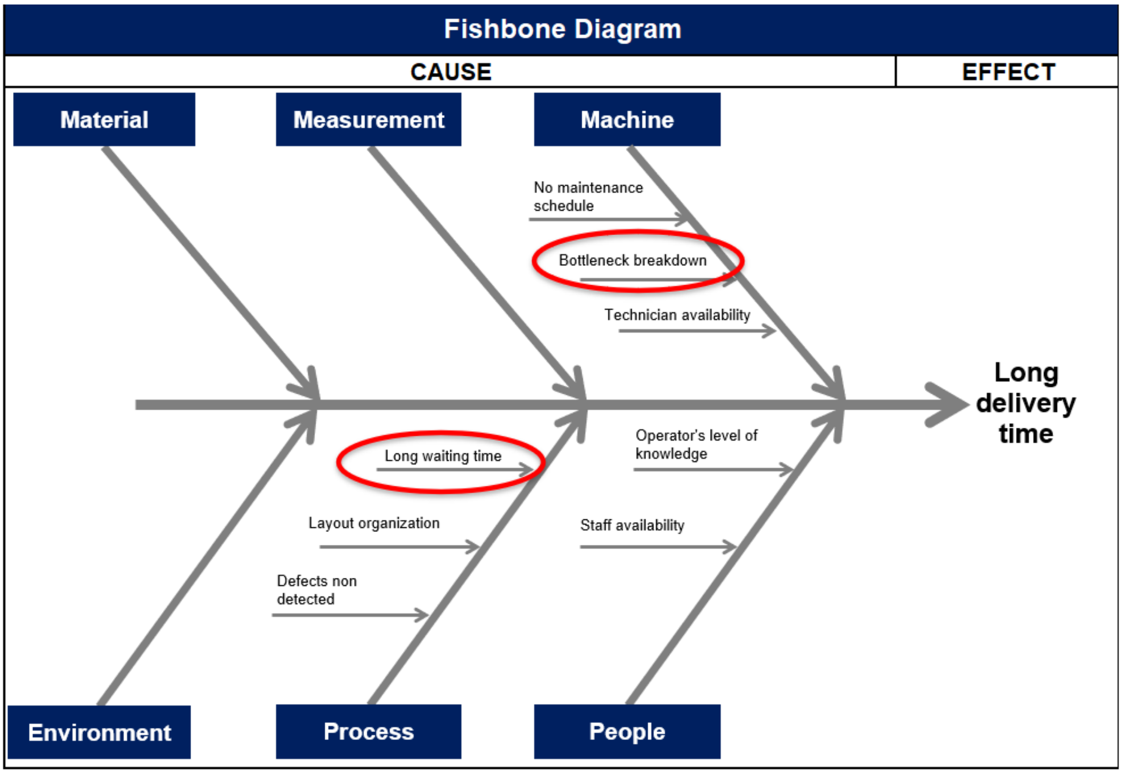

Figure 26- Fishbone Diagram Analysis

The next step of the problem solving roadmap indicates that a 5Why form must follow in order to identify the root cause of the problems and thus, design a solution that would address the problem efficiently and it does not get to repeat.

The "Bottleneck breakdown" problem was a technical problem for which the analysis was left for the technician to develop. The Long waiting time, instead, was performed by the engineering office, leaving a challenging outcome as a proposed solution, implying a simpler workflow to simplify the overall process.

5 Whys		
Identified problem	Long waiting time	
	Why?	Because
Why 1	*Many products in the queue?*	*Because the workstation is overloaded and cannot process products at the same pace they arrive*
Why 2	*Why is the WS overloaded?*	*Because products return to the same workstation multiple times*
Why 3	*Why do products return to the same workstation?*	*Because the workflow is not linear: some processes require rework, backtracking, and also "extra work"*
Why 4	*Why is the workflow not linear and generating rework and extra tasks?*	*Because the overall process has a very complex workflow, with back-and-forth movements*
Why 5		
Proposed Solution	Propose/design a simpler workflow	

Figure 27- 5Why analisis

For the rest of the issues identified, it was impertinent to apply 5S to as many workstations as possible.

5.5 Phase IV: Future State Design

As for the arrangement of the machines, Figure 17 shows that the equipment used for the first four processes is positioned very close together. Because these machines are large and space is limited, their rearrangement was not considered feasible without some civil modifications.

For the rest of the processes in the other area in the same figure, the machines could be somewhat rearranged and could be placed to go along with the process flow.

With respect to the analysis of the current state VSM, the goal was to address the waste identified in every step of the production process. As recommended in the previous section, 5S implementation is recommended to further facilitate the visualization of some other possible improvements. It could easily help to reduce the potential mixture of materials observed in process 1, the search of materials, and most importantly, reduce the risk of accidents caused by misplaced equipment or tool.

Moving on, the biggest challenge was to untangle the spaghetti map and organize the process between the steps 3 and 4. After the 5Why analysis, an alternative was foreseen that would shorten the process by eliminating some steps, simplifying the spaghetti diagram, reducing the lead time and ultimately improving the customer's satisfaction in terms of the delivery time.

The alternative implied the modification of one of the materials that made up the grinding wheel. This modification would have an impact on the weight of the product, the cost structure, and most importantly, would simplify the production process. In the VSM diagram, its implementation would mean the elimination of processes 2, 4 and 6, reducing inventory along the way.

The decision to produce this new version of the product would have an increase of approximately 10% on the cost structure of the product, but since the lead time was expected to significantly improve, the ability of the company to handle bigger numbers of orders would compensate for the cost difference. This new alternative was already produced in small numbers but needed further validation from customers in order to fully replace the current product version.

From process 8 it was observed that most machines did not have a maintenance schedule, which represented an opportunity to build a curated schedule where the technician could stop by periodically, have an assigned time to intervene the equipment, and ensure its normal operation during production times.

Processes 9, 10 and 12 exposed the need for operation standards when the process implies the utilization of such machines, and with respect to the reliability problem, it was mentioned that a project to acquire new machinery to improve the process was in order. This new machine would have an important reduction in cycle time, impacting significantly in the overall production time. This project would basically eliminate the process 12 as a bottleneck, translating the focus process 1 as the new determinant of the pace of production, and also into the other processes as they have to reduce inefficiencies as much as possible not to keep the new machine idle for so long.

From process 13 on, waste of motion was identified, and a rearrangement of the workstations was recommended to be implemented.

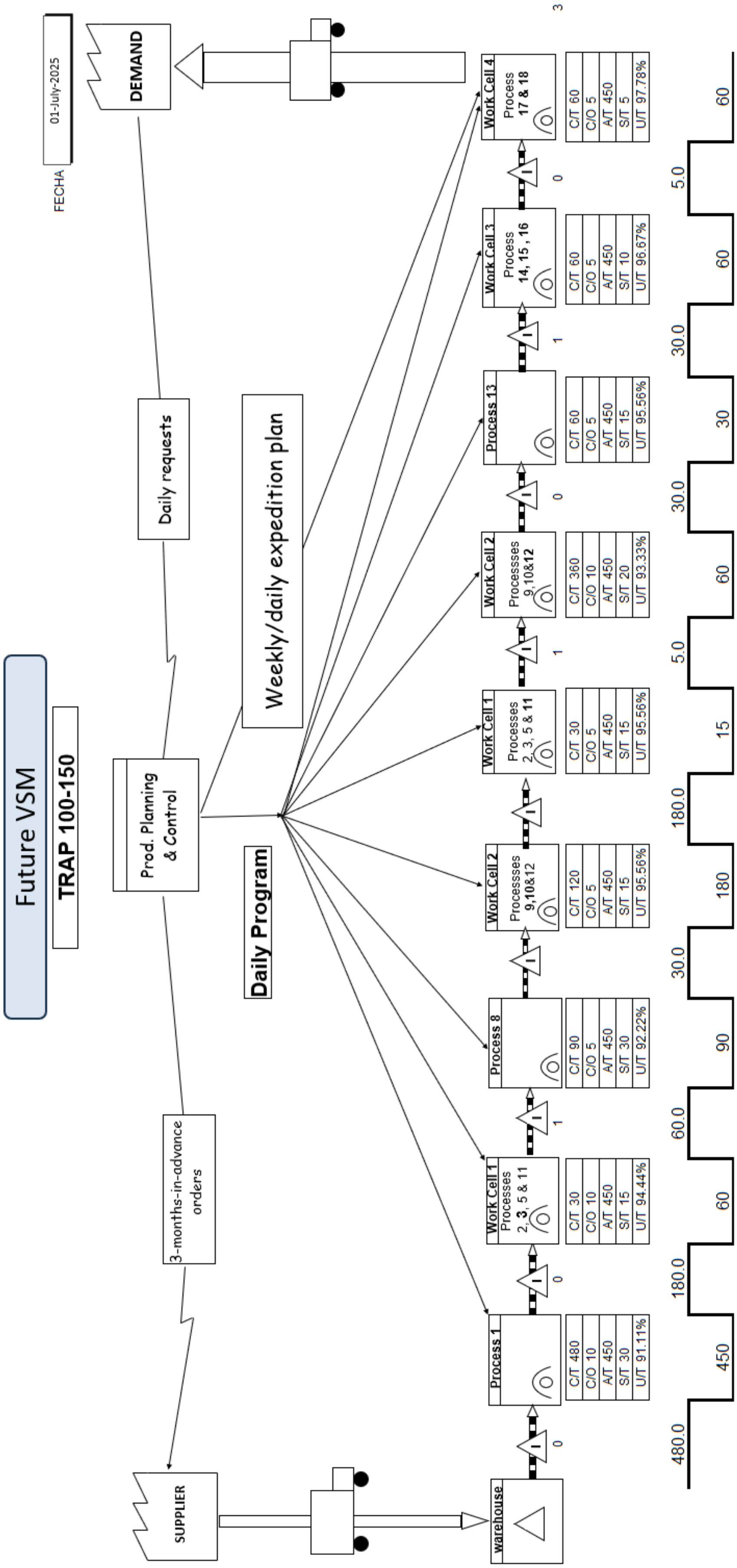

Figure 28– Future VSM

5.6 Phase V: Execution

The team invested four days to apply the 5S concepts, executing each step with the presence of a facilitator to support the team. They initiated with the classification of each and every thing they found in their workstations, separating the ones to be used on a regular basis, and putting aside the ones that were not frequently used, or were just not useful anymore. After deciding the useful things to remain in the workstation, they started to assign a specific place for every item. Later, the cleaning activity and some standardizations were done. Even though significant improvement was observed, some other 5S sessions are to be hold in the near future to raise the bar and enhance the standard.

From this point on, the execution will be separated in two stages. The first one pertains to the simplification of the process talked about in the previous section, which added a noticeable speed to the overall flow, improving inventory as well as reducing waiting time on process 4.

Figure 29 shows the new spaghetti map with a significant simplification of the flow and a reduction of roughly 40 meters in walking movement for the operator. With this single initiative, the lead time was taken down from more than 13 days to just 5 days.

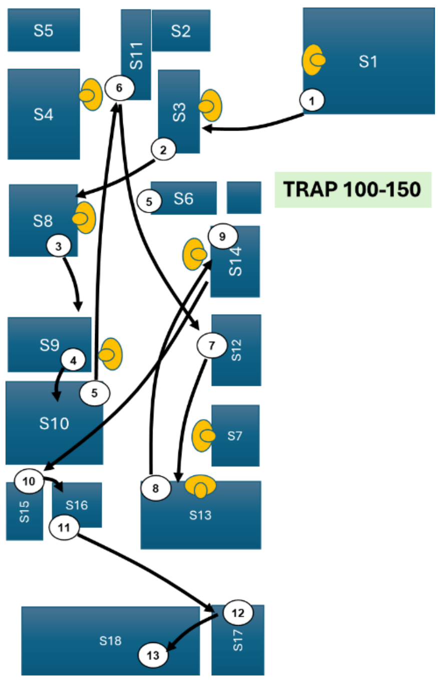

Figure 29- New spaghetti map after first modifications

Moreover, every machine on the shop floor started to have a maintenance schedule attached, so that its maintenance could be easily followed. For every process that contained machinery manually operated, an operator manual was written in order to make its usage more flexible and easier to learn and operate by other team members.

At a later stage, the company finally acquired new machinery to replace the one being used in the process 12, a very important step that has a significant impact on the delivery time but also in the quality of one of the most important aspects of the product, which is the electro-eroded profile. Taking advantage of the new machinery acquisition, a redesign of the layout was planned and executed so that the process flow could be reflected on the layout itself. This would address the waste related to transportation, and the risk of mixing products of different orders.

After the acquisition and analyzing the previous layout, some considerations were made and the equipment was organized as can be seen in Figure 29. Even though there are major improvements with respect to Figure 19, there is still room for improvement to disentangle even more the spaghetti diagram.

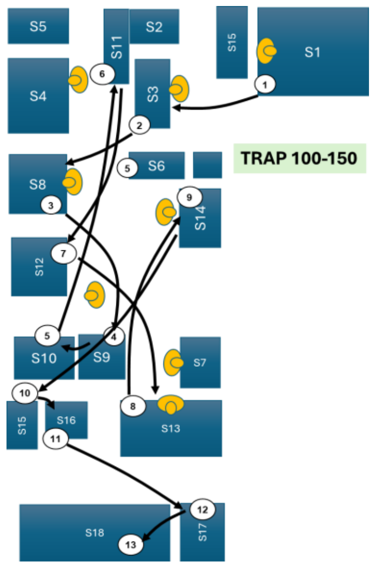

Figure 30- New spaghetti map after second modifications

Once the engineering office does the final modifications that were considered to leave the Figure 30 diagram the way it is, the recommendation made for the final layout for the shop floor is as the one shown in Figure 31.

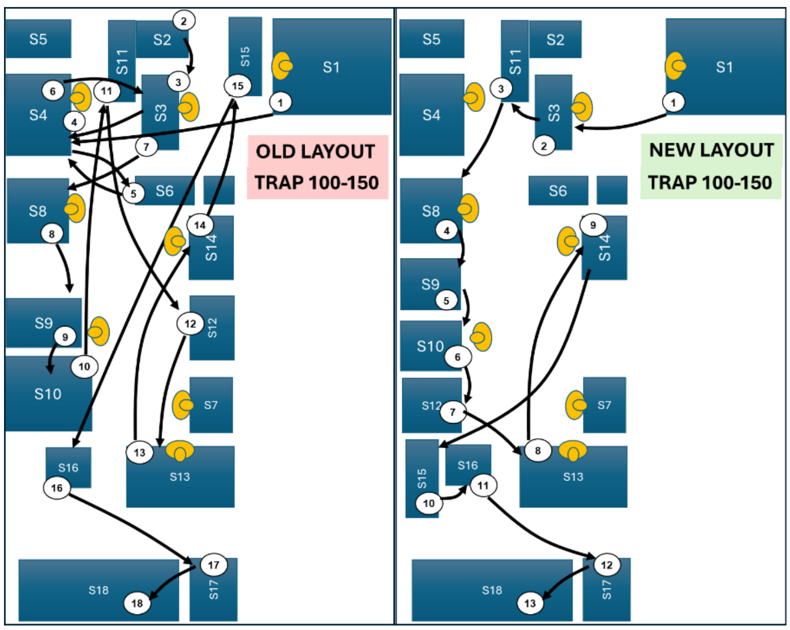

Figure 31- Old vs New spaghetti map after final modifications

In terms of the parameters, due to the early implementation phase, the preliminary improvements are shown in the table below. All indicators were significantly improved, firstly because of the simplification process and secondly because of the machine upgrade.

Even though these specific modifications are the ones responsible for the biggest changes in numbers, the other changes in 5S initiatives and work instruction standardization also have a less notorious or indirect impact, such as employee morale, safety, etc.

Key metric	Before	After	Saving
CT (min)	1874	1005	870
L (min)	5930	2005	3925
WIP (batches)	7	3	4
TAKT TIME (min)	1045	450	595
Distance (m)	170	125	45

Moreover, the improvements mentioned above only fully applied to the model TRAP100-150, which implies that the impacts on the other models are to be analyzed further.

6. Conclusions

This thesis set out to explore the adaptability of Value Stream Mapping in high-mix, low-volume manufacturing. The findings confirm that, although the tool was originally designed for repetitive production systems, it retains significant potential when applied with methodological adaptations. In the case company, VSM enabled a comprehensive visualization of material and information flows, making inefficiencies visible and guiding targeted improvement initiatives.

The results demonstrated that even in environments characterized by product variety and fluctuating demand, VSM can act as a strategic enabler of lean transformation when complemented with contextual adjustments.

Nevertheless, limitations remain. The dynamic nature of HMLV production implies that VSM alone cannot capture all variability or rapidly changing priorities. The execution phase also revealed that sustaining improvements requires a strong cultural commitment, particularly in SMEs with limited resources. Future research could focus on integrating digital tools, simulation models, and real-time data collection with VSM to strengthen its applicability in complex environments.

In conclusion, this work advances the discussion on lean in HMLV settings by showing that VSM, while imperfect, continues to be a powerful tool when reinterpreted to suit complex production realities. It offers both a critical reflection on its boundaries and a pathway for companies seeking to adapt lean methods to remain competitive in increasingly demanding markets.

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Appendix