

Operational Efficiency Improvement in the Production Process of Industrial Refrigeration Systems

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Abstract

Increasing production demands can lead manufacturing units to scale output without a corresponding adjustment to how their operations are organised, exposing inefficiencies that go unnoticed at lower volumes. Component retrieval, unnecessary handling and time-consuming manual procedures then become more evident, affecting the overall flow of production.

This is particularly significant in the production of industrial refrigeration units, a make-to-order process in which each unit progresses through a sequence of interdependent stages that demand close coordination between operators and the different stages of the process.

This dissertation focuses on the analysis and improvement of this production process, with the aim of reducing time-related inefficiencies and improving workplace organisation. To achieve this, two specific targets were defined: a 20% reduction in the time required for the preparation and separation of components and a 15% reduction in the time spent on non-value-adding activities.

Lean Manufacturing principles, particularly the 5S methodology, together with inventory management concepts, provided the theoretical basis for the work.

A detailed characterisation of the process, supported by direct observation and time studies, identified the main sources of inefficiency, namely an entirely manual, paper-based components list with no filtering mechanism, a disorganised shelving area shared by project components and stainless steel pipe fittings, a dispersed and untraceable stock of pipe clamps, and workstations lacking a defined organisational structure.

To address these issues, the components list was digitalised and restructured around a categorisation system, the material preparation and separation area was reorganised into fixed, labelled storage zones, and centralised storage solutions, supported by safety stock and box dimensioning, were designed for the pipe fittings and pipe clamps to improve their organisation and traceability. The 5S methodology was further applied to the welder's workstation and tool cart and to the pipe fitters' tool cart. Among these interventions, the digitalisation of the components list reduced the average separation and labelling time per component by 22.4%, while the storage reorganisation reduced the average material retrieval time by 54.9% and substantially decreased its variability, both results exceeding the targets initially defined.

Taken together, these improvements resulted in a more organised and efficient production process, illustrating how Lean Manufacturing and inventory management principles can be adapted to the constraints of a make-to-order, high-variability production environment. Consistent with the continuous improvement philosophy underlying these methodologies, the results obtained represent a starting point for further refinement, supporting the company's ongoing improvement efforts as production volumes increase and the process continues to evolve.

Resumo

O crescimento das exigências de produção pode conduzir as empresas a aumentar a sua atividade sem o correspondente ajuste na forma como as respetivas operações se encontram organizadas, expondo ineficiências que passam despercebidas a volumes de produção mais reduzidos. O tempo perdido na procura de materiais, as movimentações desnecessárias e as tarefas manuais demoradas tornam-se, então, mais evidentes, condicionando o fluxo global da produção.

Esta situação assume particular relevância na produção de centrais de refrigeração industriais, um processo *make-to-order* em que cada unidade passa por uma sequência de etapas interdependentes, exigindo uma coordenação rigorosa entre operadores e entre as diferentes fases do processo.

A presente dissertação foca-se na análise e na melhoria deste processo produtivo, com o objetivo de reduzir as ineficiências nos tempos de produção e de melhorar a organização do espaço de trabalho. Para tal, foram definidos dois objetivos específicos: uma redução de 20% no tempo necessário à preparação e separação de componentes, e uma redução de 15% no tempo dedicado a atividades sem valor acrescentado.

Os princípios de Lean Manufacturing, nomeadamente a metodologia 5S, associados a conceitos de gestão de inventário, constituíram o enquadramento teórico do projeto.

A caracterização detalhada do processo permitiu identificar as principais fontes de ineficiência: uma lista de componentes assente em documentação física, sem mecanismos de filtragem, uma área de separação desorganizada, utilizada simultaneamente para o armazenamento de componentes de projeto e de acessórios de tubagem em aço inoxidável, um stock disperso e sem rastreabilidade de abraçadeiras de tubagem e postos de trabalho sem um sistema de organização definido.

Para responder a estas limitações, a lista de componentes foi digitalizada e reestruturada, enquanto a área de preparação e separação de materiais foi reorganizada através da definição de zonas de armazenamento fixas. Foram ainda implementadas soluções de armazenamento centralizado para os acessórios de tubagem e abraçadeiras, suportadas pelo dimensionamento do stock de segurança e das respetivas caixas. Adicionalmente, a metodologia 5S foi aplicada aos postos de trabalho e aos carrinhos de ferramentas dos soldadores e tubistas.

Entre as intervenções implementadas, a digitalização da lista de componentes permitiu reduzir em 22,4% o tempo médio de separação por componente. Já a reorganização do armazenamento conduziu a uma redução de 54,9% no tempo médio de recolha de materiais, acompanhada por uma diminuição significativa da sua variabilidade. Em ambos os casos, os resultados obtidos superaram as metas inicialmente definidas.

Em termos gerais, as melhorias implementadas tornaram o processo produtivo mais organizado e eficiente, evidenciando a aplicabilidade dos princípios de Lean Manufacturing e de gestão de inventário num contexto *make-to-order* de elevada variabilidade. Em linha com a filosofia de melhoria contínua, os resultados obtidos constituem uma base para melhorias futuras, acompanhando a evolução da atividade produtiva e dos processos da empresa.

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"To improve is to change; to be perfect is to change often."

Winston Churchill

Contents

1	Introduction	1
1.1	Project Framework	1
1.2	Presentation of the company	1
1.3	Objectives	3
1.4	Methodology	3
1.5	Structure	4
2	Literature Review	7
2.1	Lean Manufacturing	7
2.1.1	Toyota Production System	8
2.1.2	Lean Principles	9
2.1.3	The seven wastes of Lean (Muda)	10
2.2	Lean Tools	11
2.2.1	5S Methodology	11
2.2.2	Visual Management	12
2.2.3	Gemba Walks	12
2.2.4	PDCA Cycle	12
2.2.5	Cause and Effect Diagram	13
2.2.6	5 Whys	14
2.2.7	Swimlane Diagrams	15
2.3	Inventory Management	15
2.3.1	Inventory Models	16
2.3.2	Safety Stock	20
2.3.3	ABC Analysis	21
3	Analysis of the Initial Situation	23
3.1	Description of the production process	23
3.1.1	Design	23
3.1.2	Preparation and Separation of components	24
3.1.3	Pipe prefabrication	24
3.1.4	Assembly	25
3.1.5	Finishing	25
3.2	Improvement Opportunities Identified	25
3.2.1	List of components	26
3.2.2	Bill of Materials per Spool	27
3.2.3	Material Preparation and Separation Station	27
3.2.4	Pipe fittings stock management	28
3.2.5	Pipe clamps stock management	30

4	Improvements Implemented	33
4.1	Filtered List of components	33
4.2	Material Preparation and Separation Area Reorganisation	35
4.3	Centralised Storage of Pipe fittings	37
4.4	Centralised Storage of Pipe clamps	43
4.4.1	Shelving Layout and Physical Implementation	48
4.5	Implementation of the 5S Methodology	49
4.5.1	Welder's Workstation and Tool Cart	49
4.5.2	Pipe fitters' Tool Cart	55
5	Analysis of Results	57
5.1	Impact of the Filtered List of Components	57
5.2	Impact of Material Retrieval Improvement	58
6	Conclusions and Future Work	61
6.1	Future Work	62
	References	65
A	P&ID Diagram	69
B	List of components	71
B.1	Before improvements	71
C	Ishikawa diagrams	73
C.1	Excessive time in the separation and labelling process	73
C.2	High variability and excessive time in material retrieval	74
D	Separation and Labelling Process: Time Study Observations	75
D.1	Before improvements	75
D.2	After improvements	76
E	Materials Retrieval: Time Study Observations	77
E.1	Before improvements	77
E.2	After improvements	78
F	Pipe Clamps: Material Flow and Management Process	79
G	Shelving Layout Options - Centralised Storage of Pipe Fittings	81
G.1	Second Option	82
G.2	Third Option	83
G.3	Fourth Option	84

Acronyms and Symbols

HVAC	Heating, Ventilation, and Air Conditioning
EOQ	Economic Order Quantity
JIT	Just-in-Time
KPI	Key Performance Indicator
LT	Lead Time
OUL	Order-Up-To Level
P&ID	Piping and Instrumentation Diagram
ROP	Reorder Point
SDG	Sustainable Development Goal
SKU	Stock Keeping Unit
SS	Safety Stock
TPS	Toyota Production System

List of Figures

1.1	Koolsys Organogram	2
2.1	Toyota Production System House	8
2.2	Ishikawa diagram [1]	13
2.3	Inventory level over time with reorder point (ROP). Adapted from [2].	18
3.1	2D drawing of a refrigeration unit	24
3.2	Initial state of the shelving area at the material preparation and separation station	28
3.3	Initial storage of pipe fittings	29
3.4	Initial storage of pipe clamps	31
4.1	Components list spreadsheet showing the category column	34
4.2	Components list filtered by a single control volume category	34
4.3	Components list showing the colour coding for labeled and missing components .	34
4.4	Magnetic labels applied to the shelving area	35
4.5	Improved layout of the shelving area	36
4.6	Reference dimensions used for volume estimation	40
4.7	Final shelving layout - centralised storage of pipe fittings	42
4.8	Centralised storage of pipe fittings - physical implementation	43
4.9	Implemented centralised pipe clamps storage	49
4.10	Initial state of the welder's workstation	50
4.11	Welder's workstation following the removal of unnecessary items	50
4.12	Initial storage condition of welding electrodes	51
4.13	Custom wire rack for welding electrodes	51
4.14	Fabricated support for electrode stubs	52
4.15	Initial storage condition of the angle grinder and consumables	52
4.16	Fabricated supports for angle grinder consumables and tool	53
4.17	Vertical support for the welding torch	53
4.18	Initial state of the welder's tool cart	54
4.19	Improved state of the welder's tool cart	54
4.20	Before and after of the welder's tool cart positioning	55
4.21	Initial state of the pipefitters' tool cart	55
4.22	Improved state of the pipe fitters' tool cart	56

List of Tables

3.1	Average results across the three observations of the separation and labelling process	26
3.2	Average search time grouped by number of components to retrieve	29
4.1	Number of SKUs per type	37
4.2	Sample of the base file - stainless steel pipe fittings	37
4.3	Safety stock quantities per model - 90° elbows	39
4.4	Standardised box sizes used in the centralised storage system	39
4.5	Volume estimation approach per fitting type	40
4.6	Reference dimensions and estimated unit volumes per fitting type and nominal diameter	41
4.7	Sample of box assignments for selected SKUs - SCH10 Tees	41
4.8	Pipe clamp size categories	44
4.9	Sub-component breakdown for two representative pipe clamp assembly variants .	44
4.10	Bin sizes used in the storage solution.	47
4.11	Unit volumes for plastic set bodies and base plates, by size category.	47
4.12	Sample of bin assignments for selected sub-components	48
5.1	Average results before and after implementation - separation and labelling process (per labelled component)	57
5.2	Comparison of material retrieval times before and after improvements	59

Chapter 1

Introduction

1.1 Project Framework

The rapid growth of companies leads to increasing pressure to meet tighter deadlines and higher production demands. In this context, scaling production without addressing underlying constraints can give rise to operational challenges throughout the production process.

As production volumes increase, these limitations within the system become more evident, particularly in activities that do not directly contribute to value creation, such as unnecessary movements, waiting periods, and difficulties in accessing materials. These factors lead to an inefficient use of time within daily operations and can negatively affect the overall flow of production. This challenge is particularly relevant in the production of industrial refrigeration units, where the assembly process involves a high number of components and interdependent stages. These aspects require effective coordination between operators to ensure the correct sequence of tasks and maintain the workflow.

Given this context, it becomes important to ensure that production processes are adequately structured and capable of responding to increased demand. As such, focusing on stages where time losses are more significant enables the identification of critical areas and supports the development of targeted improvement actions.

More specifically, this dissertation focuses on the analysis and improvement of a production process of refrigeration units using CO₂ technology within a growing industrial environment, aiming to reduce time waste and improve the overall organization of the workplace, thereby ensuring a more efficient use of time in production activities.

1.2 Presentation of the company

The SKK Group is a business group operating in the sectors of refrigeration, HVAC, and general building maintenance.

1.3 Objectives

From a general perspective, the purpose of this study is to enhance the operational performance of a refrigeration systems manufacturing unit, with a particular focus on reducing time-related inefficiencies in daily activities.

More specifically, this work focuses on achieving a 20% reduction in the time required for the preparation and separation of components, improving the efficiency of activities necessary to ensure the normal functioning of the production process.

In parallel, it seeks to reach a 15% reduction in the time allocated to non-value-added activities, such as component retrieval, equipment handling and other operational activities that do not contribute directly to the final product.

This involves identifying sources of waste within the process and implementing measures to eliminate or minimize them.

1.4 Methodology

Given the applied and interventional nature of this study, the research approach had to accommodate not only the analysis of the production process but also the implementation and evaluation of changes within it. The objectives were formulated as measurable reductions to be attained in a real operating environment, so the process had to be acted upon and not merely described. For this reason, the work follows an action research approach, conducted within an organisational setting and supported by a combination of qualitative and quantitative data.

Action research studies a system by taking part in it, so that understanding emerges from the changes introduced rather than from detached analysis of them. It proceeds through iterative cycles in which the context and purpose of the work are established, data are gathered and analysed, action is planned and implemented and outcomes are evaluated, each cycle informing the next. The intended result is twofold, namely a solution to a practical problem and a contribution to knowledge [4].

Alternative methodologies were considered. Within operations management, a case study approach is employed for the exploration of new topics, for theory building and for the testing and refinement of existing theory, in each instance examining a phenomenon within its real-world setting [5]. It is the preferred strategy under three conditions, namely that the research questions are of a "how" or "why" type, that little or no control is held over the events under study, and that the phenomenon under examination is contemporary [6]. The second condition is not met here. The objectives are stated as reductions to be achieved, which required the process to be deliberately altered rather than examined as found. A case study would have supported the characterisation of the existing inefficiencies, yet not the introduction of the improvement measures nor the measurement of their effect, which constitutes the core of the stated objectives. The nature of this approach is nevertheless retained here, since the work was carried out within one organisation and the findings are interpreted in the light of that specific context.

The PDCA cycle was likewise considered, given its prominence in Lean and quality management. Its stages correspond closely to those of the action research cycle, and the correspondence is not incidental, since action research is itself characterised in part as an approach to problem solving [4]. Conceived as a cycle for continuous improvement within organisations [7; 8], it governs how improvement is to be conducted, but not how evidence is to be gathered and validated or how the outcome is to be related to existing knowledge. It was therefore applied at the level of the individual improvement actions, within the broader action research design, rather than as the methodological framework of the dissertation itself.

In accordance with the methodology selected, the approach began with a direct observation of the production process, in order to identify the stages where time losses were more pronounced. Based on this analysis, the most relevant areas for intervention were defined.

For the first objective, a detailed monitoring of the preparation and separation of components process was conducted, mapping the sequence of activities and identifying the main sources of delay and inefficiency. Based on this, improvement proposals were developed, evaluated in terms of their feasibility and potential impact, and discussed with the relevant stakeholders. Once validated, the selected measures were implemented and their effectiveness assessed by comparing preparation and separation times before and after the intervention.

For the second objective, a systematic identification of waste sources within the production process was carried out through direct observation and time measurements. Alternative approaches to eliminate or minimise non-value-adding activities were proposed and analysed in terms of their advantages and disadvantages. After validation, the improvements were implemented and monitored, with results evaluated against the defined reduction targets.

1.5 Structure

The present report is organized into six chapters, each dedicated to a specific component of the study developed.

The first chapter, Introduction, presents the general context of the topic and outlines the main objectives of the study. It also describes the methodology adopted throughout the project and includes a brief presentation of the host company.

The theoretical and conceptual framework that supports the study is addressed in the second chapter, Literature Review. It covers key concepts related to Lean Thinking, including its principles and tools, as well as the topic of inventory management.

A detailed characterization of the existing processes is provided in the third chapter, Analysis of the Initial Situation, where key areas of analysis, identified inefficiencies and constraints, and opportunities for improvement within the production environment are presented.

Based on this diagnosis, the fourth chapter, Improvements Implemented, describes the solutions proposed and applied to address the identified opportunities of improvement, outlining the rationale behind each one, the methodologies and tools applied, and the steps taken during implementation.

The impact of these interventions is evaluated in the fifth chapter, Analysis of Results, through the analysis of relevant performance indicators comparing the situation before and after the improvements.

The sixth chapter, Conclusions and Future Work, summarizes the main findings of the study and presents recommendations and possible directions for further research or continued improvement.

Chapter 2

Literature Review

This chapter presents the theoretical and conceptual background that supports this study, covering main concepts, methodologies and tools related to process improvement within manufacturing and operational environments.

It introduces Lean Thinking, its principles and its origins in the Toyota Production System, highlighting waste reduction and value creation. Key Lean tools such as 5S, Visual Management, Gemba Walks and the PDCA cycle are also covered, as well as root cause analysis techniques that support continuous improvement in practice.

Finally, Inventory management is explored, including classical models, safety stock dimensioning, and ABC analysis for inventory classification.

2.1 Lean Manufacturing

Lean is a management philosophy that originated from the Toyota Production System and was introduced to the Western world as “Lean production” [9]. The authors describe Lean production as a superior alternative to traditional mass production systems, emphasizing efficiency, flexibility, and waste elimination. Unlike mass production, which relies heavily on high inventory levels and standardized outputs, Lean focuses on minimizing non-value-adding activities while maximizing value for the customer. This approach seeks to improve quality, reduce costs, and enhance responsiveness by systematically redesigning processes to eliminate waste and optimize performance.

Central to the successful implementation of this philosophy is the principle of continuous improvement. Continuous improvement is a foundational concept within Lean management and represents an ongoing commitment to improving processes, products, and services. Rather than viewing improvement as a series of isolated events, continuous improvement is understood as a systematic and sustained effort that becomes embedded in organizational routines and culture. This approach encourages individuals and teams to constantly evaluate existing practices, find inefficiencies, and implement incremental changes that lead to measurable gains in performance and value creation. It also extends beyond technical process adjustments to include cultural and behavioral dimensions. A culture of continuous improvement values curiosity, encourages open

communication, and empowers employees to contribute ideas for enhancement. This cultural orientation helps organizations remain adaptive and resilient in the face of evolving customer demands and competitive pressures [10].

2.1.1 Toyota Production System

Although Lean Thinking presents the general principles of waste reduction and value creation, these concepts originate from the Toyota Production System (TPS), which serves as the practical foundation of Lean. The TPS is a comprehensive manufacturing philosophy developed by Toyota Motor Corporation that has become a global benchmark for operational efficiency and quality [11]. It was created by engineers Eiji Toyoda and Taiichi Ohno, with its main objective being to increase production efficiency through the continuous elimination of waste. The concept of waste is defined as any operational process or procedure that consumes resources and time without adding value to the final product. In order to eliminate such waste, this system seeks to optimize the entire operational flow, aiming to meet market demands at the lowest possible cost. [12]

TPS is typically visualized as a “house” built on stable processes and standardization. Its structure rests on two fundamental pillars: Just-in-Time and Jidoka. The first one focuses on reducing inventory and lead times by synchronizing production with actual demand, ensuring that materials and components arrive just when they are needed in the process. Jidoka, often translated as automation with a human touch empowers workers and machines to stop production when problems occur, preventing the flow of defects and facilitating immediate problem resolution [13]. The overall structure of this system is commonly represented through the “TPS House” diagram, illustrated in Figure 2.1.

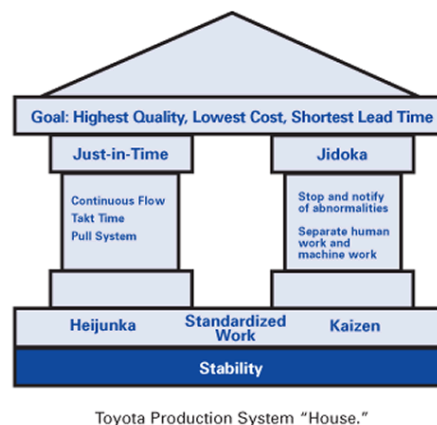


Figure 2.1: Toyota Production System House

The strength of the Toyota Production System (TPS) lies not only in the implementation of visible tools but also in the disciplined processes that ensure reliability and operational stability. A fundamental element of its foundation is standardized work, which defines the best-known method for performing a task in a safe, efficient, and consistent manner. Standardized work establishes

clear procedures, takt time, and work sequence, helping to reduce variability and ensuring that operations are performed according to defined standards. By creating a stable baseline for operations, standardized work also facilitates the identification of abnormalities and supports continuous improvement initiatives [14].

Another key foundational element is Heijunka, or production leveling. Heijunka aims to smooth production volume and product mix over time, avoiding large fluctuations that generate waste and instability. By reducing unevenness (*mura*) and overburden (*muri*), leveling supports a consistent workflow and enables the effective functioning of Just-in-Time systems. Research on TPS highlights that leveling production is critical for minimizing inventory, stabilizing demand on upstream processes, and maintaining operational balance [15]. In addition to these, process stability and visual management systems are integral to the foundation. Stable and reliable processes allow abnormalities to become visible, while visual controls such as Kanban and Andon systems facilitate rapid problem identification and response. Consequently, these foundational elements promote operational discipline, predictability, and process control.

2.1.2 Lean Principles

Lean Thinking is the antidote to waste. At its core, Lean is built around five interrelated principles that guide organizations in transforming their operations. These principles provide a structured framework for analyzing processes, identifying inefficiencies, and continuously improving performance throughout the entire value chain. These are the 5 Lean Principles [16]:

- **Specify Value:** Value can be defined only by the ultimate customer. It is essential to understand what the customer values in the product and what they are willing to pay for, specifying the necessary characteristics and attributes. All product features and functionalities that do not meet a customer requirement should be considered waste.
- **Identify the Value Stream:** The Value Stream is all the actions needed to bring a product to the customer. At this stage, all processes required for the production of the product, in accordance with customer requirements, are identified. Any activities or processes that are not necessary to fulfill these customer requirements are considered waste as they do not add value.
- **Create Flow:** To create a continuous flow of value-creating steps. This stage seeks to redefine the work performed by operators so that each task makes a meaningful contribution to value creation, while also ensuring that employees' needs are addressed, thereby contributing to their satisfaction and motivation.
- **Establish Pull:** This system is closely associated with the Just-in-Time (JIT) concept. This strategy aims to eliminate overproduction, reduce inventory levels, and minimize storage space requirements. The production order moves through the production flow in reverse, as it is triggered by actual customer demand.

- **Pursue Perfection:** There is no end to the process of reducing time, space, cost and mistakes. It seeks to eliminate waste that arises over time throughout the value chain and to exceed customer expectations.

These five principles form an integrated framework that guides organizations in eliminating waste and improving operational performance, establishing the foundation for the Lean tools and methodologies discussed in Section 2.2.

2.1.3 The seven wastes of Lean (*Muda*)

In Japanese, the term *muda* refers to waste, specifically activities that consume time or resources without adding additional value to the final product or service from the customer's perspective. These inefficiencies are commonly embedded in everyday organizational processes, which makes their recognition and elimination crucial for operational improvement. Lean methodology serves as the primary framework for tackling *muda*, as it provides structured mechanisms to detect inefficiencies and implement corrective actions in a timely manner [16]. Lean thinking categorizes waste into seven main types [12]:

- **Overproduction:** Refers to producing items in excess or before they are required by the next process or by customer demand. It is widely considered the most critical form of waste because it generates additional inefficiencies such as excess inventory, storage costs, and increased risk of obsolescence.
- **Inventory:** Consists of excess raw materials, work-in-progress, or finished goods beyond what is immediately needed. High inventory levels tie up capital, require storage space, and conceal inefficiencies such as production imbalances or quality problems. Lean systems aim to reduce inventory through pull-based production and Just-in-Time practices.
- **Overprocessing:** Refers to performing more work, higher precision, or additional steps than what is required to meet customer needs. This may include redundant approvals, excessive inspections, or overly complex procedures. Overprocessing often results from poorly designed systems or unclear quality standards.
- **Motion:** Refers to unnecessary physical movements performed by employees during work activities, such as searching for tools, walking long distances, or repetitive bending. These movements do not add value and may contribute to reduced productivity and ergonomic risks. Lean emphasizes workplace organization to minimize motion waste.
- **Waiting:** Occurs when workers, materials, information, or equipment remain idle due to delays in the production process. This type of waste reduces process efficiency and increases lead times without contributing to value creation. Waiting often results from poor process synchronization, unbalanced workloads, or equipment downtime.

- **Defects:** Involve errors, rework, scrap, or corrections required due to quality failures. This waste increases production costs and negatively affects customer satisfaction. Lean management practices prioritize built-in quality and root cause problem-solving to prevent defects rather than correcting them afterward.
- **Transportation:** Occurs when there is unnecessary movement of materials or products between processes. Although transportation may be necessary in some systems, any movement that does not directly transform the product or service from the customer's perspective is considered non-value-adding. Excess transportation increases handling time, cost and the risk of damage.

Although traditional Lean frameworks identified seven main categories of waste, subsequent developments in Lean thinking introduced an eighth waste associated with the underutilization of human talent. This form of waste refers to the failure to fully utilize employees' skills, knowledge, and creativity, which ultimately limits organizational learning and continuous improvement. [14].

2.2 Lean Tools

Lean management is supported by a set of structured tools and practices designed to eliminate waste, improve process efficiency and enhance value creation. These tools provide practical mechanisms for translating Lean principles into daily operational routines.

2.2.1 5S Methodology

The 5S methodology is an approach to operational excellence centered on workplace organization and efficiency. Popularized by Hiroyuki Hirano in 1995, the term "5S" reflects the principle expressed in the saying "*a place for everything, and everything in its place.*" To translate this principle into practice, the methodology is structured around five pillars, each addressing a specific dimension of workplace organization and supporting continuous improvement [17]:

- **Seiri (Sort):** Involves distinguishing between necessary and unnecessary items in the workplace and removing what is not required. The objective is to make the work environment more efficient and structured around value-adding resources.
- **Seiton (Set in Order):** Focuses on arranging essential materials in a logical and visually clear manner, reducing search time and streamlining workflow. Tools and equipment are clearly identified.
- **Seiso (Shine):** Consists of cleaning and inspecting the workplace regularly. By maintaining equipment in optimal condition, problems become more visible and easier to address.
- **Seiketsu (Standardize):** Ensures the maintenance of the first three steps through the establishment of visual standards, rules, and responsibilities.

- **Shitsuke (Sustain)**: Emphasizes discipline and continuous improvement. It involves regularly following established standards, conducting audits, and reinforcing good practices to ensure long-term organizational change and stability.

Finally, the 5S methodology promotes employee commitment through the active involvement of all individuals in maintaining the workplace order. This participation fosters greater awareness and improves motivation in their daily professional activities.

2.2.2 Visual Management

Visual Management is a core Lean practice aimed at enhancing transparency and facilitating real-time communication within organizations.

From a conceptual perspective, this management tool emphasizes close-range visual communication and should be simple and easy to understand. It prioritizes the use of the senses, particularly vision, as it is responsible for approximately 85% of information acquisition in human beings [18].

Visual Management can involve a wide range of tools, including visual boards, color-coded systems, standardized labels and signaling devices such as Andon systems [19].

By making operational information visible and easily accessible, visual tools reduce ambiguity, support faster decision-making, and enable employees to quickly identify deviations from standards [20], operating as a mechanism of control beyond its communicative function.

2.2.3 Gemba Walks

Gemba Walks are a key practice within Lean management that involve leaders going to the *Gemba*, a Japanese term meaning “*the real place*”, where value is created. Rather than managing processes remotely through reports or performance indicators alone, this approach emphasizes direct observation of operations in their actual context. By visiting the workplace, managers gain a clearer understanding of workflows, identify inefficiencies, and observe problems at their source. The purpose of a Gemba Walk is not to supervise or criticize employees, but to learn, ask questions, and support continuous improvement initiatives [21]. The role of managers is to improve the Gemba by minimizing, as much as possible, any factors that may delay production. Accordingly, each task should be carefully analysed and evaluated to determine whether it adds value, which requires understanding its purpose, its importance, and assessing whether the methods used are appropriate and effective. [22]

By grounding managerial decisions in direct observation, Gemba Walks promote fact-based management rather than assumption-based decision-making.

2.2.4 PDCA Cycle

The PDCA cycle, also known as the Deming Cycle or Shewhart Cycle, originated from early quality control frameworks and was later popularized in Japan as a fundamental component of

continuous improvement philosophy that helps organizations improve their processes over time and remain competitive [7; 8]. The PDCA method is iterative in nature, meaning that knowledge acquired from previous cycles is incorporated into subsequent ones, enabling incremental and systematic improvements over time [23]. Through repetition, organizations refine processes, enhance efficiency, and strengthen performance outcomes.

The cycle consists of four main stages [24]:

- **Plan:** Define a problem or identify an opportunity for improvement, examine the relevant information, and establish a structured action plan outlining clear objectives and the strategies required to achieve them.
- **Do:** Once the plan has been formulated, it is implemented on a limited scale. This phase involves executing the proposed actions while gathering data to track progress and verify that the activities are carried out as intended.
- **Check:** At this stage, the outcomes of the implementation are assessed. The data collected during the execution phase are analyzed to compare the anticipated results with the actual performance achieved.
- **Act:** Based on the evaluation conducted in the previous phase, a decision is made regarding the effectiveness of the intervention. If the results are satisfactory, the improvement is standardized and integrated into regular operations. If not, adjustments are introduced, and the cycle is repeated using the insights gained to guide further refinement.

2.2.5 Cause and Effect Diagram

The Cause and Effect diagram, also known as the Ishikawa diagram or fishbone diagram, is a quality management tool developed by Kaoru Ishikawa in the 1960s to support systematic problem analysis [25]. It is designed to identify, categorize, and visually represent the potential causes of a specific problem, thereby facilitating root cause analysis rather than merely addressing symptoms. The general structure of the diagram is illustrated in Figure 2.2.

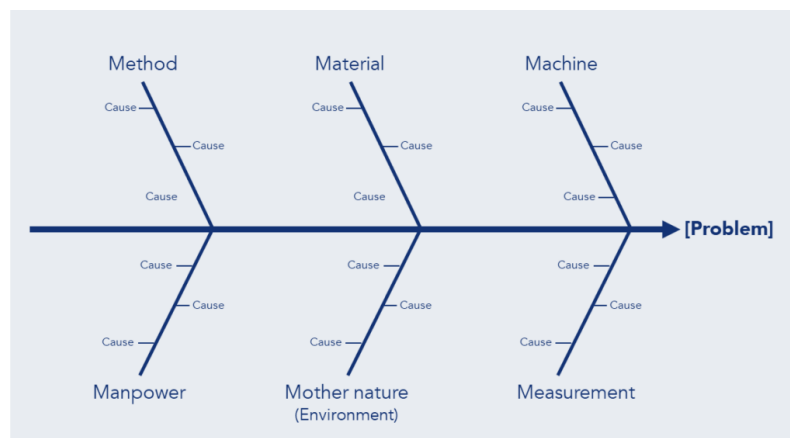


Figure 2.2: Ishikawa diagram [1]

In manufacturing and operational contexts, causes are commonly grouped into six main categories known as the “6Ms”: Methods, Machines, Materials, Manpower, Measurement, and Environment (Mother Nature) [23]. These categories help structure brainstorming sessions and guide teams in exploring possible sources of variation or failure [26]:

- **Methods:** The procedures, processes and work instructions applied during operations might play a role in generating issues. This involves evaluating whether proper planning was conducted, whether tasks were performed according to established standards, and whether appropriate tools and techniques were used.
- **Machines:** Equipment-related factors may contribute to process issues through failures or malfunctions during the process. It may involve incorrect operation, mechanical breakdowns, inadequate maintenance, or improper calibration.
- **Materials:** Raw materials or inputs used in the process that do not comply with the required specifications may be the cause of some problems. This includes materials that are defective, expired, incorrectly sized, improperly stored or outside the acceptable temperature or quality standards necessary for proper execution.
- **Manpower:** Human-related factors can also contribute to process failures. These may include insufficient training, lack of competence, inexperience, carelessness, excessive haste, or inadequate adherence to procedures during task execution.
- **Measurement:** Encompasses causes related to performance measurement and control systems. It includes issues such as inaccurate calibration instruments, ineffective performance indicators, poorly defined targets, or inadequate monitoring systems that may compromise process evaluation and decision-making.
- **Environment:** Internal and external environmental conditions may also influence process outcomes. Factors such as temperature, noise, pollution, workspace limitations, facility layout, interruptions or other contextual conditions may contribute to the occurrence of problems.

The Ishikawa diagram is widely recognized as one of the seven basic quality tools and plays a significant role in continuous improvement initiatives and quality management systems [27]. It is frequently used in conjunction with methodologies such as PDCA and other root cause analysis techniques.

2.2.6 5 Whys

The 5 Whys is a simple problem-solving method originally developed by Sakichi Toyoda and later adopted within the Toyota Production System as a core tool for root cause analysis. Its purpose is to move past surface symptoms and uncover the underlying cause of an issue by repeatedly asking the question “Why?”, typically five times. At its core, the Five Whys technique is based on the

idea that for every effect there is a cause and by persistently questioning these causes, you can peel back layers of symptoms to reach the true source of a problem [28].

In addition to its theoretical foundation, recent empirical research highlights how the 5 Whys technique is applied in real industrial contexts. A study conducted in 2023 examined how organizations actually use the method in practice. The findings showed that some companies that apply the method more rigorously tend to integrate it into structured root cause analysis processes, while those using it more flexibly often employ it to support continuous improvement initiatives. Moreover, the research reveals that the Five Whys is frequently combined with other quality management tools, particularly the Ishikawa (fishbone) diagram, which helps teams categorize and visualize potential causes before drilling down through iterative “why” questioning [29].

2.2.7 Swimlane Diagrams

A swimlane diagram, also known as a cross-functional process map, is a process mapping tool that illustrates workflow in organisations.

A workflow consists of a set and series of interrelated work activities that follow a distinct path as work inputs are transformed into outputs that customers value. The name cross-functional process map reflects the fact that the whole work process crosses several functions or organisational entities [30].

The defining structural feature of this type of map is the swimlane itself, a horizontal band that places work activities within the context of the organisational entity responsible for performing them. Each lane is labelled with the name of a specific entity, which may be a job title, a department, a function, or an information system. Inputs and outputs flow between lanes, and whenever they cross the boundary between two entities, they constitute a handoff: an internal supplier-customer relationship [30].

Therefore, swimlane diagrams are particularly suited to making several aspects of a process simultaneously visible: the boundaries of the workflow, the sequence of activities, the inputs and outputs at each step, the entities responsible for each activity, and the handoffs between them.

They also allow the identification of workflow patterns, such as serial, collaborative, or parallel activity sequences [30].

In the context of process improvement, this type of map is especially useful for documenting the current state of a process prior to any intervention, as it makes the work architecture visible, its boundaries, components, and features [30], providing the foundation for subsequent action to improve, measure, or redesign the work.

2.3 Inventory Management

Inventory refers to the stock of items and resources that an organisation maintains to support its operations, including raw materials, components, semi-finished products, and finished goods. It can be defined as the accumulated difference between what has been acquired and what has

been consumed. Effectively managing this stock requires a structured set of rules and controls to determine appropriate inventory levels, as well as the timing and quantity of replenishment orders [2].

Inventory management plays a crucial role in organisational performance and profitability, as it directly affects both operational efficiency and financial strategy. Its main objective is to maintain a balance between excess inventory and stock shortages, ensuring sufficient working capital while minimising costs related to ordering, holding, and stockouts. Ineffective inventory management may lead to financial losses, inventory imbalances, delays in order fulfilment, and reduced customer satisfaction [31].

2.3.1 Inventory Models

Inventory models provide the analytical framework for determining optimal ordering policies. They differ along several dimensions: the number of products considered, the nature and predictability of demand, whether orders can be placed once or repeatedly, and whether inventory is reviewed continuously or at fixed intervals. The appropriate model for any given situation depends on these structural characteristics. If only one ordering opportunity exists, a single-period model applies. Otherwise, a multi-period model is used, with the choice between continuous and periodic review depending on operational constraints and monitoring costs [2].

- **The Single-Period (Newsvendor) Model**

When a product can only be ordered once, before demand is known, and unsold units lose value after the selling period, the newsvendor model applies. This is common in seasonal goods, fashion items, or any context where a single procurement decision must be made under uncertainty. The model frames the problem as a trade-off between two types of error. Ordering too much incurs an overage cost (c_o) for each unit left unsold, equal to the difference between the purchase cost and the salvage value. Ordering too little incurs an underage cost (c_u) for each unit of unmet demand, equal to the profit foregone on that sale [32].

The optimal order quantity Q^* is found by identifying the point at which the expected gain from ordering one more unit exactly offsets the expected loss. Letting D denote the stochastic demand during the selling period, this leads to the critical fractile shown in Equation 2.1, which defines the optimal in-stock probability [32]:

$$P(D \leq Q^*) = \frac{c_u}{c_u + c_o} \quad (2.1)$$

For a normally distributed demand with mean μ and standard deviation σ , the optimal order quantity is given by Equation 2.2 [32]:

$$Q^* = \mu + z \left(\frac{c_u}{c_u + c_o} \right) \cdot \sigma \quad (2.2)$$

where $z\left(\frac{c_u}{c_u+c_o}\right)$ is the standard normal quantile corresponding to the critical fractile. When the cost of overstocking c_o is high relative to the cost of understocking c_u , the critical fractile is low and the optimal quantity lies below the mean. When the opposite holds, the optimal quantity exceeds the mean [32].

• The Economic Order Quantity (EOQ) Model

When inventory can be replenished repeatedly and demand is known and stable, the Economic Order Quantity model offers a tractable framework for determining how much to order at a time. The model rests on nine key assumptions [32]:

1. The demand rate is constant and deterministic;
2. The order quantity faces no minimum or maximum restrictions
3. The unit variable cost does not depend on the replenishment quantity, ruling out quantity discounts;
4. Cost factors do not change appreciably with time;
5. The item is treated independently of other items;
6. The replenishment lead time is of zero duration;
7. No shortages are allowed;
8. The entire order quantity is delivered at the same time;
9. The planning horizon is sufficiently long that all parameters can be assumed constant.

The relevant costs considered in the EOQ framework are those truly affected by the choice of order quantity. Under the stated assumptions, only two cost categories qualify: inventory carrying costs, which increase with the order quantity as larger orders imply higher average stock levels, and replenishment costs, which decrease with the order quantity as fewer orders are placed per unit time [32]. Inventory carrying costs encompass the opportunity cost of capital tied up in stock, warehousing expenses, handling, deterioration, obsolescence, insurance, and taxes. Replenishment costs, in turn, comprise all expenses associated with placing and receiving an order, including administrative processing, transit, inspection, and any production setup costs incurred when the replenishment is manufactured internally [32]. These two opposing cost components together define the total annual inventory cost, described in Equation 2.3:

$$C(Q) = \frac{Q}{2} \cdot h + \frac{D}{Q} \cdot K \quad (2.3)$$

where Q is the order quantity, h is the annual holding cost per unit, D is the annual demand, and K is the fixed ordering cost per order.

The cost-minimising order quantity, shown in Equation 2.4, is found by differentiating $C(Q)$ with respect to Q and setting the result to zero. It captures the fundamental trade-off between holding and ordering costs: At Q^* , the annual holding costs and annual ordering costs are

exactly equal, a result that follows directly from the structure of the optimisation problem [32].

As the order quantity increases, holding costs rise proportionally with average inventory levels, while ordering costs decline as fewer replenishments are required per year. The minimum total cost is therefore achieved at the point where these two opposing forces are in equilibrium [32]. This balance reflects the problem the EOQ model is designed to resolve: the inefficiency of holding excess stock and the inefficiency of placing excessively frequent orders.

$$Q^* = \sqrt{\frac{2KD}{h}} \quad (2.4)$$

EOQ with Positive Lead Time

In practice, however, orders are not fulfilled instantaneously. When there is a known lead time (LT) between placing and receiving an order, it is essential to act earlier, placing the order while there is still enough stock to cover demand during the waiting period. The stock level at which this trigger occurs is called the reorder point (ROP), and in its simplest form, given by Equation 2.5, it corresponds to the expected demand during the lead time [32]:

$$ROP = D \cdot LT \quad (2.5)$$

Figure 2.3 illustrates this mechanism. Inventory depletes at a constant rate until it reaches the ROP , at which point an order is triggered. After the lead time is over, the replenishment arrives and restores the inventory to Q^* .

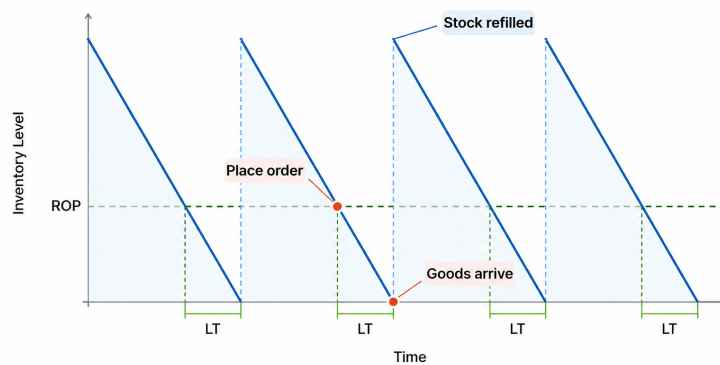


Figure 2.3: Inventory level over time with reorder point (ROP). Adapted from [2].

EOQ with Demand and Lead Time uncertainty

When demand is stochastic and replenishment lead time is uncertain, the probability of stockouts during the replenishment cycle is non-negligible [33]. Under demand uncertainty,

the total demand during the lead time LT is normally distributed with mean D_{LT} and standard deviation σ_{LT} as expressed in Equation 2.6 [33]:

$$D_{LT} = D \cdot LT \quad \sigma_{DLT} = \sqrt{LT} \cdot \sigma_D \quad (2.6)$$

where D is the mean demand per unit time and σ_D is its standard deviation. Setting the ROP equal to D_{LT} alone would result in stockouts in roughly half of all replenishment cycles [33]. A safety stock (SS) must therefore be added as a buffer above the expected lead time demand, adjusting the reorder point as described in Equation 2.7 [33]:

$$ROP = D \cdot LT + SS \quad (2.7)$$

When the lead time is also stochastic, it introduces an additional source of variability that further increases the risk of stockouts. In this case, the standard deviation of demand during the lead time must account for both sources of uncertainty simultaneously, as defined in Equation 2.8 [33]:

$$\sigma_{DLT} = \sqrt{LT \cdot \sigma_D^2 + D^2 \cdot \sigma_{LT}^2} \quad (2.8)$$

where σ_{LT} is the standard deviation of the lead time. The required safety stock grows as either source of uncertainty increases. The appropriate dimensioning of SS , including alternative service level measures and distributional assumptions, is addressed in Section 2.3.2.

• Periodic Review Model

In some operational contexts, inventory cannot be monitored continuously. Instead, stock levels are checked and orders are placed at regular, pre-defined intervals known as the review interval (T). Between review points, no replenishment orders can be placed, which means the system must hold enough stock to cover demand uncertainty over a longer window than in a continuous review model [33]. The system must therefore protect against demand variability over the combined interval $T + LT$ [32]. As a result, demand during this interval is normally distributed with mean D_{T+LT} and standard deviation σ_{T+LT} as described in Equation 2.9 [33]:

$$D_{T+LT} = D \cdot (T + LT) \quad \sigma_{T+LT} = \sqrt{T + LT} \cdot \sigma_D \quad (2.9)$$

At each review, the quantity ordered is calculated to raise the inventory position up to a target order-up-to level (OUL), defined in Equation 2.10 [33]:

$$OUL = D_{T+LT} + SS \quad (2.10)$$

The order quantity placed at each review is therefore the difference between the *OUL* and the current inventory position *I*, which includes stock on hand and any outstanding orders [32]:

$$Q = OUL - I \quad (2.11)$$

Because the protection period is longer than in a continuous review system, periodic review policies require a higher level of safety stock to achieve the same service level [33]. The appropriate dimensioning of the safety stock *SS* is addressed in Section 2.3.2.

2.3.2 Safety Stock

As introduced in Section 2.3.1, when demand or lead time are subject to variability, a safety stock (*SS*) must be held as a buffer above the expected lead time demand. The primary role of safety stock is therefore to protect against variations in demand and supply, reducing the probability of stockouts to an acceptable level [32].

Dimensioning safety stock involves a fundamental trade-off: holding too little exposes the firm to stockouts and poor customer service, while holding too much inflates inventory carrying costs unnecessarily [32].

The appropriate level depends on three key drivers: the replenishment lead time, the variability of demand and the target service level [32]. Two service level measures are commonly used to set this target. The cycle service level (P_1) defines the probability of not incurring a stockout during a replenishment cycle and the fill rate (P_2) defines the fraction of total demand satisfied directly from stock without backorders or lost sales.

Under a normally distributed lead time demand, the safety stock is expressed as in Equation 2.12 [32]:

$$SS = z \cdot \sigma_{DLT} \quad (2.12)$$

where z is the safety factor determined by the target service level and σ_{DLT} is the standard deviation of demand during the lead time.

Under demand uncertainty alone, with a fixed lead time *LT* and demand standard deviation σ_D per unit time, this is described as in Equation 2.13 [32]:

$$SS = z \cdot \sigma_D \cdot \sqrt{LT} \quad (2.13)$$

When the lead time is itself stochastic, σ_{DLT} must account for both sources of uncertainty simultaneously as shown in Equation 2.14 [32]:

$$\sigma_{DLT} = \sqrt{\bar{L}T \cdot \sigma_D^2 + \bar{D}^2 \cdot \sigma_{LT}^2} \quad (2.14)$$

where $\bar{D}$ is the mean demand per unit time, $\bar{LT}$ is the mean lead time and σ_{LT} is the standard deviation of the lead time. As either source of uncertainty increases, σ_{DLT} grows accordingly, and so does the safety stock required to maintain the same target service level [32].

2.3.3 ABC Analysis

ABC analysis is a widely used inventory management technique that classifies items into three categories: A, B and C, according to their relative importance. Several criteria can be used to perform this classification, namely: sales value or profit contribution; picking frequency; total quantity handled; and the weight and volume of products [34]. The method is based on the Pareto principle, which suggests that 80% of the effects result from 20% of the causes[35].

Category A includes the most critical items, representing a small percentage of the inventory but contributing the highest value and therefore requiring strict control and monitoring. Category B represents items of moderate importance, while Category C includes a large number of items with relatively low value and minimal impact on overall performance. This classification enables organizations to allocate resources more efficiently by focusing attention on the most significant items, thereby improving inventory control and decision-making processes [36].

In the context of this study, ABC classification can be used to identify the most frequently used items, allowing the prioritization of their availability and the definition of appropriate inventory policies, such as higher safety stock levels for these high demand items.

Chapter 3

Analysis of the Initial Situation

A clear and detailed understanding of the initial situation is essential to serve as the foundation for the implementation of any improvements. Therefore, before proposing changes, it is necessary to analyse the existing processes and identify how they currently operate, as well as their limitations and inefficiencies. To this end, a Gemba Walk approach was adopted, involving direct observation of the production floor to understand the processes in their actual context.

In this way, this chapter presents a description of the production process and the opportunities for improvement that resulted from that analysis.

3.1 Description of the production process

The production of a refrigeration unit follows a structured sequence of stages, namely Design, Preparation and Separation of components, Pipe prefabrication, Assembly, and Finishing, with strong interdependencies between them. This sequence reflects the technical constraints of the product, in which each stage builds directly upon the outputs of the previous one, making the flow of work largely sequential in nature.

The process is characterised by a make-to-order approach, where each unit is developed according to specific client requirements. This results in high variability between orders in terms of dimensions, components, and configurations, which increases planning complexity and limits the degree of standardization achievable across production runs. Each stage plays a distinct role in transforming the different components and raw materials into a finished unit, and will be described in detail in the following sections.

3.1.1 Design

The process begins with the Design phase, where the unit is engineered according to project specifications established with the customer. This includes the sizing and selection of appropriate components, taking into account essential technical requirements to ensure the proper operation of the refrigeration system. In parallel, the metal frame that supports the system is designed and later manufactured by an external supplier, while detailed 2D technical drawings of the piping

system are developed to support the following stages of the production process. An example of a 2D drawing is illustrated in Figure 3.1.

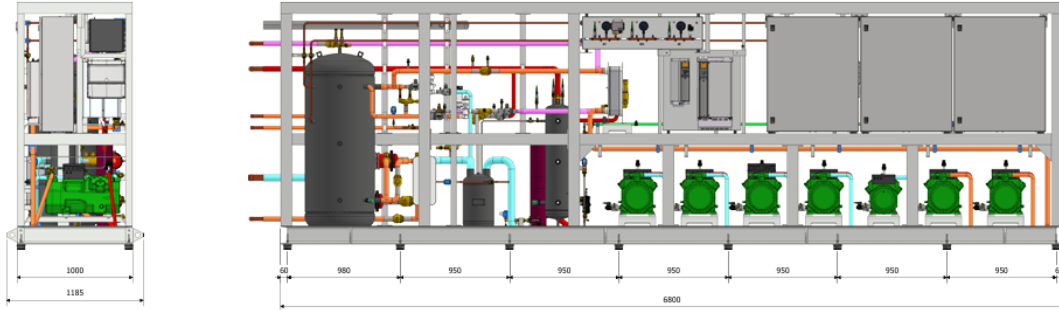


Figure 3.1: 2D drawing of a refrigeration unit

Once the design phase is completed, the process moves into the preparation and assembly stages, described in the following sections.

3.1.2 Preparation and Separation of components

Inside the production facility, following the Design stage, the process begins with the Preparation and Separation of components.

The materials required for each project are brought from the warehouse in multiple boxes, without proper prior sorting. At this stage, the items are unpacked and individually labeled according to a predefined list that specifies all materials required for the project. The operator uses the P&ID (Piping and Instrumentation Diagram), which serves as the primary reference for system construction, to identify control volumes and guide the labeling sequence accordingly. An example of this diagram is presented in Annex A. The nomenclature adopted in the components list is directly aligned with that of the P&ID, ensuring a coherent correspondence between the physical components and their representation in the diagram.

After labeling each component, the corresponding entry is marked both on the list and on the diagram, allowing the operator to track progress, avoid ambiguities and minimize errors as well as identify any missing materials that, despite being listed, have not been delivered from the warehouse. Once identified and labeled, the components are placed on shelves, where they remain until they are required for subsequent use in the process.

3.1.3 Pipe prefabrication

The next phase in the process, which takes place before the arrival of the metal frame, is pipe prefabrication.

During this stage, each spool, a prefabricated pipe sub-assembly that will later be installed directly in the final unit, is built according to a technical drawing associated with the specific part

of the refrigeration unit to be worked on. The pipefitter begins by reviewing this drawing, which is then followed by the gathering of the materials and components required for its construction.

The pipes are then cut to the dimensions specified in this drawing and their edges are chamfered and cleaned. Once cut, the piping is aligned according to the drawing and temporarily secured using spot welds. After verifying the correct positioning, the joints are permanently fixed through the application of weld beads.

3.1.4 Assembly

Once the metal frame is delivered, all components are installed onto the frame and the previously fabricated piping is positioned and connected to the other elements of the refrigeration unit. Simultaneously, electrical connections between the system components and the control panel are executed. The conclusion of this phase is defined by the execution of a pressure test, in which the unit is subjected to conditions exceeding normal operating pressure to ensure its structural integrity and reliability.

3.1.5 Finishing

After successfully completing the test, the unit advances to the Finishing phase. At this stage, safety valves, that could not be installed previously due to the pressure test requirements, are now incorporated into the system to ensure proper protection. Additionally, the piping is thermally insulated using materials appropriate for the operating conditions of the system, while finishing operations such as cleaning and painting are also carried out to ensure both the functional integrity and the final appearance of the unit. In parallel, quality control procedures are performed to verify that the system meets the required standards.

Upon completion of these steps, the unit is wrapped for protection and prepared for shipment to the customer.

3.2 Improvement Opportunities Identified

Following the detailed description of the current production process, this section presents the main inefficiencies and operational problems identified across its various stages. These were identified through direct observation of the production floor and active monitoring of the processes, informal interviews with operators and supervisors and consultation and analysis of internal documents. The identification of waste sources was guided by the Lean waste categories described in Subsection 2.1.3.

The following subsections detail each problem individually, characterizing its context, root causes and operational impact.

3.2.1 List of components

As described in Subsection 3.1.2, the component separation and labeling process constitutes a fundamental stage in the preparation for the subsequent phases of the process.

It was observed that, although the components list encompasses all materials required for the construction of the refrigeration unit, fewer than half of those components are eligible for direct labelling. Based on three observations carried out during the separation and labelling process, the average number of components present in the list was 335, of which only 124 were eligible for direct labelling, representing approximately 37% of the total. Nevertheless, for each component being labelled, the operator must manually search through the entire physical list, item by item, to identify the corresponding code and, once the label is applied, to locate and mark the respective entry as complete. An excerpt of the physical component list is presented in Annex B, illustrating the structure of the document consulted by the operator throughout the process.

To quantify the time impact of this limitation, a time study was conducted across the three observations, in which the time spent on each task was recorded by direct observation and continuous timing. The tasks considered were: retrieving materials from the warehouse boxes, labelling, confirming, and other auxiliary activities. The retrieval of materials from the warehouse boxes was grouped under "Other tasks" alongside remaining auxiliary activities, as their duration is not directly influenced by the labelling process itself but rather by external factors such as the organisation of the warehouse and the volume of materials delivered. The individual results are presented in Annex D and the average values are summarised in Table 3.1.

Table 3.1: Average results across the three observations of the separation and labelling process

Components overview		Average
No. of components (list)		335
No. of labelled components		124 (37%)
Task	Per listed component (s)	Per labelled component (s)
Labelling	6.99	18.76
Confirmation	8.86	24.00
Other tasks	11.02	29.66
Total process	26.87	72.42

The time data reveals a consistent and pronounced discrepancy between the average time per listed component and per labelled component across all tasks. This pattern is observed in both the labelling and confirmation tasks, with the confirmation step accounting for a particularly significant share of the total process duration across all observations. When considering the overall process, the average total time per labelled component was nearly three times higher than per listed component, demonstrating that a considerable portion of the operator's time is spent navigating an unfiltered document, rather than performing productive labelling activity.

Throughout this process, the operator must also continuously consult the physical P&ID to identify the relevant control volumes, adding a further layer of manual interaction. Once the label

is applied on the component, the operator must then locate and mark the respective entry on both the physical list and the diagram to confirm completion.

This entirely manual and paper-based process not only leads to considerable time expenditure and reduced efficiency, but also increases the likelihood of errors during the identification and labeling steps, given the volume of information the operator must simultaneously handle across multiple physical documents. Overall, this issue reveals a clear gap in the digitalization and filtering of the information available to the operator.

To consolidate the analysis presented above, a cause and effect diagram was developed to visually summarise the root causes identified as contributors to the excessive time spent in the separation and labelling process, and is presented in Annex C.1.

3.2.2 Bill of Materials per Spool

As described in Subsection 3.1.3, before beginning any fabrication work, pipefitters must manually identify all the pipe fittings and accessories required from the technical drawing.

This manual identification process introduces a non-value-adding activity into the workflow, as it delays the start of the actual fabrication work and is subject to human error, potentially resulting in missed components or unnecessary trips to the storage area. An improvement opportunity was therefore identified, consisting of automatically generating a bill of materials specific to each drawing, allowing pipefitters to immediately access a targeted list of required fittings and accessories without the need for manual interpretation. This would streamline the preparation step and reduce the time spent before productive work begins.

However, upon analysis of the existing system, it was found that no functionality existed to automatically associate materials with individual drawings. The available output was a single consolidated list containing all materials across multiple drawings, with no disaggregation by drawing reference.

Implementing the proposed improvement would therefore require a prior distribution of materials across the corresponding drawings, a task whose estimated time investment was found to exceed the cumulative time currently spent by pipefitters on manual identification. On this basis, this improvement was not pursued.

3.2.3 Material Preparation and Separation Station

The shelving area where components and fittings are stored until required for subsequent stages of the production process, described in Subsection 3.1.2, lacks a structured organisation system.

The shelves hold all the project components that have been labelled during the preparation and separation stage, yet no fixed storage locations, physical delimitations, or visual identification mechanisms, such as labels or markings, have been established to organise them, as illustrated in Figure 3.2, highlighting the absence of visual management practices as described in Subsection 2.2.2.



Figure 3.2: Initial state of the shelving area at the material preparation and separation station

The excess available space relative to the actual process demands has allowed materials from previous projects to accumulate in the area and items unrelated to the production process are also frequently placed on the shelves, further contributing to the overall disorder. As a result, components belonging to different projects get mixed up with unrelated objects, making it increasingly difficult to locate and retrieve the correct items efficiently.

Beyond project components, the shelving area also serves as the primary storage location for stainless steel fittings and accessories, which are addressed in Subsection 3.2.4.

Since pipe fitters access the shelving area 3 to 4 times per day to collect the materials required for each spool, this disorganisation has a direct and recurring impact on their workflow. As components are not returned once retrieved, being consumed directly in the production process, the shelving area should naturally become easier to navigate as a project progresses. However, without defined storage locations, this does not occur, as accumulated materials from previous projects and unrelated items prevent any consistent retrieval routine from being established.

3.2.4 Pipe fittings stock management

As described in Subsection 3.1.3, pipe fitters are responsible for retrieving all the materials required to produce a given spool both the labelled project components stored on the shelving area and the stainless steel fittings and accessories associated with each spool. These two categories of materials are collected together in a single retrieval trip, meaning that the efficiency of the entire retrieval process depends on how well both are organised and accessible.

Stainless steel fittings are allocated on a per-project basis, with each project having its own designated stock. However, these materials are not systematically grouped by category or schedule thickness and are primarily stored on the same shelving area as the project components, with no defined locations or separation between material types. In some instances, stainless steel fittings are also found in other locations across the factory floor, further increasing the difficulty of locating the required materials. The initial state of the fittings storage is illustrated in Figure 3.3.



Figure 3.3: Initial storage of pipe fittings

As a result, when accessing the shelving area, pipe fitters must search through a disorganised mix of labelled project components, stainless steel fittings, and unrelated objects. This frequently leads to situations where operators are unable to determine whether a required item is truly out of stock or simply misplaced, introducing uncertainty and unnecessary search time.

In order to quantify this combined impact, a direct observation study was conducted recording the time spent by pipe fitters searching for and retrieving the required components across 28 individual collection events. The full record of these is presented in Appendix E.1.

The recorded search times ranged from 23 to 430 seconds, with a mean of approximately 116 seconds (1 minute and 56 seconds) and a standard deviation of 91.5 seconds, reflecting a high degree of variability.

To assess whether the time spent was driven by the quantity of components to be retrieved, the observations were grouped by number of components and the average search time per group was computed, as presented in Table 3.2.

Table 3.2: Average search time grouped by number of components to retrieve

No. of Components	Observations	Mean (s)	Range (s)
1	4	92	39 – 194
2	4	142	33 – 279
3	5	104	23 – 228
4	5	69	40 – 134
5	5	180	66 – 430
≥ 6	5	111	47 – 152

The data reveal no consistent relationship between the number of components to be retrieved and the time required to locate them: groups with fewer components do not systematically record

lower search times than larger ones.

More notably, the high variability observed within each group, reflected in the wide ranges recorded, suggests that the time spent on any given retrieval is largely determined by the state of the storage space rather than the complexity of the task itself. This is a direct consequence of the conditions described: a required item may be found quickly on one occasion, while on another the same material takes considerably longer to locate, either because it has been misplaced among other items or because it is unclear whether it is actually in stock.

The centralisation and structured organisation of this storage space is therefore identified as the necessary intervention to address these inefficiencies.

To consolidate the analysis presented above, a cause and effect diagram was developed to visually summarise the root causes identified as contributors to the high variability and excessive time observed in the material retrieval process, and is presented in Annex C.2.

3.2.5 Pipe clamps stock management

Pipe clamps are elements installed during the Assembly phase of the production process to ensure the proper alignment and stability of the piping system, helping prevent vibrations, mechanical stress and potential damage of the refrigeration unit.

The material management process for pipe clamps begins with an initial quantity estimate at the project level, which serves as the basis for procurement. Once the design phase of the project is finalized, the actual required quantities are determined. This discrepancy between the initially estimated and the final quantities is inherent to the design process.

At the early stages of the project, quantities are estimated based on the overall dimensions of the piping system. However, it is not possible at this point to accurately define the exact locations and number of pipe clamps required. Only after the detailed technical drawings are developed does the full system layout become clear, allowing designers to determine the final quantities. At this stage, any identified shortfalls are listed and addressed.

However, the process does not account for the opposite situation. When pipe clamps are estimated and therefore received in excess of the actual project requirements, no formal procedure is triggered. The surplus is not returned, and its potential reallocation to other active projects is not supported by the system in use (SAP), as no storage location exists for materials that are not formally assigned to a specific project. As a result, excess materials remain physically present in the warehouse but are not recorded in the system, being set aside without any formal traceability. From the system's perspective, these materials do not exist. This storage condition is illustrated in Figure 3.4, which shows pipe clamps stored without any defined location or system identification prior to the implementation of the solution.

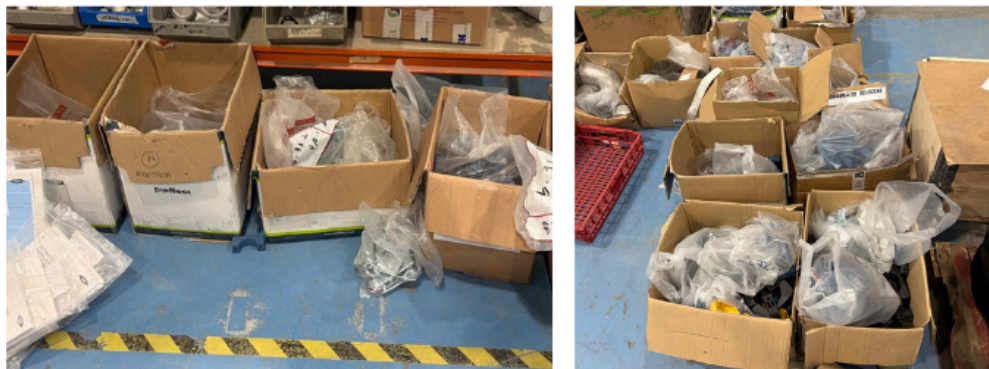


Figure 3.4: Initial storage of pipe clamps

This lack of traceability has a direct impact on subsequent process stages. When a shortage is identified during the Assembly phase, operators first attempt to locate the required materials among the unregistered surplus stored in the warehouse. If the material cannot be found, they then resort to materials already allocated to other projects. If neither option is successful, new materials are procured, leading to additional costs and delays. Even when surplus materials are located, they continue to be managed outside the system, perpetuating the absence of traceability.

This situation introduces several operational inefficiencies that directly affect the performance of the production process. The lack of system visibility over available materials increases the time spent searching for components, disrupts workflow continuity, and creates uncertainty in material availability during assembly. Furthermore, the informal reallocation of materials between projects compromises planning accuracy and may generate shortages in other ongoing units, propagating the problem across the system.

The current state of this process is illustrated in the swimlane diagram presented in Annex F, which maps the flow of activities across the involved parties: Project, Designers, Warehouse, Separation, and Factory and highlights the points at which traceability breaks down.

Chapter 4

Improvements Implemented

Building on the inefficiencies and operational problems identified in the previous chapter, this chapter presents the improvements implemented across the production process encompassing the digitalisation and filtering of process documentation, the reorganisation of the material preparation and separation area, the centralisation of material stocks, and the standardisation of workspaces through the application of the 5S methodology.

The solutions were designed to be practical and aligned with the operational reality of the production environment, with the common objective of reducing non-value-adding activities or time spent in productive tasks.

The following sections detail each improvement individually, describing the rationale behind each solution and the implementation steps carried out to tackle the identified opportunities.

4.1 Filtered List of components

In response to the problem identified in Subsection 3.2.1, namely the absence of filtering mechanisms and the entirely manual and paper-based nature of the process, a solution was developed aimed at restructuring the components list and digitalizing the operator's workflow. Although this list already existed in spreadsheet format, it was previously only used as a basis for printing, with the entire process carried out on paper. With this solution, the operator now accesses the spreadsheet directly on a computer, enabling a series of improvements to the separation and labeling process.

The most evident structural change introduced was the creation of a categorization system applied exclusively to the components eligible for direct labeling. Each of these components was assigned to a category corresponding to a specific control volume identifiable in the P&ID, which was added as a dedicated first column in the spreadsheet. Components that are not eligible for labelling were left without a category assignment, effectively distinguishing them from those that require action without removing them from the list, as illustrated in Figure 4.1.

GRUPO EMERGÊNCIA	VÁLVULA ESFERA GRUPO EMERGÊNCIA	V-29		800077644	VALV ESF CO2 5/8 80BAR 6570E/5A	1
GRUPO EMERGÊNCIA	VÁLVULA ESFERA GRUPO EMERGÊNCIA	V-30		800077644	VALV ESF CO2 5/8 80BAR 6570E/5A	1
	UNIAO ROSC V3V / VISO SEG. ALTA	V-07		800061495	UNIAO ROSC 316 3000LBS NPT 3/4"	1
GRUPO EMERGÊNCIA	VÁLVULA PRESSOSTATO EMERGÊNCIA	V-78		800085628	VALV ESF CO2 130B 3/80DS 1/4SAE 6567E/23	1
GRUPO EMERGÊNCIA	PRESSOSTATO GRUPO EMERGÊNCIA	I-23		800082234	PRESSOST CKB AUT[PSH] 54/44BAR 06124011	1
	UNIAO ROSC V3V / VISO SEG. LT	V-09'		800061735	UNIAO ROSC 316 3000LBS NPT 1/2"	1
INIEÇÃO GÁS MT	FILTRO REDE INI. GÁS MT	E-70	PDRB01787	800067186	FILTRO REDE 140BAR 4728E/M10	1
	UNIAO ROSC. V3V / VISO SEG. MT	V-10'		800061495	UNIAO ROSC 316 3000LBS NPT 3/4"	1
INIEÇÃO GÁS MT	VÁLVULA INIEÇÃO GÁS	V-04	PDXXXXXX	800092693	VALV SOL 140BAR EVT 1.2 068F0626	1
INIEÇÃO GÁS MT	VÁLVULA ESFERA LINHA DESCARGA	V-23	PDRB01789	800074106	VALV ESF CO2 C/S 1/1 10MM 6588E/M10A	1
	CASQUILHO VS/MANGUEIRA LT	V-12cc		800015028	PORCA REDC M/F (AISI316) 3/4"x1/2"	1
	MANGUEIRA LT	V-12m		800067965	TUBO 1SC 3/4 1P90 1DIR 3/4 BSP L=1400	1
	PONTEIRA COLETOR VS LT	V-12p		800007372	PONT ROSC AISI316L 3/4"	1
INIEÇÃO GÁS MT	VÁLVULA ESFERA LINHA DESCARGA	V-23A		800095787	VALV 140BAR 1/4 SAEFSAEM 6110E/X15	1
INIEÇÃO GÁS MT	VÁLVULA ESFERA LINHA GÁS	V-23'	PDRB01789	800074106	VALV ESF CO2 C/S 1/1 10MM 6588E/M10A	1
	CASQUILHO VS/MANGUEIRA MT	V-13cc		800053418	PORCA RED. M/F (AISI 316L) 1/4" X 1"	1
	MANGUEIRA MT	V-13m		800066590	TUBO 1SC 1.1/4 P90+FD A/C L=1300 S	1
	PONTEIRA COLETOR VS MT	V-13p		800007370	PONT ROSC AISI316L 1 1/4"	1
INIEÇÃO GÁS MT	VÁLVULA ESFERA LINHA GÁS	V-23'A		800095787	VALV 140BAR 1/4 SAEFSAEM 6110E/X15	1
INIEÇÃO LÍQUIDO	VÁLVULA INIEÇÃO LÍQUIDO	V-03		800077399	EXP VALV PWM 2028E/3504	1
	MANGUEIRA HP	V-14m		800066590	TUBO 1SC 1.1/4 P90+FD A/C L=1300 S	1
	PONTEIRA COLETOR VS HP	V-14p		800007370	PONT ROSC AISI316L 1 1/4"	1
INIEÇÃO LÍQUIDO	VÁLVULA ESFERA LINHA LÍQUIDO	V-38		800077642	VALV ESF CO2 3/8 80BAR 6570E/3A	1
INIEÇÃO LÍQUIDO	VÁLVULA ESFERA LINHA LÍQUIDO	V-38A		800095787	VALV 140BAR 1/4 SAEFSAEM 6110E/X15	1
	CASQUILHO VS/MANGUEIRA DL	V-15cc		800015028	PORCA REDC M/F (AISI316) 3/4"x1/2"	1
	MANGUEIRA DL	V-15m		800067966	TUBO 1SC 3/4 1P90 1DIR 3/4 BSP L=1100	1
	PONTEIRA COLETOR VS DL	V-15p		800007372	PONT ROSC AISI316L 3/4"	1
INIEÇÃO LÍQUIDO	VÁLVULA ESFERA LINHA INIEÇÃO LÍQUIDO	V-38'		800077643	VALV ESF CO2 1/2 80BAR 6570E/4A	1
INIEÇÃO LÍQUIDO	VÁLVULA ESFERA LINHA INIEÇÃO LÍQUIDO	V-38'A		800095787	VALV 140BAR 1/4 SAEFSAEM 6110E/X15	1
LÍQUIDO	FILTRO DE LÍQUIDO	E-36		800050476	FILTRO SECADOR BCY-P6-489 S 1 1/8" ODF	1

Figure 4.1: Components list spreadsheet showing the category column

This categorization enables the operator to filter the list by category and focus exclusively on the components belonging to the control volume being processed, in direct correspondence with what is visible on the P&ID. As shown in Figure 4.2, rather than navigating an extensive and unfiltered document, the operator now has immediate access to only the components within that specific group, significantly reducing the volume of information that must be handled simultaneously.

KOOLSYS	DESCRIÇÃO	P&ID No.	CÓDIGO LFE	CÓDIGO SAF	DESIGNAÇÃO	QUANTIDADE
EJETOR	FILTRO REDE EJETOR	E-73"	PDRB01788	800081938	FILTRO REDE 140BAR 4728E/M22	1
EJETOR	MULTI EJETOR DE LÍQUIDO	E-105		800081572	ME CO2 LE 400 CTM 2 032F5694	1
EJETOR	VÁLVULA ESFERA ASPIRAÇÃO PRIMÁRIA EL	V-110		800074110	VALV ESF CO2 C/S 1/1 22MM 6588E/M22A	1
EJETOR	VÁLVULA ACESSO ASPIRAÇÃO PRIMÁRIA EL	V-110A		800095787	VALV 140BAR 1/4 SAEFSAEM 6110E/X15	1
EJETOR	VÁLVULA ESFERA ASPIRAÇÃO SECUNDÁRIA EL	V-111		800074110	VALV ESF CO2 C/S 1/1 22MM 6588E/M22A	1
EJETOR	VÁLVULA ACESSO ASPIRAÇÃO SECUNDÁRIA EL	V-111A		800095787	VALV 140BAR 1/4 SAEFSAEM 6110E/X15	1
EJETOR	VÁLVULA ESFERA DESCARGA EL	V-112		800074110	VALV ESF CO2 C/S 1/1 22MM 6588E/M22A	1
EJETOR	VÁLVULA ACESSO DESCARGA EL	V-112A		800095787	VALV 140BAR 1/4 SAEFSAEM 6110E/X15	1

Figure 4.2: Components list filtered by a single control volume category

The confirmation step was likewise updated: once a component is labelled, the operator simply highlights the corresponding cell in the spreadsheet to mark it as complete, replacing the previous practice of manually locating and marking entries on a paper document. In the event that a component is identified as missing (present in the list but not delivered from the warehouse), the corresponding cell is highlighted in red, providing an immediate and unambiguous visual indication without requiring any additional annotation, as showed in Figure 4.3. Furthermore, as the spreadsheet is stored on the company's network, those responsible for stock management have direct access to this information, allowing them to promptly identify any missing materials without relying on the direct communication with the operator responsible for that process.

KOOLSYS	DESCRIÇÃO	P&ID No.	CÓDIGO SAF	DESIGNAÇÃO	QUANTIDADE
INIEÇÃO LÍQUIDO	VÁLVULA INIEÇÃO LÍQUIDO	V-03	800077399	EXP VALV PWM 2028E/3504	1
INIEÇÃO LÍQUIDO	VÁLVULA ESFERA LINHA LÍQUIDO	V-38	800077642	VALV ESF CO2 3/8 80BAR 6570E/3A	1
INIEÇÃO LÍQUIDO	VÁLVULA ESFERA LINHA LÍQUIDO	V-38A	800095787	VALV 140BAR 1/4 SAEFSAEM 6110E/X15	1
INIEÇÃO LÍQUIDO	VÁLVULA ESFERA LINHA INIEÇÃO LÍQUIDO	V-38'	800077643	VALV ESF CO2 1/2 80BAR 6570E/4A	1
INIEÇÃO LÍQUIDO	VÁLVULA ESFERA LINHA INIEÇÃO LÍQUIDO	V-38'A	800095787	VALV 140BAR 1/4 SAEFSAEM 6110E/X15	1

Figure 4.3: Components list showing the colour coding for labeled and missing components

While the P&ID remains in physical format and continues to serve as the reference for identifying control volumes, the operator now works in conjunction with the digitalized and filtered information displayed on screen.

This combination eliminates the time previously spent searching through an extensive unfiltered document, allowing the operator to focus solely on the relevant components at each stage of the process. As a result, the execution of the process becomes considerably faster and more reliable, improving the overall efficiency and consistency of this process.

The quantitative impact of these changes on the time required to complete the separation and labelling process is assessed in Chapter 5, through a comparison of time measurements recorded before and after the implementation.

4.2 Material Preparation and Separation Area Reorganisation

To address the disorganisation of the shelving area identified in Subsection 3.2.3, a structured storage layout was implemented based on the groups defined in the improved components list presented in Subsection 4.1. These groups were adopted as the organisational framework for the shelving area given that they are aligned with the P&ID, which pipe fitters consult throughout the pipe prefabrication phase, ensuring that the storage structure is intuitive and consistent with the reference documents already in use.

As a first step, all materials from previous projects and items unrelated to the production process were removed from the shelves. The definition of fixed storage zones for each component group also serves as a deterrent against the accumulation of such materials, as each area of the shelving unit is clearly assigned to a specific purpose, leaving no ambiguous space for unrelated items to be placed.

Magnetic labels were applied to the shelves to identify each storage zone according to its corresponding component group, as illustrated in Figure 4.4.



Figure 4.4: Magnetic labels applied to the shelving area

These identifiers were chosen over fixed alternatives to accommodate the variability inherent to the make-to-order production context. While the majority of component groups remain consistent across projects and are therefore maintained in the same shelf positions, some groups vary from project to project, requiring adjustments to the storage layout. Magnetic labels allow these changes to be made quickly and without permanent modifications to the shelving structure, ensuring the system remains flexible.

All components eligible for labelling were then distributed across the defined zones accordingly. The physical arrangement of the groups within the shelving area was determined based on two criteria. The first was the retrieval frequency and pattern of each group: component groups from which all items are collected at once in a single retrieval event were assigned less accessible positions, with a dedicated box introduced within each of these zones to facilitate the handling and transport of materials to the workstation. Groups accessed repeatedly throughout the course of the project were placed in the most reachable locations to minimise retrieval effort on each visit.

The second criterion was the stage of the production process at which each group of components is required: materials needed only in the later stages of the project were assigned less accessible positions, while those required earlier and more frequently were placed in the most reachable locations.

The final state of the shelving area following the implementation of the structured layout is illustrated in Figure 4.5.



Figure 4.5: Improved layout of the shelving area

By ensuring each component group has a fixed and clearly identified location, pipe fitters are expected to spend considerably less time searching for materials during each retrieval. The impact of this improvement on material retrieval time is quantitatively assessed in Chapter 5, where the search time data collected after implementation are compared against the baseline observations.

4.3 Centralised Storage of Pipe fittings

To address the dispersion of stainless steel pipe fittings across the production floor, mentioned in Subsection 3.2.4, a dedicated centralised storage solution was designed and implemented from scratch. The development process followed a structured sequence of steps: gathering of all material references, definition of a safety stock for each SKU, dimensioning of storage boxes and design of the physical shelving layout.

The process began with the consolidation of all stainless steel pipe fitting references used in the pipe prefabrication stage. All relevant SAP codes were gathered and organised across seven types of accessories, covering 90° and 45° elbows, caps, tees, reducers, threaded unions, threaded plugs and Hy-Lok fittings, totalling 96 SKUs, as detailed in Table 4.1.

Table 4.1: Number of SKUs per type

Fitting Type	No. of SKUs
Elbows	24
Caps	13
Tees	13
Reducers	26
Threaded Unions	5
Threaded Plugs	7
Hy-Lok Fittings	8
Total	96

For each one of them, the average consumption per unit and the unit cost were retrieved from historical data covering the last 50 refrigeration units produced. A sample of the resulting reference document is presented in Table 4.2.

Table 4.2: Sample of the base file - stainless steel pipe fittings

Box No.	Type	SAP Description	SAP Code	Dimension	Avg. Consumption	Unit Cost (€)
CX-01	Elbows	Elbow 90° SCH10 1/2"	800066737	1/2	6.57	1.66
CX-02	Elbows	Elbow 90° SCH10 3/4"	800050261	3/4	9.88	2.35
CX-03	Elbows	Elbow 90° SCH10 1"	800062636	1	24.41	2.68
CX-04	Elbows	Elbow 90° SCH10 1 1/4"	800062637	1 1/4	8.92	3.12
CX-05	Elbows	Elbow 90° SCH10 1 1/2"	800050260	1 1/2	2.94	3.71
CX-06	Elbows	Elbow 90° SCH10 2"	800050336	2	4.55	5.96
CX-07	Elbows	Elbow 90° SCH10 2 1/2"	800050281	2 1/2	0.84	8.09
CX-08	Elbows	Elbow 90° SCH10 3"	800050259	3	0.47	12.67
CX-9	Elbows	Elbow 90° SCH40 1 1/4"	800094961	1 1/4	3.41	4.30
CX-10	Elbows	Elbow 90° SCH40 1 1/2"	800094962	1 1/2	2.94	5.64
CX-11	Elbows	Elbow 90° SCH40 2"	800061347	2	0.43	8.86
CX-12	Elbows	Elbow 90° SCH40 2 1/2"	800094963	2 1/2	0.65	15.04
CX-13	Elbows	Elbow 90° SCH40 3"	800094964	3	0.08	20.85

With the reference document established, the next step was to determine the appropriate safety stock levels for each material.

Traditional inventory replenishment models were initially evaluated, however, their direct application was found to be unsuitable given the nature of demand. Material consumption is highly discontinuous across production units: certain pipe fittings may not be required for several consecutive units, while the following unit may require five or six pieces of that same material. Therefore, applying a standard replenishment model under these conditions risked either generating excess idle stock or failing to meet demand for a specific refrigeration unit.

An ABC classification of the materials was also initially considered as an option to differentiate safety stock levels across SKUs, with the intention of allocating higher stock quantities to high-consumption items. However, given the discontinuous and variable nature of consumption across production units, the stock quantities resulting from this classification were found to be insufficiently robust to reliably cover demand in practice, and the approach was not pursued.

Consequently, it was decided that materials would continue to be procured on a per-project basis, as specified in each project's components list, and that a safety stock would be maintained to accommodate deviations from the listed quantities and potential supply-side failures. To determine the quantity to hold, two approaches were developed and compared.

The first consisted of setting the safety stock equal to the expected consumption during the replenishment lead time, assuming a lead time of $LT = 2$ weeks and an average production rate of 2 units per week, consistent with an annual output of approximately 100 units. This alternative of SS corresponded to the average consumption across 4 production units.

The second approach incorporated the safety stock formula presented in Subsection 2.3.2:

$$SS = z \cdot \sigma_D \cdot \sqrt{LT} \quad (4.1)$$

where a service level of 95%, a standard reference value, was adopted, corresponding to $z = 1.65$. The choice of this value reflects the context of the process: in a make-to-order production environment, a missing fitting during the pre-piping stage immediately halts the pipefitter's work on that spool, justifying a high level of protection against stockouts. At the same time, given the relatively low unit cost of most pipe fittings and a replenishment lead time of two weeks, a more conservative level such as 98% would require an increase in stock for a marginal gain in protection. The 95% level therefore represents a balance between these two considerations.

The remaining parameters assumed were a demand standard deviation of $\sigma_D = 1$ unit per week and a fixed lead time of $LT = 2$ weeks.

The formula yielded a safety stock expressed in number of refrigeration units, corresponding to approximately 2.33 units. This value was then multiplied by the average consumption of each SKU per refrigeration unit to obtain the corresponding safety stock quantity for each material.

Table 4.3 illustrates the resulting safety stock quantities under both models for a selection of pipe fittings.

Table 4.3: Safety stock quantities per model - 90° elbows

SAP Code	Description	Avg. Consumption	SS-Lead Time (units)	SS-Theoretical (units)
800066737	Elbow 90° SCH10 1/2"	6.57	27	16
800050261	Elbow 90° SCH10 3/4"	9.88	40	24
800062636	Elbow 90° SCH10 1"	24.41	98	57
800062637	Elbow 90° SCH10 1 1/4"	8.92	36	21
800050260	Elbow 90° SCH10 1 1/2"	2.94	12	7
800050336	Elbow 90° SCH10 2"	4.55	19	11
800050281	Elbow 90° SCH10 2 1/2"	0.84	4	2
800050259	Elbow 90° SCH10 3"	0.47	2	2
800094961	Elbow 90° SCH40 1 1/4"	3.41	14	8
800094962	Elbow 90° SCH40 1 1/2"	2.94	12	7
800061347	Elbow 90° SCH40 2"	0.43	2	2
800094963	Elbow 90° SCH40 2 1/2"	0.65	3	2
800094964	Elbow 90° SCH40 3"	0.08	1	1

Following this analysis, although the theoretical model yields a lower safety stock quantity and consequently a lower investment, the resulting buffer covers only approximately 2.33 refrigeration units, equivalent to roughly 1.17 weeks of production, which given the discontinuous nature of consumption may prove insufficient to absorb demand spikes or supply disruptions. The demand-during-lead-time alternative, by covering the full expected consumption over the replenishment period, provides a more conservative and robust buffer that reduces the risk of production stoppages due to material shortages and gives the company greater flexibility, ensuring that production scheduling is not constrained by material availability. For these reasons, the demand-during-lead-time model was selected.

With the safety stock defined, the physical dimensioning of the storage solution was carried out. Since the implementation was being built from the ground up, including the shelving unit itself, box sizing was based on a projected annual output of 300 units, a one-off investment that ensures the solution remains valid as production scales up, without requiring future redesign of the storage system. The safety stock quantity, however, was kept at the 100 unit level, as dimensioning it for a future production scenario would represent an unnecessary financial commitment that does not reflect current operational reality.

With the projection scenarios defined, the next step consisted of determining the appropriate box size for each SKU. Three standardised box sizes were defined to accommodate the varying dimensions of the different fittings, as detailed in Table 4.4.

Table 4.4: Standardised box sizes used in the centralised storage system

Box Type	Dimensions (L×W×H cm)	Capacity (L)	Unit Cost (€)
Small	40.0 × 22.5 × 17.0	11	4.25
Medium	50.0 × 30.0 × 21.0	24	7.30
Large	60.0 × 40.0 × 32.0	51.3	13.25

To determine the appropriate box size for each SKU, it was first necessary to estimate the volume occupied by each fitting. Since the exact geometry of pipe fittings is irregular and varies by type, each component was approximated to an equivalent rectangular parallelepiped, using standardised dimensional data as the basis for the calculation.

The reference dimensions used were the outer diameter D and the centre-to-end dimension C (or face-to-face dimension M for symmetrical fittings), as illustrated in Figure 4.6.

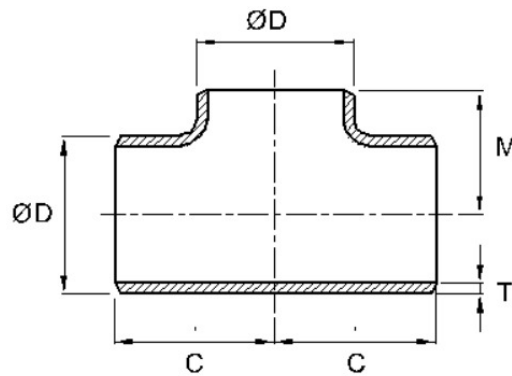


Figure 4.6: Reference dimensions used for volume estimation

These dimensions, sourced from standard fitting dimension tables, vary with the nominal diameter in inches and served as the basis for estimating the volume of each fitting type. For each fitting type, the occupied volume was estimated by approximating the component to a bounding rectangular parallelepiped, as summarised in Table 4.5.

Table 4.5: Volume estimation approach per fitting type

Fitting Type	Parallelepiped Dimensions
Elbows & Tees	$V = D \times \left(D + \frac{C}{2}\right) \times 2C$
Caps	$V = C \times D \times D$
Reducers	$V = 2C \times D \times D$
Unions & Plugs	$V = D \times D \times \left(C + \frac{D}{2}\right)$

The resulting reference dimensions and estimated unit volumes for each fitting type and nominal diameter are presented in Table 4.6. In all cases, the resulting volume in mm^3 was divided by 1,000,000 to convert to litres.

Table 4.6: Reference dimensions and estimated unit volumes per fitting type and nominal diameter

Size (in)	D (mm)	C & M (mm)	Vol. Elbow&Tees (L)	Vol. Cap (L)	Vol. Reducer (L)	Vol. Union&Plug (L)
1/2	21.34	25.4	0.0391	0.0116	0.0231	0.0164
3/4	26.67	28.6	0.0640	0.0203	0.0407	0.0298
1	33.40	38.1	0.1395	0.0425	0.0850	0.0611
1 1/4	42.16	47.6	0.2757	0.0846	0.1692	0.1221
1 1/2	48.26	57.2	0.4490	0.1332	0.2664	0.1894
2	60.33	63.5	0.7177	0.2311	0.4622	0.3409
2 1/2	73.03	76.2	1.2545	0.4064	0.8128	0.6012
3	88.90	85.7	1.9832	0.6773	1.3546	1.0286

The unit volume of each SKU was then used to determine the most suitable box size. For each one, the maximum stock quantity was first defined as the sum of the safety stock and the working stock, with the latter corresponding to the average consumption across six simultaneous refrigeration units in production - the maximum number of concurrent units projected for the 300 unit scenario. The total volume required was calculated by multiplying the unit volume by this maximum stock quantity.

A safety factor of 1.2 was then applied to account for non-optimal stacking and irregular component placement within the box, reflecting the fact that components are unlikely to be arranged in the most space-efficient configuration in practice. The resulting volume was compared against the capacity of each box size, and the smallest box capable of accommodating the required volume was initially assigned to each SKU. The occupancy rate of each assigned box was then calculated and whenever it exceeded 90%, the assignment was upgraded to the next larger box size to avoid overfilling and ensure ease of access to the components. Table 4.7 presents a sample of the resulting assignments.

Table 4.7: Sample of box assignments for selected SKUs - SCH10 Tees

SKU	Dim. (in)	Avg. Cons./Unit	Unit Vol. (L)	SS (units)	Max. Stock	Max. Stock Vol. (L)	Box Assigned
Tee SCH10 1/2"	1/2	0.71	0.0391	3	14	0.55	Small
Tee SCH10 3/4"	3/4	1.59	0.0640	7	30	1.92	Small
Tee SCH10 1"	1	6.98	0.1395	28	126	17.57	Large
Tee SCH10 1 1/4"	1 1/4	2.29	0.2757	10	42	11.58	Medium
Tee SCH10 1 1/2"	1 1/2	0.86	0.4490	4	17	7.63	Medium
Tee SCH10 2"	2	2.22	0.7177	9	41	29.42	Large
Tee SCH10 2 1/2"	2 1/2	0.55	1.2545	3	11	13.80	Medium
Tee SCH10 3"	3	0.35	1.9832	2	8	15.87	Medium

In total, the implementation required 96 boxes: 72 small, 19 medium and 5 large, distributed across the shelving unit.

With the box assignments defined, the shelving layout was designed. Given the space constraints of the factory floor, the goal was to minimise the total width of the shelving unit while maintaining a reachable height for the boxes placed on the upper levels.

To avoid confusion between materials of the same fitting type but different schedules, which differ only in wall thickness and are visually similar, SCH10 materials were placed on the left side

of the shelving unit, corresponding to Zone 1 in Figure 4.8, and SCH40 materials on the right, corresponding to Zone 3. Threaded unions, threaded plugs, and Hy-Lok fittings were placed in the central section (Zone 2), serving as a physical divider between the two schedule groups. Within each category, materials were further arranged from left to right in ascending order of nominal diameter, grouping boxes of the same size together wherever possible to produce a visually consistent and organised appearance.

Four layout options were developed and compared, differing primarily in the total width of the shelving unit and the arrangement of material categories across the levels.

The first option, with a total width of 420 cm and a height of 169 cm, organises materials across four levels, with each fitting category clearly segmented across a distinct horizontal level, making it the most intuitive for operators to locate materials, though at the cost of a larger footprint.

The second option, at 477.5 cm wide and 126 cm tall with only three levels, offers a lower height that improves accessibility to the upper level but results in the widest footprint and reduced visual clarity by compressing all categories into fewer levels.

The third option, at 387 cm wide and 160 cm tall with four levels, achieves a more compact footprint while maintaining a reasonable height, but requires some categories to be split across levels, compromising organisation.

The fourth option, at 367.5 cm tall and 160 cm wide, offers the smallest footprint, but at the cost of visual clarity: the internal dividers are not uniformly aligned across shelf levels, making the boundaries between component groups less immediately identifiable and therefore material retrieval less straightforward.

Given the importance of ease of retrieval and visual clarity on the production floor, the first option was selected, as it provides the clearest segmentation of fitting categories across levels, making it the most intuitive for operators to locate materials quickly.

The layouts of the three options not selected are presented in Annex G for reference.

The final shelving layout is illustrated in Figure 4.7, comprising a unit measuring 420 cm in length and 175 cm in height. The additional 6 cm relative to the 169 cm shown in the layout scheme correspond to the height of the shelving feet.

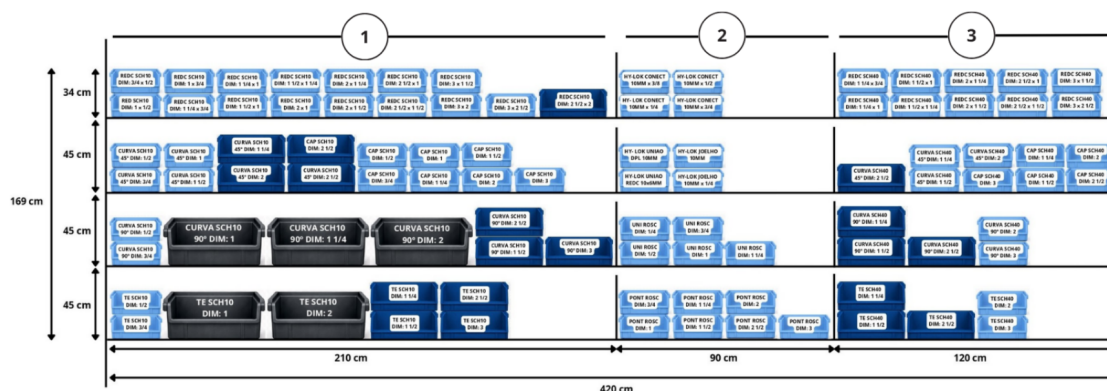


Figure 4.7: Final shelving layout - centralised storage of pipe fittings

Each box was labelled with the component designation, nominal diameter, and schedule, enabling immediate visual identification without the need to inspect the contents. The definition of fixed storage zones for each component group also discourages the reaccumulation of unrelated materials, as every section of the shelving unit is designated for a specific component group.

The physical implementation of the solution is shown in Figure 4.8.



Figure 4.8: Centralised storage of pipe fittings - physical implementation

The implemented solution centralises all 96 stainless steel pipe fitting references in a single, organised location, eliminating the need for operators to search across multiple storage areas on the production floor. In addition to improving material accessibility, the maintained safety stock ensures production continuity in the event of supply disruptions or deviations from the project components list. At the same time, the physical separation of SCH10 and SCH40 materials reduces the risk of incorrect material selection, which could otherwise compromise weld quality. Beyond these immediate operational benefits, the solution was designed with future scalability in mind, ensuring that the storage system remains adequate as production volumes increase. The impact of this improvement is assessed alongside the shelving area reorganisation in Chapter 5, as both interventions contribute directly to reducing material retrieval time.

4.4 Centralised Storage of Pipe clamps

The solution to the pipe clamps traceability problem explored in Subsection 3.2.5 was developed in parallel with an ongoing process of SAP code restructuring already underway within the company.

Pipe clamps are produced in two material variants, polyamide and polypropylene, and are classified into eight size categories, C2 through C9, each covering one or more nominal pipe diameters. The size category determines the geometry of the base plate and hex screw, which are shared across both material types. The plastic set, by contrast, is specific to both the material type and the nominal diameter, as the clamping geometry must conform precisely to the pipe

outer diameter. Table 4.8 summarises the resulting classification across all eight categories and the respective number of sets per category.

Table 4.8: Pipe clamp size categories

Cat.	Diameters (mm)	Base plate	Hex screw	Variants
C2	9.5 / 12	APKZ1-A1	IS-A1	4
C3	16 / 18	APKZ1-A2	IS-A2	4
C4	22	APKZ1-A3	IS-A3	2
C5	26.9 / 28	APKZ1-A4	IS-A4	4
C6	33.7 / 35 / 42	APKZ1-A5	IS-A5	6
C7	48	APKZ1-A6	IS-A6	2
C8	60.3 / 73	APKZ1-A7	IS-A7	4
C9	88.9	APKZ1-A8	IS-A8	2
Total				28

Since each diameter-material combination requires a distinct plastic set code, a category covering two diameters in two material types produces four variants, while C6, with three diameters and two materials, produces six. The table totals 28 plastic set codes, adding the 8 base plate codes and 8 hex screw codes, one per size category each, gives 44 individual sub-component references managed in the centralised storage solution.

Dimensioning the storage for each of these 44 references requires knowing the expected consumption per refrigeration unit produced, which can then be scaled to any anticipated production volume.

Annual consumption figures were estimated for 2026 based on an expected production volume of 100 refrigeration units, which allowed the consumption per unit to be obtained directly by dividing the annual figure by 100. This normalised value serves as the basis for the storage dimensioning model. Table 4.9 illustrates the resulting sub-component breakdown for two representative category variants.

Table 4.9: Sub-component breakdown for two representative pipe clamp assembly variants

Variant	Sub-component	Annual	Consum/central
Polyamide 9.5 mm	PLAST POLIAMIDA RANR-A1-9.5MM	100	1.00
	CHAPA BASE APKZ1-A1	100	1.00
	PARAFUSO HEX IS-A1	200	2.00
Polypropylene 9.5 mm	PLAST POLIPROPILENO RAPR-A1-9.5MM	475	4.75
	CHAPA BASE APKZ1-A1	475	4.75
	PARAFUSO HEX IS-A1	950	9.50

With the consumption per unit established for each of the 44 references, the next step was to determine the appropriate stock levels for each one.

Under the revised process, procurement is no longer triggered by individual projects, instead, stock is managed centrally according to the EOQ model presented in Subsection 2.3.1 and allocated to each project once the detailed design is finalised and the exact quantities are known.

Although the EOQ model in its basic form assumes constant and deterministic demand, the aggregate demand on the centralised stock at any given time depends on the number of projects simultaneously in the design phase and their specific requirements. The model was therefore extended with a safety stock component, following the formulation presented in Subsection 2.3.2, to protect against stockouts in exceptional circumstances where demand exceeds expectations during the replenishment period.

Cost Parameters

Applying the model requires, for each component, the specification of two cost inputs: the ordering cost (K) and the inventory carrying cost (h), both computed individually and treated as constants within the model.

The ordering cost K_i for each item comprises three components:

- Administrative purchasing cost (1.04€ per order): based on the time allocated by the buyer to process each order, estimated at 5 minutes at 12.50€/h;
- Receiving cost (1.67€ per order): based on the time allocated by the warehouse operator to process each incoming delivery, estimated at 10 minutes at 10.00€/h;
- Transport cost: estimated as 2.59% of the unit purchase value p_i , reflecting the typical freight charge applied per delivery.

Since purchase orders typically contain multiple line items, the administrative and receiving costs were allocated to each SKU by analysing historical procurement records to determine the average number of order lines in which each item appeared, yielding a constant cost per order line independent of the quantity ordered. The total ordering cost is therefore:

$$K_i = k_{admin,i} + 0.0259 \cdot p_i + k_{recep,i} \quad (4.2)$$

The inventory carrying cost h_i accounts for the cost of holding one unit in stock for one year and comprises two components:

- Capital cost: 7% of the unit purchase value p_i , representing the opportunity cost of capital tied up in stock. This rate was provided by the company and reflects its internal cost of capital, defined as the minimum return foregone by investing capital in inventory rather than in alternative uses;
- Storage cost: the annual cost of the shelving unit (1.35 m² at 48€/m²/year = 64.80/year) is divided equally across the 44 bins, giving 1.47€ per bin per year. This value is then divided by the number of units of that component that the assigned bin can accommodate, yielding a storage cost per unit that reflects both the bin size and the physical dimensions of the item.

The total carrying cost per unit per year is therefore:

$$h_i = 0.07 \cdot p_i + \frac{1.47}{n_i} \quad (4.3)$$

where n_i is the number of units of component i that the assigned bin can accommodate.

Order Quantity

With the cost parameters established, the optimal order quantity was computed. It minimises the total annual cost of ordering and holding inventory, as described in Subsection 2.3.1, using D as the annual demand of each SKU:

$$Q^* = \sqrt{\frac{2DK_i}{h_i}} \quad (4.4)$$

Since K_i and h_i incorporate the unit purchase value of each item, the resulting order quantity reflects both the procurement and holding costs specific to that sub-component.

Reorder Point and Safety Stock

Since replenishment orders are not fulfilled instantaneously, stock must be sufficient to cover demand during the supplier lead time of 4 weeks.

Demand quantities are expressed in units of each sub-component, and the demand during lead time was obtained by multiplying the consumption per refrigeration unit (C) by the 8 units produced during that period, given a production rate of 2 refrigeration units per week:

$$d_{LT} = C \times 8 \quad (4.5)$$

This covers the expected demand during the replenishment period under normal conditions. However, as discussed previously, variability inherent to the projects introduces uncertainty in the volume of allocations. A safety stock component was therefore incorporated following the formulation presented in Subsection 2.3.2, with a fixed lead time of 4 weeks, given the relatively stable replenishment conditions for this category of components, a service level of 95% ($Z = 1.65$) and a demand standard deviation of 1 refrigeration unit per week. Under these parameters, the expression becomes:

$$SS = Z \times \sigma_D \times \sqrt{LT} = 3.3 \times C \quad (4.6)$$

representing the stock required to cover demand for 3.3 additional production units beyond the expected lead time demand.

The reorder point was then obtained by applying Equation 2.7, combining the expected demand during the lead time with the safety stock buffer:

$$ROP = d_{LT} + SS \quad (4.7)$$

Maximum Stock Level

Once a replenishment order is triggered at the *ROP*, stock continues to be consumed during the lead time until the order arrives. At that point, inventory is replenished by Q^* , reaching its maximum level:

$$Q_{\max} = Q^* + SS \quad (4.8)$$

This value defines the physical storage requirement for each bin, as it represents the highest inventory level that each container must be capable of accommodating. With $Q_{\max}$ established for each of the 44 components, the next step was to translate these quantities into physical storage volumes and determine the appropriate bin size for each item.

The process followed the same logic applied to the stainless steel pipe fittings storage solution.

Three standardised bin sizes were defined to accommodate the varying volumes of the different items, as detailed in Table 4.10.

Table 4.10: Bin sizes used in the storage solution.

Bin type	Dimensions (cm)	Capacity (L)	Unit Cost (€)
Extra small	30×15×12.5	4.1	2.50
Small	40×22.5×17	11.0	4.25
Medium	50×30×21	24.0	7.30

To determine which of these bins should be assigned to each sub-component, the unit volume of each sub-component was obtained from dimensions sourced from the manufacturer's catalogue, the total storage volume required at $Q_{\max}$ was calculated, a safety factor was applied, and the result was compared against the available bin sizes.

For plastic set bodies, the component was approximated to an equivalent rectangular parallelepiped, with length and height varying by size category and a constant width of 30 mm across all categories. Base plates, being flat rectangular elements, had their volume computed directly from their actual dimensions. Given their small dimensions, hex screws were assigned the smallest available bin size directly, without volume calculation. The resulting unit volumes across all size categories are presented in Table 4.11.

Table 4.11: Unit volumes for plastic set bodies and base plates, by size category.

Cat.	Diameters (mm)	Plastic body (L)	Base plate (L)
C2	9.5 / 12	0.0150	0.0033
C3	16 / 18	0.0208	0.0039
C4	22	0.0270	0.0046
C5	26.9 / 28	0.0359	0.0055
C6	33.7 / 35 / 42	0.0618	0.0065
C7	48	0.0568	0.0081
C8	60.3 / 73	0.1688	0.0113
C9	88.9	0.2602	0.0135

The total volume required for each sub-component was obtained by multiplying the maximum stock quantity by the unit volume of that item.

A safety factor of 1.2 was then applied to account for non-optimal stacking and irregular component placement within the bin, reflecting the fact that components are unlikely to be arranged in the most space-efficient configuration in practice.

The resulting volume was compared against the capacity of each bin size, and the smallest bin capable of accommodating the required volume was initially assigned to each sub-component. The occupancy rate of each assigned bin was then calculated, and whenever it exceeded 90%, the assignment was upgraded to the next larger bin size to avoid overfilling and ensure ease of access to the components.

Table 4.12 illustrates the resulting assignments for a representative selection of sub-components.

Table 4.12: Sample of bin assignments for selected sub-components

Sub-component	Avg. Cons./Unit	Unit Vol. (L)	SS (units)	Max. Stock	Max. Stock Vol. (L)	Box Assigned
CHAPA BASE APKZ1-A1	8.65	0.0033	29	118	0.47	Extra Small
CHAPA BASE APKZ1-A5	44.75	0.0065	148	361	2.82	Extra Small
PLAST PA RANR-A4-26.9MM	7.60	0.0359	26	77	3.32	Extra Small
PLAST PA RANR-A5-42MM	9.50	0.0618	32	85	6.30	Small
PLAST PP RAPR-A7-73MM	4.75	0.1688	16	51	10.33	Medium
PLAST PP RAPR-A7-60.3MM	9.50	0.1688	32	79	16.00	Medium
PARAFUSO HEX IS-A5	88.50	—	293	949	—	Extra Small

In total, the solution required 44 bins: 33 extra small, 9 small, and 2 medium, distributed across the available shelving units.

4.4.1 Shelving Layout and Physical Implementation

The 44 boxes were accommodated within an existing shelving structure on the factory floor. Containers were organised first by component type: plastic sets, base plates, and hex screws, and then, within the plastic sets group, polyamide and polypropylene variants were assigned to separate shelves, with bins arranged in ascending order of nominal diameter within each material group. This organisation ensures that the structure of the storage system is immediately legible to operators, reducing the time needed to locate a specific sub-component.

Each bin was labelled with the sub-component designation, including material type, size category, and nominal diameter, where applicable. This correspondence is what enables the traceability objective described in Subsection 3.2.5: surplus sub-components returned from a project can be placed directly in their designated bin and recorded under the matching SAP code, making them visible and retrievable for subsequent projects rather than remaining as unregistered stock.

The physical implementation of the solution is shown in Figure 4.9.



Figure 4.9: Implemented centralised pipe clamps storage

Under the revised process, materials required for the Assembly phase are retrieved directly from the centralised stock once the detailed design is finalised and the exact quantities are known, rather than being pre-allocated to the project based on an initial estimate. As a result, the shortage scenario described in Subsection 3.2.5 where operators searched for unregistered surplus before resorting to materials from other projects or new procurement, no longer arises in the same form. The required items are available on the shelves and can be collected directly, avoiding the unnecessary procurement of new materials that previously occurred frequently under the prior process and considerably reducing the time spent searching for materials.

4.5 Implementation of the 5S Methodology

The workspaces within the production facility were characterised by the absence of defined storage locations for tools and equipment, the accumulation of unnecessary items, and the lack of standardised procedures for workspace organisation and maintenance. These conditions resulted in recurring time losses associated with searching for tools and an overall working environment that did not support consistent and efficient task execution.

To address these issues, the 5S methodology was applied to two distinct workspaces: the welder's workstation and tool cart, and the pipe fitters' tool cart. The following subsections detail the actions undertaken in each case and the outcomes achieved as a result of their implementation.

4.5.1 Welder's Workstation and Tool Cart

The welder's workstation and its associated tool cart were the first areas targeted for the application of the 5S methodology. Figure 4.10 illustrates the state of the workstation prior to the implementation of any improvements.

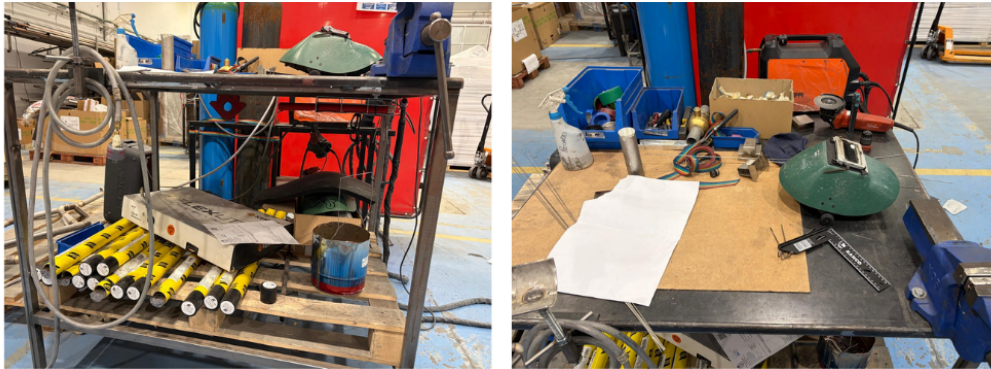


Figure 4.10: Initial state of the welder's workstation

As highlighted in Figure 4.10 the work surface was occupied by a heterogeneous set of items including welding equipment, hand tools, measurement instruments, the technical drawings consulted during fabrication, boxes containing residues and items that had accumulated over time without serving any active operational purpose. Cables were left without a designated placement and lacked a proper support structure, causing them to frequently drag along the floor and further contributing to a cluttered working environment. Additionally, the lower shelf of the station served as general storage location for welding electrode stock.

These conditions required the operator to spend additional time locating the necessary items before and during task execution, disrupting the workflow. To address them, the first step consisted of removing all items that were not necessary for daily work activities from the workstation as shown in Figure 4.11, relocating them outside the working area.

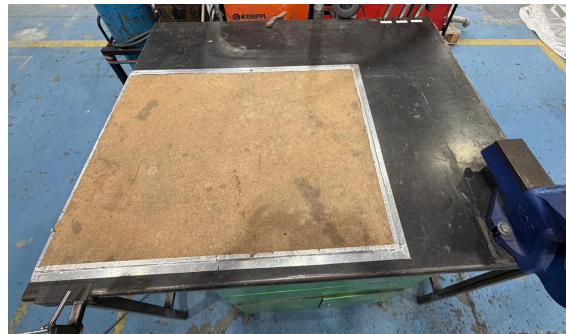


Figure 4.11: Welder's workstation following the removal of unnecessary items

With the workstation cleared, a set of targeted improvements were then implemented to address the specific issues identified during the initial assessment.

One of these concerned the storage of welding electrodes, which were kept on the lower shelf of this workstation. Since electrodes are supplied in tubular packaging with the specification indicated only at the top of the tube, and given that the stock was not organised by size, identifying the correct electrode quickly was not straightforward. Additionally, as the shelf was located close to the floor level, retrieving the tubes required the operator to bend down each time, which represented an unnecessary physical effort given the frequency with which they are handled throughout

the day. Furthermore, as no dedicated stock location existed at the remaining workstations, other operators would periodically collect electrodes from this shelf, returning for more when their supply ran out, resulting in multiple open tubes of the same specification in circulation simultaneously with no visibility over actual consumption or remaining stock.

In addition to full electrodes, half-length electrodes are also regularly employed during welding operations. These were stored separately in different containers, however, without any organisation by size or immediately visible label. The initial storage condition of both electrode types is visible in Figure 4.12.

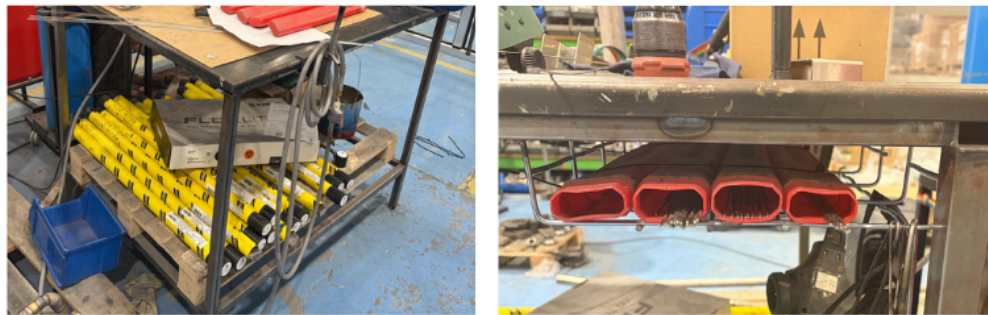


Figure 4.12: Initial storage condition of welding electrodes

To tackle these issues, a custom wire rack was designed and fabricated in-house to serve as a dedicated electrode storage support, welded directly underneath the workstation surface, as shown in Figure 4.13. The rack was structured to store electrodes in an organised and immediately accessible manner, with half-length electrodes arranged first by size, followed by the full-length ones, each section clearly labelled to allow the correct specification to be easily identified.

By positioning the support directly beneath the work surface rather than at floor level, the physical effort required to retrieve electrodes was significantly reduced. Furthermore, the electrode stock was redistributed, with a dedicated allocation assigned to each welder, eliminating the previous dependence on a single centralised point and preventing the simultaneous circulation of multiple open tubes of the same specification.



Figure 4.13: Custom wire rack for welding electrodes

A separate solution was implemented for the storage of electrode stubs of each specification frequently used, which were previously kept loose in a container without any organisation. A short tube section was welded to the workstation surface with the stubs organised by size and clearly

labelled, providing an immediately accessible location for their storage, as illustrated in Figure 4.14.



Figure 4.14: Fabricated support for electrode stubs

A further improvement concerned the storage of angle grinder consumables, namely cutting discs, grinding discs, and flap discs, as well as the angle grinder itself. As presented in Figure 4.15, these items were previously left on the shelves of the welding cart, with the grinder and its associated discs simply resting on available surfaces alongside other unrelated items.



Figure 4.15: Initial storage condition of the angle grinder and consumables

To rectify this, dedicated pins were welded along the edge of the workstation tabletop, allowing each disc type to be hung by its central hole and kept readily accessible without occupying the work surface. A dedicated support was likewise fabricated for the angle grinder, ensuring it remained within reach. Figure 4.16 illustrates the implemented solution.

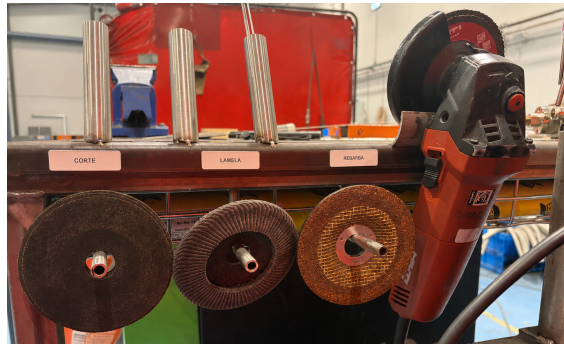


Figure 4.16: Fabricated supports for angle grinder consumables and tool

To address the issue of the welding torch cable dragging along the floor, a vertical support was fabricated and installed at the workstation, providing also a designated resting point for the torch head. This solution not only eliminated the organisation concerns associated with the cable being left on the floor, but also improved the ergonomic conditions of the workspace by keeping the torch at a more accessible height for the operator. Figure 4.17 presents the resulting structure.



Figure 4.17: Vertical support for the welding torch

The tool cart was then considered, which presented a similarly disorganised state to that initially observed at the workstation.

The top surface of the cart was cluttered with tools, consumables, and personal items accumulated without any defined placement, while the interior drawers and shelves contained a mixture of work-related materials and unrelated items stored without any organisational criteria, as shown in Figure 4.18. The absence of a standardised layout made it difficult to locate specific tools or materials quickly, requiring the operator to search through the available surfaces and compartments each time an item was needed.



Figure 4.18: Initial state of the welder's tool cart

The improvement of the tool cart followed the same rationale applied to the workstation, with all items not required for daily operations removed from the cart and relocated outside the working area. The remaining elements were then reorganised according to the frequency of use and nature of the items. A small drawer was reserved for personal belongings, keeping them contained without interfering with the working space. A second drawer was assigned to welding-related materials and frequently used tools, ensuring they remained readily accessible during operations. A third drawer, positioned lower on the cart, was designated for personal protective equipment accessed less frequently throughout the working day. The resulting state of the tool cart is illustrated in Figure 4.19.



Figure 4.19: Improved state of the welder's tool cart

Additionally, the side bins of the cart were each assigned to a specific category of materials, replacing the boxes that had previously been used as improvised storage.

The cart itself was also repositioned, moving it from behind the workstation to underneath it, ensuring that all tools and materials remained within immediate reach of the operator without requiring unnecessary movement. Figure 4.20 presents the before and after state of the cart positioning.



Figure 4.20: Before and after of the welder's tool cart positioning

The resulting workspace reflects a tidier and more standardised working environment, where every tool and item has its designated place and unnecessary disruptions to the operator's workflow are minimised.

4.5.2 Pipe fitters' Tool Cart

Similarly to the welder's tool cart, the tool carts assigned to the pipe fitters lacked any defined structure of storage criteria.

As illustrated in Figure 4.21, tools, consumables and personal items were stored without defined locations, used materials and residues had accumulated alongside operational tools and technical drawings were left on the cart surface without a designated placement. These conditions made it difficult to locate specific items quickly, requiring the operator to search through the available compartments each time a tool was needed.



Figure 4.21: Initial state of the pipefitters' tool cart

To address the disorganisation of the pipe fitters' tool carts, a new model was introduced, equipped with foam-lined drawers with custom cutouts shaped to the profile of each individual tool. This approach allows the operator to instantly detect the absence of any item and to locate it without unnecessary searching. The tools were distributed across the drawers according to their type. Figure 4.22 shows the resulting state of the tool cart following the implementation of these improvements.



Figure 4.22: Improved state of the pipe fitters' tool cart

Overall, the application of the 5S methodology across both workspaces resulted in a working environment where tools, consumables, and equipment are stored in clearly defined locations, reducing unnecessary interruptions and supporting a more productive daily routine for the operators.

The improvements introduced establish a structured baseline that can serve as a reference for the extension of this practices to other workspaces within the facility. The long-term effectiveness of these improvements will nonetheless depend on the consistent compliance with the standards established.

Chapter 5

Analysis of Results

This chapter presents the results obtained following the implementation of the improvement actions described in the previous chapter. The objective is to assess the effectiveness of each intervention by comparing quantitative performance indicators measured before and after implementation.

The first section analyses the impact of the filtered components list on the separation and labelling process, evaluating changes in the time required to label and verify components per project. The second section presents the results of the material preparation and separation area reorganisation and the centralised storage of pipe fittings, focusing on the reduction of material retrieval time during the pipe prefabrication phase.

5.1 Impact of the Filtered List of Components

The implementation of the filtered components list was assessed through a time study conducted across three observations before and after the improvement, following the same methodology applied in the initial analysis presented in Subsection 3.2.1. Performance is expressed as the average time per labelled component, focusing on the components directly processed during the separation and labelling tasks and allowing a consistent comparison across observations with different project sizes. The individual results for each observation are presented in Appendix D.2. The average values across the three before and after observations are summarised in Table 5.1.

Table 5.1: Average results before and after implementation - separation and labelling process (per labelled component)

Task	Before (s)	After (s)	Reduction
Labelling	18.76	13.57	27.7%
Verification	24.00	11.99	50.0%
Other tasks	29.66	30.68	–
Total process	72.42	56.24	22.4%

The results show a reduction in the average total separation time per labelled component from 72.42 to 56.24 seconds, corresponding to a 22.4% decrease and exceeding the 20% target initially defined in Subsection 1.3.

The most pronounced improvement is observed in the verification step, where the average time decreased by 50.0%, from 24.00 to 11.99 seconds per labelled component. This result is consistent with the nature of the improvement: with the list filtered by control volume category, the operator works with a significantly reduced set of entries at each stage, eliminating the need to navigate an unfiltered document to locate and mark each component. The labelling step also improved by 27.7%, from 18.76 to 13.57 seconds, reflecting the reduced effort required to search for and locate the correct label within a shorter and more focused list.

The "Other tasks" category, which groups the retrieval of materials from warehouse boxes and remaining auxiliary activities, shows no meaningful change, as expected, since these activities are not directly influenced by the structure of the components list. Their slight variation across observations is attributable to factors unrelated to the implemented change, such as differences in warehouse delivery conditions, the number of valve caps to be removed, or the occurrence of brief interruptions during the process.

Considering an average of 130 labelled components per project and an annual production of 100 refrigeration units, the total time saving amounts to approximately 58.5 hours per year.

To further contextualise the impact of this improvement, this total annual time saving is equivalent to the time required to perform the separation and labelling process for approximately 29 additional refrigeration units per year, based on an average process duration of approximately 122 minutes per project, derived from the average time per labelled component recorded after implementation and an average of 130 labelled components per project. This means that the same operator capacity could, in principle, support the preparation of 29 more units annually without any increase in labour cost or hours worked.

5.2 Impact of Material Retrieval Improvement

The impact of the material preparation and separation area reorganisation and the centralised storage of pipe fittings was assessed through a time study of material retrieval times, following the same methodology applied in the initial analysis presented in Subsection 3.2.4. As mentioned, pipe fitters retrieve all materials required for a given drawing, both the labelled project components and the stainless steel pipe fittings, in a single retrieval trip. Although the implemented improvements introduced separate, organised storage locations for each of these material categories, the time study conducted after implementation continued to measure the total time required to retrieve all materials needed for a given drawing, allowing a direct and consistent comparison with the before measurements.

The combined effect of both improvements on this retrieval process is therefore evaluated through a single set of before and after observations, with the after observations presented in

Appendix E.2, quantifying the extent to which the structured organisation of both storage areas reduced the time and variability associated with material retrieval.

The average values are summarised in Table 5.2.

Table 5.2: Comparison of material retrieval times before and after improvements

	Before	After
Mean (s)	116.0	52.3
Std. Dev. (s)	91.5	27.6
Range (s)	23 - 430	16 - 127

The average material retrieval time decreased from 116.0 to 52.3 seconds, corresponding to a reduction of 54.9%, considerably exceeding the 15% target defined in Subsection 1.3 for the reduction of non-value-added activities such as searching for components. Beyond this reduction in average time, the standard deviation decreased from 91.5 to 27.6 seconds, and the range of recorded times narrowed considerably, from 23-430 seconds to 16-127 seconds.

As discussed in Subsection 3.2.4, the wide range and high standard deviation observed before the implementation indicated that retrieval times were not primarily determined by the number of components to be retrieved, but rather by the state of the shelving area at the time of retrieval since a required item could be located quickly on one occasion, while the same material could take considerably longer on another, depending on whether it had been misplaced or its availability was unclear. The substantial reduction in both the standard deviation and the range observed after the implementation indicates that retrieval times have become considerably more consistent, providing evidence that the centralisation and structured organisation of the shelving area addressed the root cause of the variability identified in the initial analysis.

Chapter 6

Conclusions and Future Work

This dissertation addressed the reduction of non-value-added activities and the improvement of organisation across components, materials and workspaces in the production of industrial refrigeration units at Koolsys.

The investigation followed an action research approach, grounded in direct observation, time studies and Gemba Walk practice, which provided the empirical foundation for both the identification of inefficiencies and the validation of the improvements implemented. Lean Manufacturing principles such as waste identification, the 5S methodology and visual management along with inventory management concepts provided the conceptual framework within which the improvements were developed, with cause and effect and swimlane diagrams further supporting the analytical work. Together, these formed a coherent methodological framework that translated academic concepts into concrete interventions adapted to the operational reality of the company.

The work was guided by two main objectives: a reduction of at least 20% in the time required for the preparation and separation of components, and a reduction of at least 15% in the time allocated to non-value-added activities. Both objectives were met and exceeded.

The first objective was addressed through the digitalisation and filtering of the components list, which reduced the average separation and labelling time per labelled component from 72.42 to 56.24 seconds, a reduction of 22.4%, exceeding the 20% target. The most pronounced gain was observed in the verification step, which decreased by 50.0%, from 24.00 to 11.99 seconds, a direct consequence of replacing an unfiltered paper-based list with a digitally filtered document organised by control volume category. This result also clarifies something that had not been previously quantified at the company: the proportion of the operator's time during separation consumed by navigating the document rather than performing productive labelling work, which both justified the intervention and explains why the improvement exceeded the target by such a margin.

Considering an average of 130 labelled components per project and an annual production of 100 refrigeration units, the total time saving amounts to approximately 58.5 hours per year, equivalent to the capacity required to perform the separation and labelling process for approximately 29 additional units annually, without any increase in labour cost or hours worked. This translates into an estimated annual saving of approximately 631€, achieved at no implementation cost, as

the improvement consisted exclusively of structural changes to an existing spreadsheet.

The second objective was met through the reorganisation of the material preparation and separation area and the centralised storage of stainless steel pipe fittings. Average material retrieval time decreased from 116.0 to 52.3 seconds, a reduction of 54.9%, well above the 15% target. The standard deviation decreased from 91.5 to 27.6 seconds and the range narrowed from 23–430 to 16–127 seconds, reflecting that the improvement addressed the root cause of the variability identified in the initial analysis rather than merely reducing average retrieval times.

Based on an average of 20 drawings per project and an annual production of 100 units, the combined effect of both improvements is estimated to generate an annual saving of approximately 569€ in pipe fitter labour time.

Beyond the two quantified objectives, additional improvements were implemented that introduced structures with no prior equivalent at Koolsys. The centralised storage solution for pipe clamps addressed a traceability gap that had been generating operational disruption. The application of the 5S methodology to the welder's workstation and the pipe fitters' tool carts established defined storage locations and visual identification systems in areas where none had previously existed.

The development of these improvements encountered however some constraints. One improvement opportunity, the automatic generation of a bill of materials per spool drawing, was analysed in detail but ultimately not pursued, as the time investment required to distribute materials across individual drawings was found to exceed the cumulative time currently spent by pipe fitters on manual identification. This opportunity could be revisited in the future if the system in use develops the necessary functionality to support it. This decision reflects a broader principle applied throughout the project: improvement opportunities were evaluated on the basis of evidence rather than assumption, and only implemented where the expected impact justified the effort. A further limitation concerns the inventory model developed for pipe clamps, whose EOQ and safety stock parameters were necessarily based on consumption projections provided by the company rather than historical data. As production data accumulates, these parameters should be revisited to ensure the model reflects actual demand patterns.

The results obtained reinforce the value of a systematic, evidence-based approach in addressing operational inefficiencies within an industrial environment. Beyond the immediate gains, the data collected, the models developed and the organisational standards introduced provide Koolsys with a foundation that did not previously exist and from which further improvements can be pursued.

6.1 Future Work

The improvements implemented in this dissertation address specific inefficiencies identified within the production process but the work also points to a number of directions in which further developments could be pursued.

Future work could address the storage of spools once fabrication is completed during the pipe prefabrication stage. A dedicated support structure would provide finished spools with an adequate location until they are required for Assembly, reducing the risk of damage and facilitating their handling. In parallel, introducing a simple identification system for spools, linking each fabricated spool to its corresponding drawing reference, would reduce the risk of misidentification when multiple spools are stored together before being used in the Assembly phase, extending the labelling and visual management principles already applied in this work to this stage of the process.

Another direction concerns tools that are shared between operators rather than assigned to a specific workstation or tool cart. The introduction of a dedicated panel for these common tools, with defined positions and outlines for each item following the same logic applied to the pipe fitters' tool carts, would make it easier to locate them and to immediately identify missing items.

The 5S methodology could also be extended to other areas of the production facility that were not addressed in this work, namely the insulation and electrical workstations and the warehouse. Each of these areas presents characteristics similar to those that motivated the interventions carried out in this project: lack of defined storage locations, absence of visual identification systems, and accumulation of unrelated materials and could therefore benefit from the same structured approach. To sustain the improvements already implemented and those that may follow, the introduction of periodic 5S audits would be a valuable complement, providing a formal mechanism to monitor compliance, identify deviations, and ensure that the organisational standards established are maintained over time.

In parallel, the parameters used in the safety stock and EOQ models for pipe fittings and pipe clamps should be revisited as production volumes increase and more consumption data becomes available, to ensure that stock levels remain adequate.

More broadly, the Muda identification framework applied in this work could be extended transversally across the remaining stages of the production process. A systematic analysis of non-value-adding activities, following the same observation and time study methodology adopted could reveal further opportunities for improvement and contribute to a more comprehensive reduction of waste across the full production flow.

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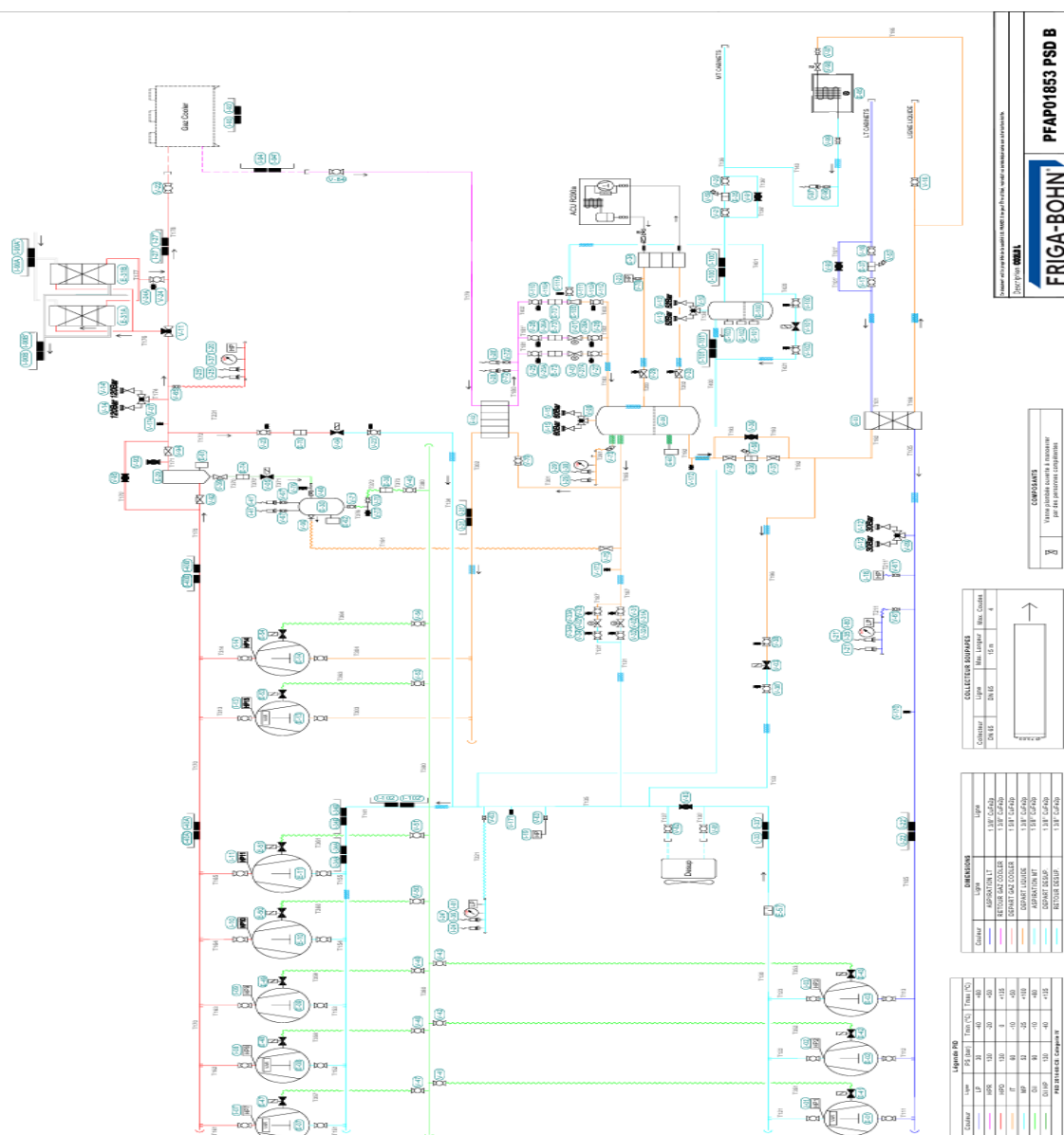
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Appendix A

P&ID Diagram



Appendix B

List of components

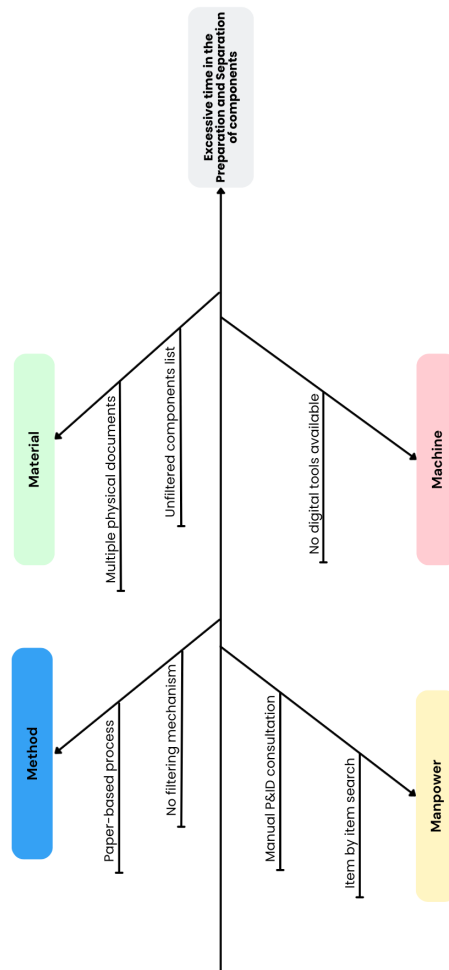
B.1 Before improvements

KOOLSYS -	DESCRIÇÃO -	PAID No. -	CÓDIGO SAP -	DESCRIÇÃO -	QUANTIDADE -
TRIMORIM					
21/11/2025 09:29					
JT					
	ESTRUTURA				
MARCA:				Estrutura	1
FB				Pictura	1
	EQUIPAMENTO				
COMPRESSOR LT	E-01	904210391	COHPR SH 4DSL-10K		1
RESISTÊNCIAS CARTER COMPRESSOR LT	E-01.1	904902163	RESIST CARTER 120w/200-400v 343219-01		1
COMPRESSOR LT	E-02	904210391	COHPR SH 4DSL-10K		1
RESISTÊNCIAS CARTER COMPRESSOR LT	E-02.1	904902163	RESIST CARTER 120w/200-400v 343219-01		1
COMPRESSOR LT	E-03	904210391	COHPR SH 4DSL-10K		1
RESISTÊNCIAS CARTER COMPRESSOR LT	E-03.1	904902163	RESIST CARTER 120w/200-400v 343219-01		1
COMPRESSOR LT	E-04	904210391	COHPR SH 4DSL-10K		1
RESISTÊNCIAS CARTER COMPRESSOR LT	E-04.1	904902163	RESIST CARTER 120w/200-400v 343219-01		1
COMPRESSOR MT	E-07	900049074	COHPR SH 4FTE-30K		1
VÁLVULA ASPIRAÇÃO COMPRESSOR MT	E-07NA	900077624	VALV ASP COMPRI DIZ#DA35FTR 34131554		1
VÁLVULA DESCARGA COMPRESSOR MT	E-07ND	900041107	VALV DESO COMPRI DIN#DA25F/TT 34134726		1
EXTENSAO MÓDULO CM-10-A-10 MT 1	E-07E1	900000974	EXTENSAO MÓDULO CM-10-A-10		1
SONDA DE CARGA PT1000-10 MT 1	E-07 S1	900000975	SONDA DE CARGA PT1000-10		1
REGULAÇÃO CAP CKHE-10 MT 1	E-07R1	900001401	REGULAÇÃO CAP CKHE-10		2
COMPRESSOR HT	E-08	900049074	COHPR SH 4FTE-30K		1
VÁLVULA ASPIRAÇÃO COMPRESSOR HT	E-08NA	900077624	VALV ASP COMPRI DIZ#DA35FTR 34131554		1
VÁLVULA DESCARGA COMPRESSOR HT	E-08ND	900041107	VALV DESO COMPRI DIN#DA25F/TT 34134726		1
COMPRESSOR HT	E-09	900000974	COHPR SH 4FTE-30K		1
VÁLVULA ASPIRAÇÃO COMPRESSOR HT	E-09NA	900077624	VALV ASP COMPRI DIZ#DA35FTR 34131554		1
VÁLVULA DESCARGA COMPRESSOR HT	E-09ND	900041107	VALV DESO COMPRI DIN#DA25F/TT 34134726		1
COMPRESSOR HT	E-10	900000974	COHPR SH 4FTE-30K		1
VÁLVULA ASPIRAÇÃO COMPRESSOR HT	E-10NA	900077624	VALV ASP COMPRI DIZ#DA35FTR 34131554		1
VÁLVULA DESCARGA COMPRESSOR HT	E-10ND	900041107	VALV DESO COMPRI DIN#DA25F/TT 34134726		1
COMPRESSOR PARALELO	E-13	900049074	COHPR SH 4FTE-30K		1
VÁLVULA ASPIRAÇÃO COMPRESSOR IT	E-13NA	900077624	VALV ASP COMPRI DIZ#DA35FTR 34131554		1
VÁLVULA DE CARGA COMPRESSOR IT	E-13ND	900041107	VALV DESO COMPRI DIN#DA25F/TT 34134726		1
EXTENSAO MÓDULO CM-10-A-10 IT 1	E-13 E1	900000974	EXTENSAO MÓDULO CM-10-A-10		1
SONDA DE CARGA PT1000-10 IT 1	E-13 S1	900000975	SONDA DE CARGA PT1000-10		1
REGULAÇÃO CAP CKHE-10 IT 1	E-13 R1	900001401	REGULAÇÃO CAP CKHE-10		2
VÁLVULA ASPIRAÇÃO COMPRESSOR IT	E-14	900049074	COHPR SH 4FTE-30K		1
VÁLVULA DE CARGA COMPRESSOR IT	E-14NA	900077624	VALV ASP COMPRI DIZ#DA35FTR 34131554		1
VÁLVULA DESCARGA COMPRESSOR IT	E-14ND	900041107	VALV DESO COMPRI DIN#DA25F/TT 34134726		1
DEPÓSITO DE LÍQUIDO	E-20	900000974	COHPR SH 4FTE-30K		1
SEPARADOR DE ÓLEO	E-20	900000974	COHPR SH 4FTE-30K		1
CARGA FILTRANTE SEPARADOR DE ÓLEO	E-20F	900000974	COHPR SH 4FTE-30K		1
DEPÓSITO DE ÓLEO	E-20	900000974	COHPR SH 4FTE-30K		1
PERMUTADOR IT-HP	E-22	900000974	COHPR SH 4FTE-30K		1
PERMUTADOR LT-LÍQUIDO	E-22	900000974	COHPR SH 4FTE-30K		1
PERMUTADOR 2x2x	E-24	900000974	COHPR SH 4FTE-30K		1
FILTRO ASPIRAÇÃO HT	E-28	900000974	COHPR SH 4FTE-30K		1
CARGA FILTRANTE	E-28F	900000974	COHPR SH 4FTE-30K		1
FILTRO DE LÍQUIDO	E-28	900000974	COHPR SH 4FTE-30K		1
CARGA FILTRANTE HP	E-28F	900000974	COHPR SH 4FTE-30K		1
FILTRO ASPIRAÇÃO LT	E-27	900000974	COHPR SH 4FTE-30K		1
CARGA FILTRANTE N	E-27F	900000974	COHPR SH 4FTE-30K		1
CARGA FILTRANTE F	E-27F	900000974	COHPR SH 4FTE-30K		1
CARGA FILTRANTE I	E-27F	900000974	COHPR SH 4FTE-30K		1
FILTRO DE ÓLEO	E-28	900000974	COHPR SH 4FTE-30K		1
REGULADOR NÍVEL ÓLEO	E-41	900000974	COHPR SH 4FTE-30K		1
REGULADOR NÍVEL ÓLEO	E-42	900000974	COHPR SH 4FTE-30K		1
REGULADOR NÍVEL ÓLEO	E-43	900000974	COHPR SH 4FTE-30K		1
REGULADOR NÍVEL ÓLEO	E-44	900000974	COHPR SH 4FTE-30K		1
REGULADOR NÍVEL ÓLEO	E-47	900000974	COHPR SH 4FTE-30K		1
REGULADOR NÍVEL ÓLEO	E-48	900000974	COHPR SH 4FTE-30K		1
REGULADOR NÍVEL ÓLEO	E-49	900000974	COHPR SH 4FTE-30K		1
REGULADOR NÍVEL ÓLEO	E-50	900000974	COHPR SH 4FTE-30K		1
REGULADOR NÍVEL ÓLEO	E-53	900000974	COHPR SH 4FTE-30K		1
REGULADOR NÍVEL ÓLEO	E-54	900000974	COHPR SH 4FTE-30K		1
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ADAPTADOR REGULADOR NÍVEL ÓLEO	E-42.1	900000974	COHPR SH 4FTE-30K		1
ADAPTADOR REGULADOR NÍVEL ÓLEO	E-43.1	900000974	COHPR SH 4FTE-30K		1
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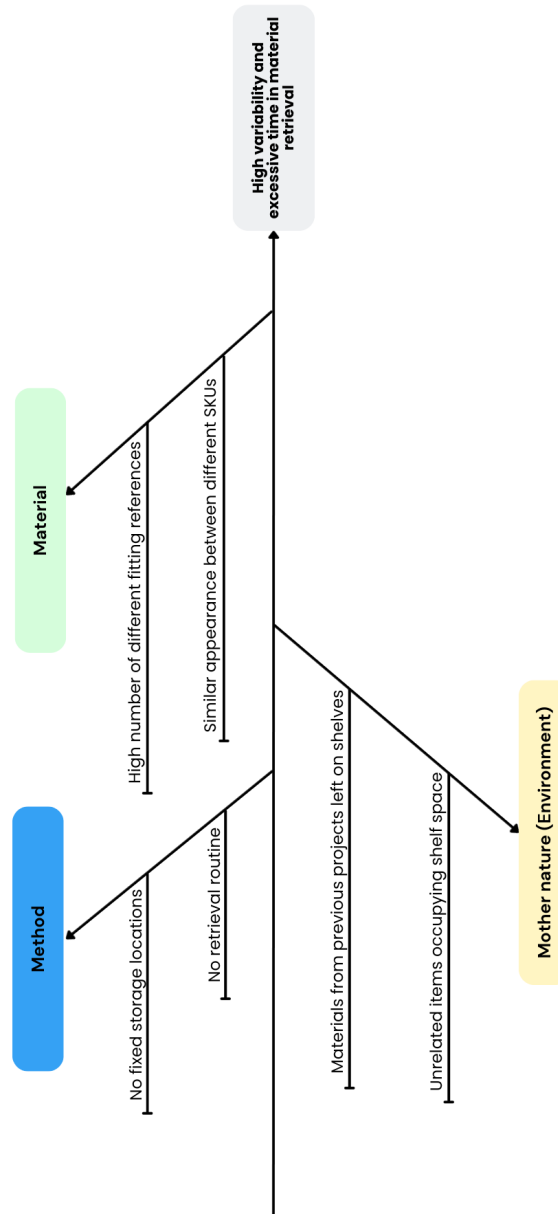
Appendix C

Ishikawa diagrams

C.1 Excessive time in the separation and labelling process



C.2 High variability and excessive time in material retrieval



Appendix D

Separation and Labelling Process: Time Study Observations

D.1 Before improvements

1ª OBSERVAÇÃO				2ª OBSERVAÇÃO				3ª OBSERVAÇÃO			
Nº DE COMPONENTES (LISTA)		Nº DE COMPONENTES ETIQUETADOS		Nº DE COMPONENTES (LISTA)		Nº DE COMPONENTES ETIQUETADOS		Nº DE COMPONENTES (LISTA)		Nº DE COMPONENTES ETIQUETADOS	
241		101		344		121		419		149	
41.91%		41.91%		35.17%		35.17%		35.56%		35.56%	
TAREFA	TEMPO	SEG	%	TAREFA	TEMPO	SEG	%	TAREFA	TEMPO	SEG	%
Relizar materialização da simulação	37' 12"	2160	26.34%	Relizar materialização da simulação	51' 06"	3060	25.21%	Relizar materialização da simulação	58' 51"	3531	18.52%
Etiquetar	26' 42"	1602	27.59%	Etiquetar	28' 14"	1574	16.68%	Etiquetar	68' 51"	4085	33.67%
Confeitar	29' 15"	1755	30.23%	Confeitar	59' 11"	3541	37.55%	Confeitar	62' 59"	3779	31.15%
Outras tarefas	3' 37"	217	3.74%	Outras tarefas	40' 47"	2447	25.81%	Outras tarefas	32' 8"	1988	16.39%
TOTAL	96' 46"	5808	100.00%	TOTAL	158'	9480	100%	TOTAL	202' 12"	12132	100%
TAREFA				TAREFA				TAREFA			
TEMPO MÉDIO				TEMPO MÉDIO				TEMPO MÉDIO			
Etiquetagem por componente listado				Etiquetagem por componente listado				Etiquetagem por componente listado			
15.66				13.01				9.75			
Etiquetagem por componente etiquetado				Etiquetagem por componente etiquetado				Etiquetagem por componente etiquetado			
7.28				10.29				9.02			
Confirmação por componente listado				Confirmação por componente listado				Confirmação por componente listado			
17.38				29.26				25.36			
Separação por componente listado				Separação por componente listado				Separação por componente listado			
24.09				27.56				26.95			
Separação por componente etiquetado				Separação por componente etiquetado				Separação por componente etiquetado			
57.49				78.35				81.42			

D.2 After improvements

1ª OBSERVAÇÃO					2ª OBSERVAÇÃO					3ª OBSERVAÇÃO										
Nº DE COMPONENTES (LISTA)		223	Nº DE COMPONENTES ETIQUETADOS		90	Nº DE COMPONENTES (LISTA)		393	Nº DE COMPONENTES ETIQUETADOS		160	Nº DE COMPONENTES (LISTA)		392	Nº DE COMPONENTES ETIQUETADOS		160	Nº DE COMPONENTES ETIQUETADOS		40.82%
TAREFA	1ª	SEG	%	TAREFA	1ª	SEG	%	TAREFA	1ª	SEG	%	TAREFA	1ª	SEG	%	TAREFA	1ª	SEG	%	
Retirar material das caixas armazen	45'	2700	38.09%	Retirar material das caixas armazen	36	2160	28.31%	Retirar material das caixas armazen	35'	2100	31.04%	Retirar material das caixas armazen	35'	2100	31.04%	Retirar material das caixas armazen	35'	2100	31.04%	
Etiquetar	27' 53"	1673	23.69%	Etiquetar	32' 47"	1967	25.78%	Etiquetar	26' 11"	1571	23.22%	Etiquetar	26' 11"	1571	23.22%	Etiquetar	26' 11"	1571	23.22%	
Confeirir	23' 59"	1439	20.30%	Confeirir	29' 17"	1757	23.02%	Confeirir	24' 2"	1442	21.32%	Confeirir	24' 2"	1442	21.32%	Confeirir	24' 2"	1442	21.32%	
Outras tarefas	21' 16"	1276	18.00%	Outras tarefas	29' 7"	1747	22.89%	Outras tarefas	27' 32"	1652	24.42%	Outras tarefas	27' 32"	1652	24.42%	Outras tarefas	27' 32"	1652	24.42%	
TOTAL	118' 8"	7088	100.00%	TOTAL	127' 11"	7631	100.00%	TOTAL	117' 45"	6765	100.00%	TOTAL	117' 45"	6765	100.00%	TOTAL	117' 45"	6765	100.00%	
TAREFA	TEMPO MEDIO			TAREFA	TEMPO MEDIO			TAREFA	TEMPO MEDIO			TAREFA	TEMPO MEDIO							
Etiquetagem por componente listado	7.50			Etiquetagem por componente listado	5.01			Etiquetagem por componente listado	4.01			Etiquetagem por componente listado	4.01							
Etiquetagem por componente etiquetado	18.59			Etiquetagem por componente etiquetado	12.29			Etiquetagem por componente etiquetado	9.82			Etiquetagem por componente etiquetado	9.82							
Confirmação por componente listado	6.45			Confirmação por componente listado	4.47			Confirmação por componente listado	3.68			Confirmação por componente listado	3.68							
Confirmação por componente etiquetado	15.99			Confirmação por componente etiquetado	10.98			Confirmação por componente etiquetado	9.01			Confirmação por componente etiquetado	9.01							
Separação por componente listado	31.78			Separação por componente listado	19.42			Separação por componente listado	17.26			Separação por componente listado	17.26							
Separação por componente etiquetado	78.76			Separação por componente etiquetado	47.69			Separação por componente etiquetado	42.28			Separação por componente etiquetado	42.28							

Appendix E

Materials Retrieval: Time Study Observations

E.1 Before improvements

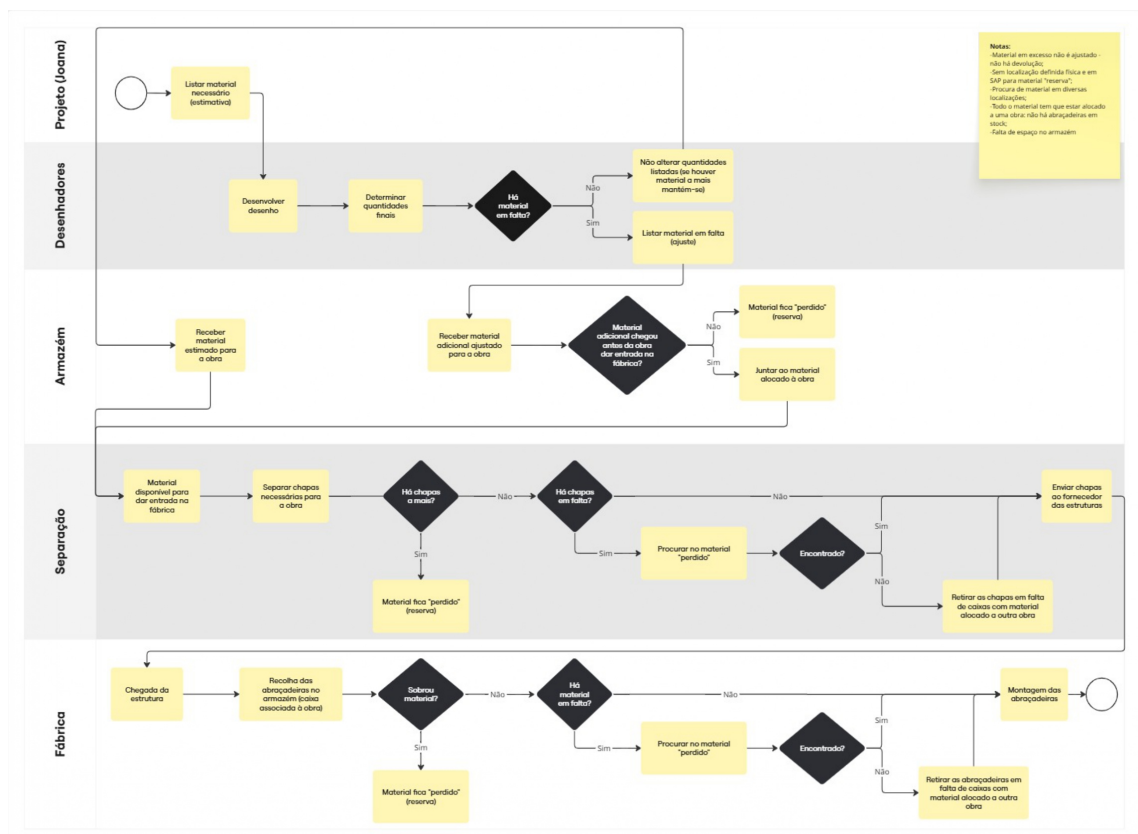
TEMPO DE PROCURA MATERIAL TUBAGEM											
OBSERVAÇÃO	# PEÇAS	VALVULA	FILTRO	CURVAS	CAPS	REDUÇÃO	TES	UNID. ROSCADA	TIPO DE COMPONENTES	MINUTOS	SEGUNDOS
1	4	-	-	3	-	-	1	-	1 Curva, 1 Te	2	14
2	1	-	-	-	-	-	-	-	1 Redução	0	18
3	3	-	-	2	-	1	-	-	2 Curvas, 1 Redução	1	28
4	3	1	-	2	-	-	-	-	2 Curvas, 1 Valvula	0	29
5	4	1	-	3	-	-	-	-	1 Valvula, 3 Curvas	0	54
6	2	1	-	1	-	-	-	-	1 Redução, 1 Curva	0	33
7	2	-	-	2	-	-	-	-	2 Curvas	0	33
8	4	1	-	3	-	-	-	-	3 Curvas, 1 Valvula	0	40
9	7	7	-	-	-	-	-	-	7 Valvulas	0	47
10	2	7	-	-	-	-	-	-	4 Curvas, 1 Te	0	47
11	2	-	-	1	1	-	1	-	1 Curva e 1 Te	4	59
12	2	-	-	1	-	-	-	-	1 Curva e 1 Curva	3	10
13	1	1	-	1	-	-	-	-	1 Valvula e 1 Te	0	59
14	2	1	-	1	1	-	-	-	1 Redução	0	59
15	1	-	-	-	-	1	-	-	1 Redução	0	59
16	7	1	-	3	-	1	1	1	1 Valvula, 1 Te, 2 Curvas, 1 Redução, 1 Unid. roscada	2	32
17	3	1	-	3	-	-	2	-	2 Valvulas, 1 Curva, 1 Redução	2	32
18	6	2	-	4	-	-	-	-	2 Valvulas, 4 Curvas	1	22
19	4	4	-	-	-	-	-	-	4 Valvulas	1	2
20	8	-	-	6	-	-	-	-	6 Curvas e 2 Tes	2	28
21	1	-	-	1	-	-	-	-	1 Redução e 1 Curva	0	148
22	5	1	-	4	-	-	-	-	1 Valvula e 4 Curvas	3	18
23	3	-	-	-	-	1	-	2	1 Redução e 2 Unid. roscadas	3	48
24	4	-	-	2	-	-	-	-	1 Valvula, 1 Te, 2 Curvas	0	53
25	5	1	-	2	-	1	1	-	1 Valvula, 1 Te, 2 Curvas e 1 Redução	2	4
26	5	-	-	2	-	1	-	2	2 Unid. roscadas, 2 Curvas e 1 Redução	7	10
27	5	1	-	4	-	-	-	-	4 Curvas e 1 Valvula	1	20
28	3	3	-	-	-	-	-	-	3 Valvulas	1	30

E.2 After improvements

OBSERVAÇÃO	# PEÇAS	TEMPO PROCURA MATERIAL TUBAGEM										TIPO DE COMPONENTES	MINUTOS	SEGUNDOS	TEMPO (SEG)	TUBISTA
		VALVULAS	FILTROS	CURVAS	CAPS	REDUÇÕES	TES	UNID. ROSCADAS	PONTEIRAS ROSCADAS							
1	4	-	-	4	-	-	-	-	-	-	4 Curvas	0	35	35	Ricardo	
2	3	-	-	3	-	-	-	-	-	-	3 Curvas	0	29	29	Ricardo	
3	5	-	-	3	1	1	-	-	-	-	3 Curvas, 1 Redução e 1 Cap	0	48	48	João	
4	4	1	-	3	-	-	-	-	-	-	1 Válvula e 3 Curvas	0	41	41	Jorge	
5	7	-	-	3	-	2	-	-	2	-	3 Curvas, 2 Reduções e 2 Ponteiros roscadas	0	51	51	João	
6	5	-	-	-	1	-	-	-	4	-	4 Ponteiros roscados e 1 Cap	0	28	28	João	
7	3	-	-	7	3	-	-	-	-	-	3 Caps	0	33	33	Ricardo	
8	15	6	2	1	-	2	4	-	-	-	6 Válvulas, 2 Filtros, 4 Tes, 1 Curva e 2 Reduções	2	7	127	João	
9	8	3	1	2	-	-	2	-	-	-	3 Válvulas, 1 Filtro, 2 Curvas e 2 Tes	1	22	82	Jorge	
10	1	1	-	1	-	-	-	-	-	-	1 Válvula	0	56	56	Jorge	
11	6	1	-	4	-	-	1	-	-	-	1 Válvula, 4 Curvas e 1 Te	1	27	87	João	
12	4	-	-	3	-	1	-	-	-	-	3 Curvas e 1 Redução	0	40	40	João	
13	3	-	-	2	-	-	-	-	-	-	1 Te e 2 Curvas	0	16	16	João	
14	3	2	1	-	-	-	-	-	-	-	2 Válvulas e 1 Filtro	0	48	48	Jorge	
15	4	1	-	3	-	-	-	-	-	-	1 Válvula e 3 Curvas	1	52	112	Jorge	
16	4	2	-	-	-	-	1	1	-	-	1 Te, 1 União roscada e 2 Válvulas	0	52	52	João	
17	3	1	-	2	-	-	-	-	-	-	1 Válvula e 2 Curvas	0	37	37	João	
18	4	-	-	4	-	-	-	-	-	-	4 Curvas	0	35	35	Jorge	
19	2	-	-	4	-	-	-	2	-	-	2 Unid. roscadas	0	27	27	Jorge	
20	12	6	-	4	-	-	2	-	-	-	6 Válvulas, 4 Curvas e 2 Tes	1	33	93	Jorge	
21	3	2	-	1	-	-	-	-	-	-	2 Válvulas e 1 Curva	0	34	34	João	
22	4	1	-	2	-	1	-	-	-	-	1 Válvula, 2 Curvas e 1 Redução	0	39	39	João	
23	7	-	-	4	-	2	1	-	-	-	4 Curvas, 2 Reduções e 1 Te	0	55	55	Ricardo	
24	1	1	1	-	-	-	-	-	-	-	1 Válvula	1	2	62	Ricardo	
25	6	-	-	2	-	-	-	4	-	-	2 Curvas e 4 Unid. roscadas	0	40	40	Ricardo	

Appendix F

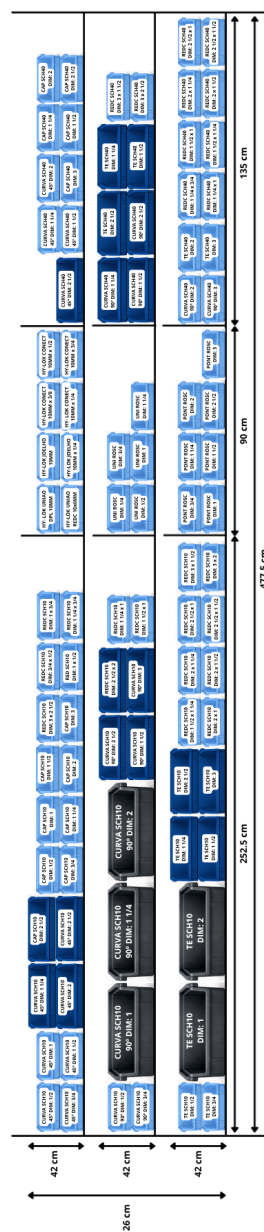
Pipe Clamps: Material Flow and Management Process



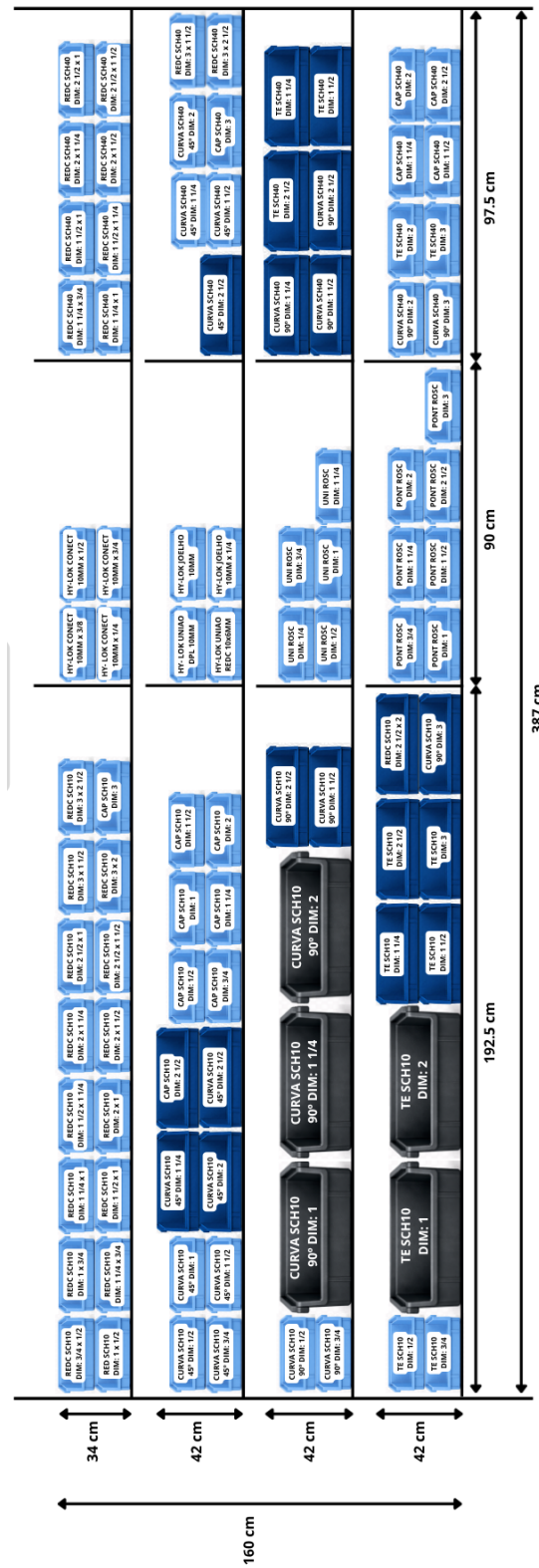
Appendix G

Shelving Layout Options - Centralised Storage of Pipe Fittings

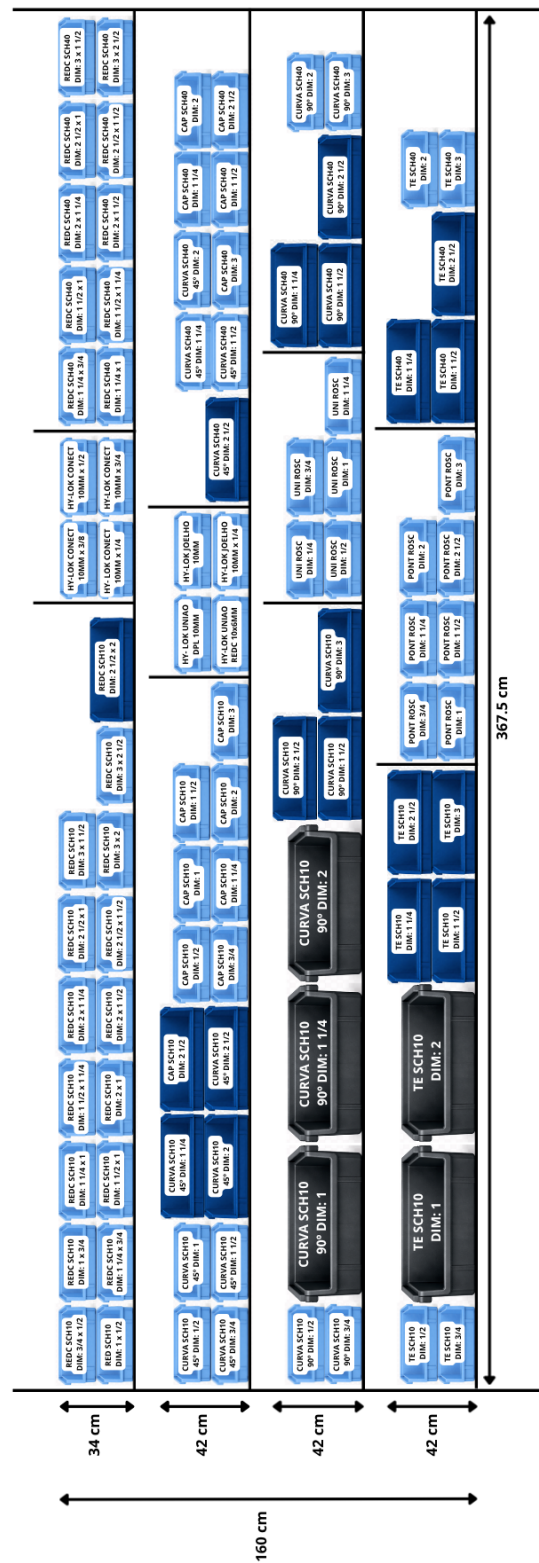
G.1 Second Option



G.2 Third Option



G.3 Fourth Option



Reflexion on the Sustainable Development Goals

The United Nations Sustainable Development Goals (SDGs) offer a lens through which the broader implications of this dissertation can be examined, beyond its immediate operational scope. The goals to which this work most directly relates are the following:

SDG 8 – Decent Work and Economic Growth: The 5S improvements applied to welder’s workstations and pipe fitters’ tool carts directly address the physical organisation of the work environment, reducing unnecessary physical effort, improving tool accessibility and contributing to safer daily routines. In doing so, the dissertation supports conditions under which workers can perform more consistently, with direct implications for both well-being and sustained productivity.

SDG 12 - Responsible Consumption and Production: The elimination of non-value-added activities reduces operational waste without additional resource consumption. The introduction of safety stock modelling and volumetric storage sizing ensures that materials are held and consumed in a controlled manner, minimising excess and supporting leaner, more responsible use of physical resources across the production cycle.

Taken together, the improvements proposed in this dissertation reflect a broader alignment between operational engineering work and sustainable development principles. The quantitative metrics established to evaluate each intervention provide a foundation for tracking progress against these dimensions over time.