



Mestrado em Engenharia Mecânica

Improvement of Production Processes in a Refrigeration Plant Manufacturing Unit

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Dissertação de mestrado

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January, 2025

Abstract

The constant need to shorten delivery times while simultaneously meeting quality standards creates an increasing demand for an effective production strategy. This work explores solutions to improve the production process of refrigeration units using CO_2 as the working fluid, a technological solution that has been gaining relevance due to its high energy efficiency and low environmental impact, particularly in cold climate regions. CO_2 stands out for being sustainable and enabling the use of smaller components due to its high latent heat of vaporization per volume.

The main objective of this project is to increase the efficiency of the production process, reduce waste, and improve resource utilization without compromising the quality of the final product. To achieve this, two main approaches were defined: improving the production process and reconfiguring the factory layout.

Initially, methodologies based on Lean Manufacturing principles were studied, including the Kaizen philosophy, the PDCA cycle, and tools such as 5S and Value Stream Mapping (VSM), as well as performance indicators. A study was also conducted to analyze the factory layout, presenting existing types and planning methodologies.

Subsequently, thermodynamic concepts underlying the operation of the refrigeration units under study were explained.

The methodologies initially studied proved fundamental for analyzing the production process, as they allowed the identification of bottlenecks, the elimination of waste, and the implementation of gradual and continuous improvements in production stages. Automation and targeted employee training also played a crucial role, ensuring greater operational efficiency and better use of available human resources. A goal was set to reduce total production time by at least 15%, with significant gains in productivity and process control.

In parallel, the factory layout was reconfigured to improve the flow of materials and operators, ensuring greater ergonomics, safety, and efficiency in internal logistics. A detailed analysis of the existing layout was carried out, and using the Systematic Layout Planning (SLP) methodology, different layout alternatives were created, analyzed, and compared, validating the implementation of changes on a solid foundation.

Thus, this work not only addresses the operational and commercial needs of the studied company but also reinforces the importance of sustainable and innovative production practices. The proposed and implemented improvements resulted in increased production efficiency, cost reduction, and a positive impact on business competitiveness, aligning with current market demands and expectations for continuous innovation.

Resumo

A constante necessidade de encurtar os tempos de entrega, cumprindo simultaneamente os padrões de qualidade, gera uma crescente exigência por uma estratégia produtiva eficaz. Este trabalho explora soluções para a melhoria do processo de produção de centrais frigoríficas que utilizam CO_2 como fluido de trabalho, uma solução tecnológica que tem vindo a ganhar relevância devido à sua elevada eficiência energética e baixo impacto ambiental, especialmente em regiões de clima frio. O CO_2 destaca-se por ser sustentável e por possibilitar o uso de componentes de menores dimensões, devido ao seu elevado calor latente de vaporização por volume.

O principal objetivo deste projeto é aumentar a eficiência do processo produtivo, reduzir desperdícios e melhorar a utilização dos recursos, sem comprometer a qualidade do produto final. Para tal, foram definidas duas abordagens principais: a melhoria do processo produtivo e a reconfiguração do layout fabril.

Inicialmente, foram estudadas metodologias baseadas nos princípios do Lean Manufacturing, incluindo a filosofia Kaizen, o ciclo PDCA e ferramentas como os 5S e o Mapeamento do Fluxo de Valor (VSM), bem como alguns indicadores de desempenho. Foi também elaborado um estudo para a análise do layout de fábrica, apresentando os tipos existentes e as metodologias de planeamento.

De seguida, foram explicados conceitos termodinâmicos que servem de base ao funcionamento das centrais frigoríficas em estudo.

As metodologias inicialmente estudadas revelaram-se fundamentais para analisar o processo produtivo, pois permitiram identificar gargalos, eliminar desperdícios e implementar melhorias graduais e contínuas nas etapas produtivas. A automação e a formação direcionada dos colaboradores também desempenharam um papel crucial, assegurando maior eficiência operacional e um melhor aproveitamento dos recursos humanos disponíveis. Como meta, foi proposta a redução do tempo total de produção em pelo menos 15%, com ganhos significativos na produtividade e no controlo do processo.

Paralelamente, realizou-se a reconfiguração do layout fabril, que teve como objetivo melhorar o fluxo de materiais e operadores, assegurando uma maior ergonomia, segurança e eficiência na logística interna. Foi feita uma análise detalhada do layout existente e, com recurso à metodologia Systematic Layout Planning (SLP), foi possível criar diferentes alternativas de layout, posteriormente analisadas e comparadas, validando a implementação das mudanças de forma fundamentada.

Desta forma, o trabalho não só responde às necessidades operacionais e comerciais da empresa estudada, como também reforça a importância de práticas produtivas sustentáveis e inovadoras. As melhorias propostas e implementadas resultaram num aumento da eficiência produtiva, redução de custos e impacto positivo na competitividade empresarial, alinhando-se às exigências do mercado atual e às expectativas de inovação contínua.

Acknowledgements

First of all, I would like to thank FEUP for the knowledge and values shared throughout these years, which have allowed me to grow both personally and professionally.

To Professor Jonas André Rodrigues Henriques de Lima, for his continuous guidance and support throughout this work, always providing the necessary help to ensure everything went smoothly.

To RACE S.A., for the opportunity to develop this project in a business environment, providing me with an enriching experience that allowed me to grow and learn in a practical way.

To all the people who were part of the internship and contributed to the achievement of the proposed objectives.

To Bernardo Pinheiro e Silva, my supervisor at the company, who was a fundamental and tireless support throughout the entire process, always offering the necessary assistance.

Finally, I would like to thank my family and close friends, who have been part of this entire journey, offering crucial support at every moment.

To all of them, my heartfelt thanks.

Duarte Silva

"It's impossible to progress without change, and those who don't change their minds can't change anything."

George Bernard Shaw

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Acronyms and Symbols

ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
DHW	Domestic Hot Water
FEUP	Faculdade de Engenharia Mecânica da Universidade do Porto
GC	Gas Cooler
GWP	Global Warming Potential
HE	Heat Exchanger
HVAC	Heating, Ventilating and Air Conditioning
KPI	Key Performance Indicator
LT	Low Temperature
LR	Liquid Receiver
MT	Medium Temperature
ODP	Ozone Depletion Potential
OR	Oil Receiver
OS	Oil Separator
RACE	Refrigeration & Air Conditioning Engineering, S.A.
REL	Relationship Charts
ROI	Return On Investment
SLP	Systematic Layout Planning
SWOT	Strengths, Weaknesses, Opportunities and Threats
VSM	Value Stream Mapping

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Chapter 1

Introduction

1.1 Project Framework

Meeting deadlines and the constant need to shorten delivery times increasingly demand the adoption of a robust production strategy. To address these needs, various strategies aimed at reorganizing production and reducing associated times have been studied. In addition to these efforts, it is crucial to maintain the quality of the produced goods while minimizing waste, both in terms of time and materials.

To tackle these challenges, one of the main strategies involves a detailed study of operation times and the interconnections between stages of the production process. Analyzing the components that form the system and identifying possible "pre-work" that can be performed play a fundamental role in this improvement process. Additionally, using software capable of simulating production times emerges as a beneficial alternative, as it allows tests to be conducted at a low cost.

Beyond analyzing the stages of the production process, the layout of the factory floor also plays a crucial role in this improvement process. A well-designed layout can reduce the time required for material and operator movement, contributing to greater productivity. Analyzing different layout design hypothesis, coupled with evaluation methodologies, allows the identification of the most suitable solution to implement.

Therefore, there is a need to investigate these practices in the specific context of refrigeration systems, which present significant particularities. This dissertation focuses on improving the production process of a refrigeration unit with the goal of reducing times and meeting the company's needs. All the methodologies mentioned earlier will be fundamental to addressing the identified problem.

This research focuses on refrigeration units using CO₂, equipment that has gained considerable relevance in recent years. This type of unit has stood out particularly in cold climate regions, where it demonstrates better energy efficiency.

1.2 Objective

The main objective of this work is to improve the production process of KoolSys refrigeration units, reducing the time from the arrival of components at the factory to the departure of the final product, without compromising quality standards. This primary goal will be subdivided into two distinct areas of focus.

The first area is to identify potential improvements and errors in production that enable a 15% reduction in the production time of refrigeration units. This will involve eliminating bottlenecks and waste through the use of Lean methodologies, automation, and employee training, with the goal of achieving greater efficiency and performance control.

The second focus is the reconfiguration of the factory layout, which will play a key role in this project. This will involve improving the flow of materials and operators, enhancing ergonomics and safety, reducing unnecessary movements, and optimizing internal logistics.

1.3 Methodology

The approach to the proposed problem divided the primary objective into two distinct goals, each addressed separately.

For the first goal, which aims to identify potential improvements to the process, a detailed monitoring of the production process for various refrigeration units will be conducted. During this monitoring, errors will be identified, and alternatives will be suggested to optimize the production flow. These suggestions will be analyzed in terms of their advantages and disadvantages, taking into account their feasibility of implementation. Once applied, the results will be monitored and analyzed to assess the impact on production time reduction.

The second goal, focused on improving the factory layout, will involve a thorough analysis of the current layout to identify key issues that may be hindering production flow efficiency. Alternatives will be presented and discussed with process stakeholders, evaluating their pros and cons. After validation of the improvements through simulation, the changes will be implemented, and the results will be analyzed to confirm their effectiveness.

1.4 Structure

This report is organized into six chapters, each addressing different aspects of the study conducted, with the aim of providing a continuous and organized reading experience, facilitating the understanding of the document.

In **Chapter 1 – Introduction**, the topic is contextualized, the objectives of the work are established, and the methodology adopted is outlined. Additionally, the host company is introduced, giving the reader an overview of the study.

Chapter 2 – Literature Review, discusses the key concepts related to process improvement, with a focus on established methodologies such as Lean Manufacturing and Kaizen. The importance of performance indicators (KPIs) is emphasized, as they play a critical role in analysis and effective decision-making. Additionally, the chapter explores the application of decision-making methods as tools for layout optimization, highlighting their practical relevance in operational improvement.

Chapter 3 – Analysis of the Process provides an in-depth exploration of refrigeration principles, including the operation of the thermodynamic cycle, the refrigerant used, and the main components of the system along with their functions. It also outlines the production stages of the refrigeration unit, identifies potential failures, and proposes enhancements to improve the system's efficiency and performance.

Chapter 4 – Improvements Implemented outlines the approach used to analyze and enhance the production system under study. The chapter highlights the key improvements made to the process and discusses layout modifications, including a comparison of three proposed alternatives. Finally, it evaluates the results achieved, emphasizing the gains in efficiency and process performance.

Chapter 5 – Analysis of Results presents the approach used to evaluate the outcomes of the improvements implemented. It begins with an assessment of the improved process, highlighting key changes and their impact on efficiency and performance. Following this, the improved layout is analyzed, focusing on its contribution to optimizing workflows and addressing previously identified issues. Together, these analyses provide a comprehensive understanding of the effectiveness of the enhancements made.

Chapter 6 – Conclusions summarizes the main findings of the study and suggests directions for future work, indicating areas that could be further explored or complemented.

Appendices – The appendices include additional information and technical details used throughout the study, such as tables, graphs, calculations, and other supporting documents that help contextualize and reinforce the results presented.

1.5 Presentation of the Host Company

The **SKK** group consists of several companies operating in the fields of air conditioning, refrigeration, and industrial engineering.

One of these companies is **SKK**, founded in 1998, whose main activity is the selection and distribution of refrigeration and air conditioning system equipment.

With a highly qualified engineering team and a diverse portfolio of leading global brands ensuring reliability, solid performance, and energy efficiency, SKK actively supports and accompanies its partners in the search and selection of equipment tailored to each specific need.

Since 2015, with its new name, **upK - Facility Management and Maintenance, SA**, the company has continued the legacy of the originally named **SMP - Maintenance Services and Planning, SA**, with over 20 years of experience in industrial and building maintenance, more than

250 employees, and the accumulated expertise. UpK positions itself as one of the key players in the maintenance of commercial office buildings and facility management.

One of upK's priorities is to keep its employees continuously motivated and customer-oriented, relying on a young and dynamic team dedicated to this goal, which is continually strengthened.

Now focusing on **RACE – Refrigeration & Air Conditioning Engineering, S.A.**, a Portuguese company founded in 1985 and located in Guifões. RACE develops innovative engineering solutions for sectors such as commercial and industrial refrigeration, hospitality, HVAC (heating, ventilation, and air conditioning), and technical assistance. They cover all stages of the process, from design and manufacturing to the installation of custom-made equipment based on their clients' specific needs.

Within the structure of RACE is **KoolSys**, specialized in the development and manufacturing of CO₂ refrigeration units tailored to various market segments, ranging from small supermarkets to large industrial facilities. KoolSys focuses on robust, efficient, and user-friendly refrigeration systems, backed by the expertise its teams have accumulated over the years. Their solutions ensure the highest energy efficiency, utilizing advanced algorithms and monitoring and control systems that are compatible with the leading systems on the market.

This project was developed in the production department of KoolSys, which provided the necessary support, from access to technical information to collaboration with the involved teams. The goal was to analyze and improve the production processes, in line with the company's commitment to promoting innovation and operational efficiency.

Chapter 2

Literature Review

This chapter addresses the main concepts and theoretical tools used in the analysis and improvement of industrial processes, with a focus on Lean Manufacturing. Topics such as Kaizen Philosophy, Just-in-Time, PDCA Cycle, 5S, Cause and Effect Diagram, Value Stream Mapping, Standardized Work, and Bottleneck Analysis are explored, highlighting their contributions to waste elimination and operational efficiency.

In addition, the importance of Key Performance Indicators is discussed, as they are fundamental tools for measuring and monitoring process performance, enabling informed decisions aligned with strategic objectives.

Finally, the chapter examines industrial layout, detailing the existing types and the steps for planning and selection, which are essential for optimizing space utilization and improving workflow. These elements provide the theoretical foundation necessary for the development and implementation of continuous improvements in production systems.

2.1 Lean Manufacturing

Process management in an organization and its continuous improvement are fundamental to keeping a company competitive by increasing efficiency, reducing costs, improving quality, and better meeting customer needs. Continuous improvement involves a constant effort to assess performance, identify opportunities, and implement gradual changes in processes, products, and teams. To achieve these goals, various methodologies have been developed, enabling the desired outcomes.

In the pursuit of these results, a philosophy emerged with the goal of maximizing customer value through the elimination of waste. In other words, it aims to optimize processes by using fewer resources and focusing on what is essential to meet customer demands. This philosophy is **Lean Manufacturing** [1]. It is a management approach originating from the Toyota Production System, developed in Japan after World War II.

This production model stands out for being a comprehensive and integrated approach, focusing on the elimination of activities that do not add value to the final product [2]. “Waste” can take

many forms, including overproduction, transportation, excessive processing, defects, and others. The Lean philosophy uses specific tools and techniques to identify and eliminate these wastes [3].

The meaning of Lean Manufacturing goes beyond merely reducing costs or operational efficiency. It aims to develop a culture of continuous improvement, where active participation of employees at all levels of the organization is essential [4]. This approach not only improves product and process quality but also contributes to a better working environment. Therefore, this philosophy becomes a key element in this project, as its implementation will allow for the elimination of waste and errors that are hindering the smooth operation of the production process. It also adds a culture of continuous improvement that allows the company to keep up with temporal changes and maintain a positive mindset towards necessary change and progress.

To achieve the desired results with this methodology, it is necessary to use various tools and methods that help organize production [5], making the process as efficient as possible.

2.1.1 Kaizen Philosophy

Originating in Japan, the term **Kaizen** translates to **continuous improvement**. Kaizen is a management philosophy that involves the entire organization in improving processes, products, and services. It focuses on eliminating waste and increasing value for the customer. It functions as a fundamental pillar of Lean, providing the continuous improvement mindset that supports the application of various Lean tools and practices.

This approach will bring about a significant change in terms of continuously and systematically improving processes, involving all employees, from top management to line operators [6]. To achieve the proposed objectives, the following rules must be followed:

- **Continuous Improvement:** The central concept of Kaizen is based on the idea that small and constant changes can bring significant long-term benefits. Instead of large, one-time transformations, Kaizen focuses on incremental adjustments that improve efficiency and quality. In Figure 2.1, a comparative graph illustrates the timeline of progress both with and without the implementation of the Kaizen philosophy.

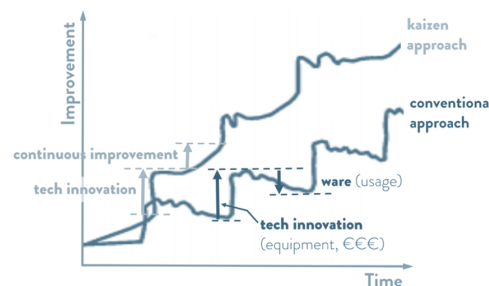


Figure 2.1: Kaizen approach vs Conventional approach [7].

- **Involvement of everyone:** One of the key aspects of Kaizen is the participation of all members of the organization. In this specific case, it is essential that all employees understand

the process and are committed to implementing the changes, actively contributing ideas and solutions.

- **Elimination of waste:** Kaizen aims to identify and eliminate waste in all its forms. It is essential to reduce or eliminate any element that causes waste, making the process more efficient and productive.
- **Simplicity and pragmatism:** The solutions proposed by Kaizen should be practical and easy to implement, avoiding the need for large investments.
- **Data and fact-based:** Improvement decisions should be based on concrete data and detailed analysis. This approach ensures that the proposed changes are effective and lead to real results.

By consistently applying this methodology during the analysis of the processes in the production of refrigeration units, it will be possible to ensure the active involvement of all employees, promoting a more collaborative and productive work environment. The participation of all team members is crucial to identifying critical points in the production flow, proposing practical solutions, and implementing continuous improvements.

This approach will allow for the implementation of small changes at various stages of the process. In terms of process improvement, it enables the practical knowledge of employees to be leveraged to identify issues and propose effective solutions. At the layout level, it ensures that employees feel comfortable with the suggested changes, facilitating their acceptance and integration into daily operations.

Although each individual improvement may seem modest, the cumulative impact of these actions will bring significant benefits, such as reduced production time, greater logistical efficiency, and better working conditions for operators, fostering a more productive and sustainable environment.

Thus, the constant use of this methodology not only ensures continuous improvement in operational efficiency but also aligns the company's strategic objectives with the commitment of all employees to the success of the production process.

2.1.2 Just in Time

Just in Time **JIT** is one of the fundamental pillars of Lean Manufacturing, being a strategy that aims to align production with demand, ensuring that materials, components, or products are delivered or produced exactly when needed and in the right quantity [8]. This approach allows for the elimination of idle stock and waste of raw materials, as only what is truly necessary is ordered and used.

For JIT to be effectively implemented, a deep understanding of the production process is essential. This requires the use of a large set of data, which, when monitored, enables the continuous optimization of workflows.

In the context of this study, JIT will be a key tool in eliminating waiting times caused by a lack of certain components or excess stock of others. Implementing this concept will make the production process more fluid by reducing downtime and idle periods, directly contributing to the overall efficiency of the operation [9].

To achieve this deep understanding of the process, Kanban becomes a crucial tool. It acts as a visual workflow management system, using physical or digital cards to signal when it is necessary to restock or produce a specific item [10]. This system ensures that each step of the process receives only what is needed for the next step, at the right time. Kanban facilitates communication between different departments, helps prevent overloading of work, minimizes waste, and ensures that the system remains agile and responsive to customer needs.

2.1.3 PDCA Cycle

The **PDCA** method is a cyclical, iterative management approach aimed at the continuous improvement of processes within a company, ensuring that it remains competitive and does not stagnate over time [11].

The acronym PDCA represents the four fundamental stages of this process [12]:

- **Plan:** Identify a problem or an opportunity for improvement, analyze relevant data, and develop an action plan with clear goals and strategies to achieve them.
- **Do:** After planning, actions should be executed on a small scale. This stage includes the implementation of the plan and the collection of data during the process to monitor performance and ensure everything is being done as planned.
- **Check:** In this stage, the results obtained during the execution phase are evaluated. The collected data is analyzed to compare expected results with actual results.
- **Act:** Based on the analysis from the "Check" stage, it is now possible to determine whether the action will be beneficial or not for the organization. If the plan is successful, it can be standardized and adopted as a regular practice. Otherwise, necessary adjustments are made, and the cycle starts again with new information for further improvement.

During the application and study of the production process of the units, this cycle will be considered several times. It offers a simple and iterative approach that facilitates the organization of improvements to be implemented. Furthermore, it was essential to demonstrate that this tool will be crucial in the future to establish a culture of continuous improvement.

This continuity allows the company to constantly adapt to changes, optimize its practices, and maintain operational efficiency. The continuous repetition of this cycle enables the gradual and systematic evolution of procedures, consolidating a culture of constant enhancement and innovation.

2.1.4 5S

The **5S** is a management methodology originating from Japan. Its main goal is to create and maintain an organized, clean, and efficient work environment, promoting discipline and continuous improvement.

The 5S acronym refers to five Japanese words that describe the steps of the process [13]:

- **Seiri (Sort):** Eliminate unnecessary items by separating essential tools and materials from those not needed. Remove or store rarely used items to create a more organized and efficient workspace.
- **Seiton (Set in Order):** Arrange remaining items efficiently by assigning designated, accessible locations. Label tools and organize strategically to optimize workflow and productivity.
- **Seiso (Shine):** Keep the workspace clean and orderly through regular cleaning of tools and equipment, improving appearance and helping identify potential issues.
- **Seiketsu (Standardize):** Establish clear standards and procedures to sustain sorting, organizing, and cleaning, such as checklists and cleaning schedules.
- **Shitsuke (Sustain):** Promote discipline to uphold 5S standards through training, regular reviews, and fostering commitment among employees.

This tool will be one of the key elements when it comes to improving the layout. In addition to improving and organizing the space according to the work areas, it is essential that this organization extends to the workbenches and is maintained over time. Therefore, it is crucial to instill in workers the practice of regularly analyzing the stages of this cycle, ensuring that the organization is maintained and continuously improved.

2.1.5 Cause and Effect Diagram

The **Cause and Effect Diagram**, also known as the Ishikawa Diagram or Fishbone Diagram, is a tool used to identify and organize the main causes of a problem, allowing for a comprehensive analysis of all the factors influencing the execution of a process [14]. The purpose of this diagram is to highlight the primary factors that lead an organization to face difficulties and failures in its processes.

Developed in Japan in 1982 by Kaoru Ishikawa, the Ishikawa Diagram is based on the 6Ms of manufacturing, a classification that groups potential causes of a problem into six categories [15]:

- **Machines:** Issues from equipment failures, poor maintenance, or improper use.
- **Manpower:** Errors due to employee attitudes, inexperience, or demotivation, highlighting the need for proper training.
- **Materials:** Problems with raw materials, including quality or suitability for the product.

- **Methods:** Flaws in practices or procedures impacting task execution.
- **Environment:** Workplace conditions like space, pollution, or temperature.
- **Measurement:** Issues with metrics, such as calibration errors or flawed evaluations.

Each of these categories represents a main group to which the identified problems can be related. Once grouped into families, all these problems will be organized in the traditional format of the diagram to make it visually perceptible which causes are contributing to the problem under analysis. This visual organization allows for a systematic analysis of the causes, facilitating the identification of critical factors and prioritizing corrective actions.

This visual representation will be essential in analyzing the production process, as it will allow for a clear mapping of the process limitations. After identifying all the problems, it is essential to organize them into categories, creating relationships between them. This way, problem-solving will be clearer, and some issues might be resolved together, making the improvement process more efficient.

2.1.6 Value Stream Mapping

Value Stream Mapping **VSM** is a visual representation of the flow of materials and information from the start to the end of the production or delivery of a product or service. The purpose of this tool is to provide a clear and comprehensive view of the process as it happens in reality, highlighting where resources and time may be underutilized or misused [16].

This methodology allows for the analysis of activities, which are then segmented into three categories based on the value they add to the process: they can add a lot of value, add little value but are essential, or add no value at all [17].

Once this mapping of the current situation is created, it becomes possible to set directions for the future. Brainstorming sessions, which involve the entire team, are typically the foundation for this new mapping [18], which seeks to identify elements that should be considered waste in this equation.

It is important to note that, to standardize this method, a set of universally recognized symbols has been created [19], which are illustrated in Appendix A.0.1.

In Appendix A.0.2, we can see an example of a VSM, in this case representing the process from the moment an order for a meal is placed to its delivery to the customer. This document provides various insights into the company's process, including the times for each step and how they are interconnected.

To read this VSM, it is necessary to consider the symbols presented in Appendix A.0.1. This allows us to gather information about the main steps of the process, their sequence, and how they are linked.

In the case under study, this tool will be essential for sequencing and organizing all the process steps, enabling the creation of a clear workflow and identifying steps that do not add value

and, therefore, can be eliminated. It will be used as a starting point and will guide the entire improvement process. Using the full sequence of process steps as a foundation allows us to organize them in a structured manner and identify which ones are truly important for overall efficiency, facilitating waste elimination and optimizing operations.

2.1.7 Standardized Work

Standardized work, in the context of Lean Manufacturing, is a practice aimed at optimizing processes, reducing waste, and ensuring efficiency. It involves defining a specific method for performing tasks, establishing a work sequence, the Takt time (the rhythm needed to meet demand), and the work-in-progress stock [20].

The main benefits of standardized work include reducing variations in processes, leading to more consistent products, identifying opportunities for continuous improvement, promoting workplace safety, and facilitating the training of new employees.

This approach helps ensure that everyone follows the same standards, resulting in greater efficiency and product quality. In the production of refrigeration units, it becomes a fundamental step because the process is divided into small tasks performed by different workers. It is essential that these tasks are executed consistently so that the final assembly is homogeneous and of high quality, ensuring the final product meets established standards. Furthermore, given the constant need to hire new workers, standardized work enables a faster adaptation, allowing new employees to integrate more efficiently into the production process.

2.1.8 Bottleneck Analyses

Bottleneck analysis is a technique used to identify limitations that hinder the efficient flow of processes in production or service systems. A "bottleneck" refers to points or stages in a process that restrict workflow, causing delays or inefficiencies [21].

The importance of this analysis lies in its ability to increase operational efficiency, improve quality, reduce costs, and enhance customer satisfaction. To conduct a bottleneck analysis, it is necessary to map the process, identify the bottlenecks, analyze performance data, discover root causes, develop solutions, and implement improvements.

After the initial process analysis, as we move into the phase of improvement analysis, this tool becomes essential. It will help us identify critical stages and those where improvements will have a practical impact on the process enhancement.

2.2 KPI's for Process Study

To efficiently organize a production process, it is essential to analyze and quantify various parameters that provide a comprehensive and detailed view of operations. These parameters, when

measured through specific indicators, offer valuable data about performance and production efficiency, allowing the identification of bottlenecks, improvement opportunities, and areas that require greater control.

Performance indicators, often referred to as KPI's, **Key Performance Indicators**, are tools that assist in measuring different aspects of production and enable more informed decision-making. It is important to note that when selecting a performance indicator, certain steps should be followed to ensure it is the right fit for the project being analyzed [22]. A KPI should meet specific criteria that make it valuable for the context under analysis, and for this reason, it should present the parameters described in Table 2.1.

Table 2.1: Criteria for Selecting a KPI.

Criteria	Description
Strategic Relevance	Should be directly aligned with the organization's goals.
Clarity and Simplicity	The data to be measured by the indicator must be easy to understand, without any ambiguities in interpretation.
Measurability	The KPI should be quantitative; the data derived from it should not allow qualitative analysis, so its interpretation does not depend on who performs it.
Data Collection Feasibility	It should be possible to collect the data practically, with the available tools.
Timeliness	The indicator should allow monitoring of the process at regular intervals so that there is a basis for comparison.
Comparability	Comparisons over time should be possible to measure the evolution of the process.

For each selected KPI, it is essential to evaluate its characteristics. When the indicator meets the selection criteria, it becomes a reliable source of relevant information about the process [22]. In this sense, it is important for KPI's to have well-defined characteristics, making them a solid foundation for analysis.

A tool commonly used to evaluate these characteristics is the **SMART** principle [23], which ensures that the KPI meets predefined criteria and guarantees that it is:

- **Specific:** Focused and clear about what it intends to measure;
- **Measurable:** Based on objective and quantifiable data;
- **Attainable:** Realistic, considering the available resources and capabilities;
- **Relevant:** Aligned with strategic objectives;
- **Time-bound:** Monitored at defined time intervals.

In addition to meeting these requirements, a good KPI should have two essential qualities [24] that reinforce its importance as a management tool:

1. **Actionable:** The indicator should provide clear and useful insights for decision-making and the implementation of concrete actions;
2. **Reacting quickly to changes:** An effective KPI should allow for rapid adjustments in response to changes in the process, which is crucial for maintaining competitiveness and efficiency.

These characteristics ensure that the KPI is not just a static number, but a dynamic tool that guides strategies, promotes continuous improvements, and enables agile and well-founded management.

However, it is important to consider that there are certain critical points that may limit the selection. To better address these points, Table 2.2 has been developed as a guide to ensure these critical points are always present.

Table 2.2: Critical Points in KPI Selection.

Critical Point	Suggestion
Excess of KPI's	Prioritize 5 to 10 truly critical KPI's.
Lack of Strategic Alignment	Select KPI's that are aligned with the analysis objectives.
Measurement of Results vs. Activities	Focus on final results rather than the activities performed.
Inadequate or Unreliable Data	Collected data should undergo a critical analysis.
Qualitative Feedback	If the KPI includes any qualitative dimension, it should be as unbiased as possible.
KPI Review	Indicators should be reviewed periodically to ensure they remain relevant in the face of changes.

Thus, the selection of KPI's should be based on the specific needs and objectives of the organization, without neglecting the guidelines that make KPI's truly useful for analysis. This evaluation process will allow the selection of indicators that are best suited for the proposed study, ensuring their relevance and effectiveness. The following will present indicators that are important in industrial process studies, serving as the foundation for future process analysis.

1. **Capacity Utilization Rate [25]:** This indicator is used to measure the efficiency of the production capacity in an industrial unit, assessing how much of the resources are actually being used in a given period compared to their maximum capacity. This KPI is important for identifying underutilization or overload, allowing production planning adjustments and improving operational efficiency.
2. **Cycle Time [26]:** Cycle Time measures the effective time required to produce a unit of product or complete a specific phase of the process, from the start of production to its completion. Cycle Time does not consider waiting times or delays between stages. It is a measure of internal productivity and efficiency for each phase.

3. **Labor Productivity Rate [27]:** This performance indicator measures the efficiency of workers in the production process. This KPI calculates the amount of production generated by each worker in a given period. It is useful for assessing workers' contribution to production, identifying potential bottlenecks, and allows for a good distribution of tasks among workers, ensuring that no worker is overloaded or underloaded.
4. **Average Set-up Time [28]:** This KPI is used in the industry to measure the time required to prepare a machine or equipment to start a new production batch. This time includes all activities needed to switch from one product to another, such as machine adjustments, tool changes, cleaning, and quality checks.
5. **Sales Forecasting [29]:** Sales forecasting refers to estimating the quantity of products or services that customers will request during a specific future period. Accurate forecasts enable better production planning, inventory management, and logistics, optimizing resources and increasing the company's ability to respond to customer needs.
6. **Avoided Costs [30]:** Avoided costs can be used as a KPI to measure the effectiveness of cost-reduction initiatives within an organization, including potential studies for equipment replacement. This KPI helps companies monitor the financial benefits resulting from operational improvements, more efficient processes, and the implementation of best practices.

For the correct implementation of these metrics, it is essential to carry out a critical and detailed analysis. First, the process should be mapped, identifying all the steps and visualizing the workflow in order to detect waste and inefficiencies. Next, it is crucial to collect historical and real-time data that support the evaluation.

The **SWOT** analysis can be used to identify problems and opportunities, while feedback from employees can provide valuable insights [31]. After this, clear goals should be set. Improvements should be implemented through action plans and, if possible, pilot tests should be conducted before full-scale implementation.

After implementation, results should be monitored, and adjustments should be made as needed. Regular reports should be prepared to assess performance against the KPI's, and transparent communication with all stakeholders is essential. This approach ensures that the metrics remain relevant, promoting a culture of continuous improvement and efficiency within the organization.

2.3 Layout

The choice of layout is a crucial phase in facility planning, as it defines the physical connections between activities. Since the final layout will be selected from the alternatives generated, it is essential to be both creative and comprehensive in developing these alternatives [32].

This subsection focuses on the development of layout alternatives, specifically the development of a block layout, which shows the relative locations and sizes of planning departments, in

contrast to a detailed layout, which presents the exact location of all equipment, workstations, and storage areas within each department.

It is important to note that selecting a more efficient layout can bring various advantages, including the optimization of the production process, faster product flow, improved factory environment quality, and facilitating the supervision of all stages of the production process [33].

2.3.1 Types of Layout

When choosing the best way to organize the different stages of production, it is essential to consider which layout type best fits each production case. There are four fundamental types:

1. Production line product layout

Flow line manufacturing is an approach used to produce large volumes of products efficiently and at a low cost, typically found in industries with high demand and the need for continuous production [32]. In this system, also known as product layout, each product has a dedicated production line equipped with specific machines that perform tasks in a defined sequence. The main characteristics of this type of production include a high production rate, ensured by the configuration of machines in series, allowing for fast and uninterrupted production, and low cost, achieved through process standardization and repetition.

Moreover, the process follows a continuous sequence, where raw materials enter at one end of the line and pass through each stage until they become finished products at the other end, in an uninterrupted flow. Flow line manufacturing is ideal for mass production industries, such as the automotive industry, where a specific line can be dedicated to each type of product, ensuring efficient and consistent production. Below are some advantages and limitations of this type of production.

- **Advantages:**

- Smooth and logical flow of materials;
- Less skill is required for personal;
- Simplified production planning and control;
- Reduced material handling costs;
- Shorter production lead times;
- Small amount of work-in-progress inventory;.

- **Limitations:**

- Lack of flexibility;
- High investment in machines and equipment;
- Lack of specialization in supervision;
- Machine breakdowns halt production;
- Changes in the product may render the layout obsolete.

2. Fixed product layout

This is a layout in which the product being manufactured remains fixed in one location, while operators, machines, and parts move toward and around the product. This type of layout is typically used for the manufacturing of very large and difficult-to-move products, such as airplanes, submarines, and ships. In these cases, the product is allocated in a specific space for most of the manufacturing process, and resources move around it to perform the necessary tasks. Thus, we can understand that the nature of the product forces the physical arrangement to adapt to its characteristics and limitations [32]. A model of this system is presented in Figure 2.2.

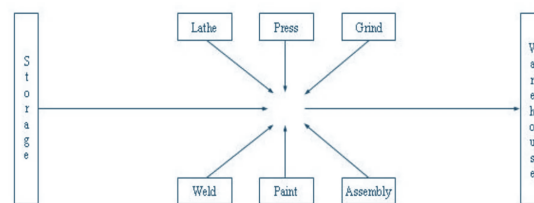


Figure 2.2: Fixed Product Layout[32].

- **Advantages:**

- Material movement is reduced;
- When a team approach is used, continuity of operations and responsibility results;
- Provides job enrichment opportunities;
- Promotes pride and quality because an individual can complete the “whole job”;
- Highly flexible; can accommodate changes in product and production.

- **Limitations:**

- Personal and equipment movement is increased;
- May result in duplicate equipment;
- Requires greater skill for personnel;
- Requires general supervision;
- May result in increased space and greater work-in-progress;
- Requires close control and coordination in scheduling production.

3. Process layout

The process layout, also known as functional layout, is a physical organization in which machines and equipment that perform similar functions are grouped into specific areas. In this type of layout, the workflow is flexible, adapting to the different needs of products and allowing for the customization of operations.

In a process layout, equipment and resources that perform similar tasks, such as cutting, welding, or painting, are organized into their own sections, which provides great adaptability. This type of layout is ideal for diversified and small-batch production, allowing for variable customer requirements and facilitating product customization. The process layout, as shown in Figure 2.3, is common in industries that require flexibility and the ability to adapt quickly, such as machine shops, hospitals, laboratories, and factories producing small batches of differentiated products. It becomes ideal for operations where product variety and customization are priorities [32].

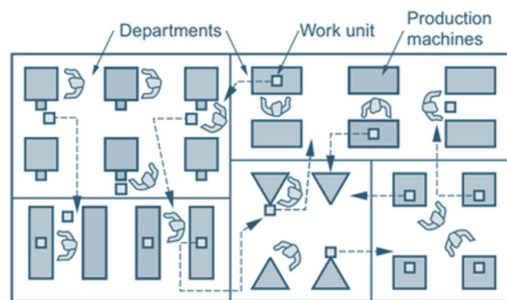


Figure 2.3: Process Layout [32].

- **Advantages:**

- Increased machine utilization;
- General-purpose equipment can be used;
- High flexible in allocating personal and equipment;
- Diversity of tasks for personnel;
- Specialized supervision is possible.

- **Limitations:**

- Increased material handling requirements;
- More complicated production control required;
- Increased work-in-progress;
- Longer production lines;
- Higher skills required to accommodate diversity of tasks required.

4. Cell layout

This type of industrial layout, known as cellular layout, combines elements from both line and process layouts to create independent work cells. Each cell is a self-managed unit, dedicated to the production of a specific product or a family of products with similar characteristics. This organization allows the production process to be carried out from start to finish within the same area, reducing the need for extensive movement of machines, materials, and labor between different zones of the factory [32]. Below are some advantages and limitations of this type of production.

- **Advantages:**

- Higher machine utilization;
- Smoother flow lines and shorter travel distances are expected;
- Team atmosphere and job enlargement benefits often result;
- Has some of the benefits of product layouts and process layouts;
- Encourages consideration of general-purpose equipment.

- **Limitations:**

- General supervision required;
- Greater labor skills required for team members to be skilled on all operations;
- Critically dependent on production control balancing the flows through the individual cells;
- Has some of the disadvantages of product layouts and process layouts;
- Decreases the opportunity to use special-purpose equipment.

2.3.2 Planning and Selection

There are several methods used for selecting a layout in facility planning. The choice of the ideal layout depends on the specific needs of the company, the type of product or service, and the strategic goals.

The Sistematic Layout Planning **SLP** system is one of these tools used for planning and developing physical arrangements, with the goal of achieving maximum efficiency in the production process. The SLP system was proposed in the 1950s as a systematic method for analyzing process layout design [34]. The SLP is developed in stages, as shown in Figure 2.4, outlining the steps to be followed in the development of the method, along with its respective tools.

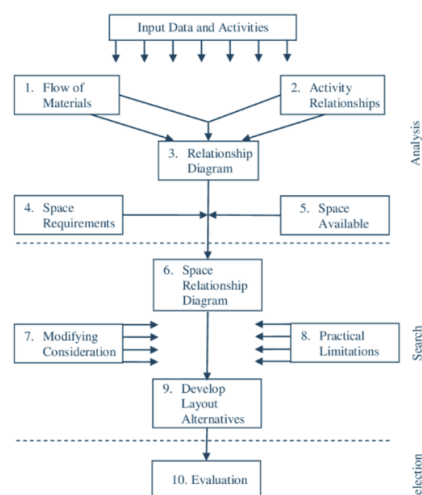


Figure 2.4: SLP procedure [32].

1. Material Flow Analysis

The focus is on understanding the movements of materials, tools, and operators within the facility. In this phase, the mapping of the paths traveled by materials is performed, from receipt to storage, processing, and shipping [35].

Tools such as flow diagrams or spaghetti diagrams are frequently used to visualize the movements. Additionally, "from-to" matrices are commonly used to quantify the volumes of materials moved between areas, providing essential data to prioritize the proximity between interdependent departments.

2. Identification and Inclusion of Qualitative Factors

In this stage, these qualitative factors complement the quantitative data with information about the specific needs of the layout. At this stage, the proximity requirements between areas are evaluated, considering aspects such as safety and communication. For example, it is important to ensure that areas with high interaction are located close to each other, while others, which require isolation, are placed farther apart. To organize this information, a proximity matrix is used, as shown in Figure 2.5, where the relationships between areas are classified, guiding decisions about the grouping or separation of sectors [32].

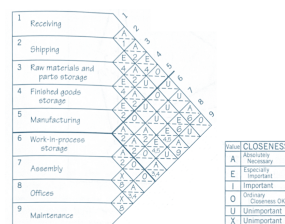


Figure 2.5: Activity relationship chart [32].

3. Evaluation of Data and Arrangement of Work Areas

This stage involves creating preliminary layout diagrams, representing each area as a block or cell. The proximity priorities and flow relationships identified earlier guide the grouping of related areas. Additionally, the space required for each department is calculated [35]. The goal is to strike a balance between the quantitative and qualitative requirements.

Tools like REL, **Relationship Charts**, shown in Figure 2.6, are commonly used to visualize and test these initial arrangements.

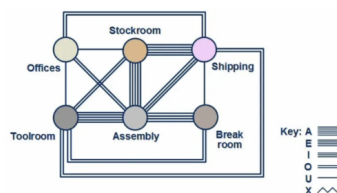


Figure 2.6: Relationship Diagram [36].

4. Determination of a Space Arrangement Plan

In the fourth stage, the preliminary layouts are refined to create a detailed occupation plan. At this stage, the areas are distributed within the available space, taking into account physical constraints such as columns, walls, and access points. Pathways and corridors are also planned to ensure the efficient transportation of materials and safe movement of operators. Support areas, such as offices, restrooms, and break areas, are integrated into the plan to ensure a balanced and functional operation. For the implementation of this step, block diagrams, as shown in Figure 2.7, are often used to provide a clearer visualization of the space and the proposed ideas [32].

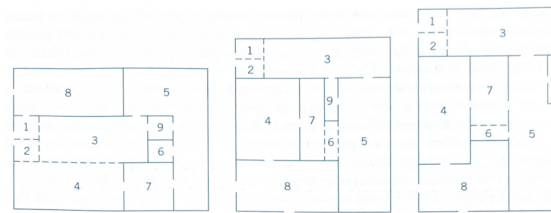


Figure 2.7: Alternative block layouts [32].

5. Adjustment of the Layout in the Available Space

Finally, the layout is adjusted within the available space, ensuring that the final plan is feasible and adapted to the real conditions of the facility. In this phase, detailed checks are carried out to adjust the layout to specific physical constraints. Furthermore, the plan is reviewed in collaboration with stakeholders, such as process managers and operators, to ensure that all needs have been met and that the proposed layout is practical and effective.

This method will play a crucial role in achieving the second goal of this work, as it will enable the creation of a well-structured and optimized layout. Through the application of the systematic planning method, it will be possible to thoroughly analyze the specific needs of the production process, identify areas that require closer proximity or separation, and adjust the physical arrangement of the facility to the limitations of the available space.

This will result in the development of a coherent layout that not only meets operational requirements but also minimizes the limitations identified in the initial layout, such as material flow issues, excessive distances between interdependent areas, and difficulties in the movement of operators and equipment [33]. Furthermore, the continuous review and adjustment of the layout ensure that it remains flexible enough to adapt to future changes, fostering continuous improvement of the production process. In this way, the final layout not only optimizes operational efficiency but also significantly contributes to cost reduction and increased productivity within the company.

Chapter 3

Analysis of the Process

To understand the theoretical concepts behind the systems and before analyzing the problem and potential solutions, a study was conducted on the principles supporting the operation of refrigeration plants, including refrigeration cycles, the refrigerant used, and its environmental impact.

Next, the production process of the plant under study will be analyzed, detailing all stages, from material preparation to the completion of the final product. This review will help identify critical points and areas for improvement, providing a clear view of current practices.

This chapter will serve as a foundation for implementing the proposed improvements, offering the necessary insights to address challenges and opportunities for process enhancement, ensuring that the changes meet efficiency and cost reduction goals while contributing to sustainability and continuous quality.

3.1 Principles of Refrigeration

Refrigeration is the process of removing heat from a space or body to reduce and maintain its temperature below the ambient temperature. This basic principle is grounded in the laws of thermodynamics, which state that heat transfers from a region of higher temperature to one of lower temperature [37]. For heat to be removed from a body or environment, a system is required that facilitates this transfer, creating a temperature difference between the object to be cooled (**cold source**) and the surrounding environment (**hot source**). This process is outlined in Figure 3.1.

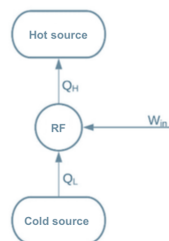


Figure 3.1: Refrigeration Machine [38].

Heat transfer is achieved with the help of external energy, such as electricity, to drive the cycle, as heat does not naturally move from colder regions to hotter regions without the intervention of an external force.

The essential process involves the evaporation and condensation of the refrigerant, which absorbs heat during evaporation and releases it during condensation.

3.2 Refrigerants

Refrigerants are substances used as the working fluid in refrigeration systems, enabling evaporation and condensation at the cold and hot sources, respectively, under acceptable pressure and temperature levels, ensuring efficient heat transfer.

They can be natural, found in nature without processing, or synthetic, produced artificially in laboratories from methane or ethane [39]. Refrigerants are typically identified by a nomenclature defined by ASHRAE, with the prefix "R" followed by a number, such as **R-744**, also known as **carbon dioxide** [38].

The development and use of refrigerants have been influenced by environmental concerns, initially focused on the preservation of the ozone layer and more recently on global warming. This led to international agreements, such as the Montreal Protocol and the EU F-Gas Regulation, which impose restrictions on the use of certain refrigerants.

These regulations aim to reduce the use of synthetic refrigerants, promoting natural ones with lower environmental impact. The greater the potential of a refrigerant to harm the ozone layer or contribute to global warming, the stricter the restrictions on its use [38].

3.2.1 Refrigerant Used in the Studied Systems

When selecting a refrigerant for a specific application, several parameters define what might be considered an "ideal" refrigerant. These characteristics can be thermodynamic, chemical, physical, environmental, or economic.

Given the vast number of factors influencing refrigerant selection, it is not feasible to identify a single "ideal" fluid. Therefore, the decision among the various options available in the market is made based on the specific application and by balancing these characteristics [39, 40, 41].

The refrigerant used in the system under study in this work is carbon dioxide CO_2 , whose main characteristics are as follows [39, 42, 43, 44, 45].

- ODP and GWP values of 0 and 1, respectively, indicating that current legislation does not affect the use of this refrigerant. It is considered sustainable, with no foreseeable need to reduce its usage in the near future;
- High latent heat of vaporization per volume, allowing for the use of smaller components;
- High thermal conductivity, which contribute to more efficient heat transfer;

- Non-toxic (in low quantities) and non-flammable (Class A1 according to the EN 378-1);
- Relative low refrigerant cost.

One of the greatest advantages of using CO_2 cycles is the fact that the working fluid is natural and has an ODP of 0 and a GWP of 1. This has been one of the main drivers behind the exponential increase in the number of CO_2 -based installations in operation over recent years [38].

3.3 Description of the Unit Operation

This section analyzes one of the refrigeration units produced by KoolSys to gain insight into its operation and to make an initial assessment of the production process steps and components.

This unit is designed for commercial applications, particularly supermarkets, to refrigerate and freeze food.

Figure 3.2 presents the simplified operating diagram of the described refrigeration system, highlighting the main components and the flow of the refrigerant. The system consists of four main components: compressors, evaporators, condensers, and expansion valves, which play essential roles in the stages of the refrigeration cycle [46].

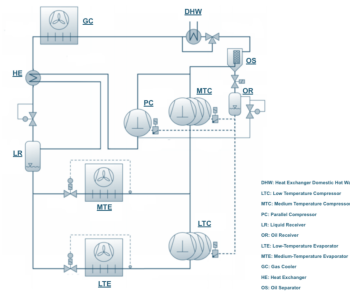


Figure 3.2: Diagram of the refrigeration system's operation [46].

The system operates with the same refrigerant between the low and medium temperature compressors, providing integration between these components. At the output of the expansion valve of the gas cooler, a mixture of liquid and gas is directed to the liquid receiver, which feeds the low (LT) and medium temperature (MT) evaporators with CO_2 in the liquid phase. After the evaporators, the refrigerant, now in the gas phase, flows from the LT evaporators to the LT compressors, which act as boosters for the MT compressors. After evaporation in the MT evaporator, the fluid is directed to the MT compressors. In the system, the flash gas generated in the liquid receiver is compressed in the parallel compressor, instead of being directed to the MT compressors. This strategy helps improve the system's energy efficiency. Finally, the refrigerant is transferred from the MT and parallel compressors to the gas cooler, where the system's heat is dissipated into the environment, completing the refrigeration cycle [46].

3.4 Production Stages

The production process of a refrigeration unit is composed of well-defined stages, subdivided into smaller phases that, when articulated together, culminate in the final product. After a brief analysis, it was found that this process encompasses several phases, from the first contact with the customer to after-sales support. However, this study will focus exclusively on four of these phases: **Design, Preparation, Assembly, and Finishing.**

It is important to note that the **Design** phase will be included in the analysis solely due to the need for structural changes, which are essential for implementing the proposed improvements.

The four phases are naturally interconnected and follow a well-defined sequence of dependencies. The first phase is the **Design of the unit**, which marks the beginning of detailed planning. This process begins with sizing and selecting the most suitable components for each specific case, such as thermal capacity and application requirements. Since the equipment is custom-made, each unit requires a unique and tailored design.

During this phase, the metal structure, illustrated in blue in Figure 3.3, will also be designed. This structure serves as the base for all the components of the unit and is manufactured by specialized external companies.

It is also prepared the detailed design of the piping in 2D technical drawings. These drawings are then sent to the production manager, who uses them as a basis for manufacturing the necessary parts, thus marking the beginning of a new production stage.

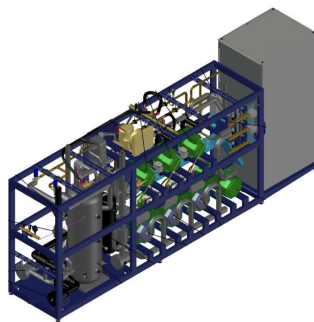


Figure 3.3: Metal structure [46].

This **Preparation** stage encompasses all activities carried out before the arrival of the metal structure at the factory. During this phase, the racks are prepared with the necessary materials for building the unit, the piping is fabricated based on the 2D technical drawings, and all essential components for the unit's operation are received and prepared.

After the Preparation phase is completed, the arrival of the metal structure marks the beginning of the **Assembly** phase. In this stage, all components are installed onto the metal structure. The previously built piping is attached and connected to the unit's components. At the same time, electrical connections between the components and the electrical panel are initiated. It is important to note that the electrical panel is produced externally to the assembly process.

After the full installation, the end of this stage is marked by the pressure test. During this procedure, the unit is subjected to pressures higher than its operational pressure, ensuring that the system can withstand more demanding conditions than those it will encounter in normal operation.

The successful completion of this test allows the unit to move to the next phase, with the assurance that there are no technical issues that could compromise its performance or safety.

With the Assembly completed and the unit passing the pressure test, the **Finishing** phase begins. In this stage, safety equipment is installed to ensure the unit automatically shuts down in case of anomalies, thus complying with safety standards.

Subsequently, additional tests are carried out to verify the quality of the equipment, ensuring that all components function correctly and meet the established requirements.

Finally, all piping that requires thermal insulation is properly insulated using flexible elastomeric foams to minimize energy losses and ensure system efficiency. Additionally, final touches such as cleaning and painting are carried out to guarantee that the unit has a flawless visual and functional finish. Once all these stages are completed, the unit is ready to be packed and shipped to the customer, thus completing the production process.

3.5 Process Analysis

In this subsection, the production process will be analyzed from the arrival of the drawings to the shop floor until the completion of the unit, before any improvements are implemented. An initial analysis will be carried out, measuring parameters based on the performance indicators presented in **Chapter 2, Section 2.2**.

The unit under analysis will be of the **Series 3** type, as it is a widely produced model. However, this analysis can be applied and expanded to all other units, providing a comprehensive view of the production process. It is worth noting that the model names vary according to the number and size of the components, as well as the dimensions of their piping.

To fully understand the entire production process, a Flow Mapping, shown in Figure 3.4, was created with the aim of identifying where resources and time may be underutilized or inefficiently used. The different steps of the process, outlined below, were detailed for this purpose.

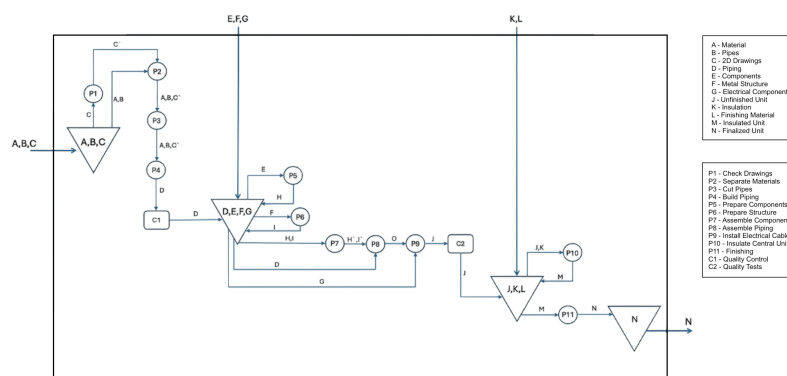


Figure 3.4: Flow Diagram.

After analyzing all these stages, it was possible to establish dependencies between them. The execution times for each of these phases were also studied, allowing the creation of a production schedule where it is clearly defined which stage is underway at each unit of time. The results of this analysis are presented in Appendix B.0.1.

The developed production plan was designed with the capacity to adapt to variations that occur between different refrigeration units. These variations include factors such as the quantity and diameter of the piping installed in the unit, as well as the total number of components required for its operation. Thus, the schedule is not presented as a fixed model, but rather as a dynamic and flexible tool capable of adjusting to the specifics of each unit, regardless of its particularities or complexity.

Additionally, the creation of this schedule enabled an in-depth analysis of the execution times for each phase, allowing the identification of the dependencies between the various stages. This schedule also helped calculate the cycle time of the process, providing a clear view of the total time required to produce a unit. In the case of the model under study, the cycle time was determined to be **114 hours**. It is important to highlight that the defined goal aims for a **15% reduction** in this parameter. Therefore, the final time required for the production of this unit should approach **97 hours**. This target represents a significant challenge and serves as a benchmark for the analysis and implementation of the necessary improvements to the production process.

With a clear view of the entire production process, it was possible to identify the stages that were causing bottlenecks. The identified bottlenecks were as follows:

- **Pre-piping steel:** This process caused frequent delays in the production flow, as it was necessary to wait for the completion of the piping before proceeding with the assembly of the unit.
- **Preparation of the structure:** The process faced delays due to necessary adjustments in the structure, which had to be made before continuing with the production.
- **Installation of components:** In order for the piping assembly to begin, it was essential that this stage be in an advanced phase. Thus, the need to shorten the time for this task was identified.
- **Insulation:** Within the finishing phase, insulation was the step that caused the most delays in the entire process, as it was not possible to proceed to painting without completing the insulation.

These phases were identified as the most critical, as they present the greatest limitations and where delays occur. As a result, these were the stages that received special attention, with the goal of implementing improvements to optimize the workflow and, consequently, increase the efficiency of the entire production process.

Once the production system was organized, it was possible to apply Lean tools to identify problems and implement methodologies that would lead to process improvements.

3.6 Analysis of the Previous Layout

Based on the theoretical knowledge explored in **Chapter 2.3** of this document, we can conclude that, for this type of production, the most suitable layout is a combination of the **fixed product layout** and the **process layout**. This is due to the fact that, in the initial phase, preliminary work is carried out in different specialized departments, resulting in individual parts. Subsequently, these parts are gathered and assembled in a single location, giving rise to the final product.

In this sense, when considering the ideal arrangement for this factory, we must be aware of both the advantages and limitations associated with this type of model. On the one hand, the combination of these layouts can improve flexibility and optimize the use of specialized resources. However, it can also result in challenges related to the coordination between departments and the efficient management of material flows, requiring special attention to the organization of space and communication processes among the various areas involved.

The existing layout, Figure 3.5, corresponds to the original configuration of the factory, established based on the needs and operational conditions at the time it was implemented. This arrangement reflects the organization of work areas, equipment, and operational flows in the available space. However, over time, several limitations have been observed that compromise the efficiency of the production process. Among the main challenges are the inadequate spacing between interdependent sectors, the occurrence of cross flows that increase movement times, and the difficulty in adapting the space to new needs. This initial layout represents the starting point for the study, being essential to understanding the problems and supporting the improvement proposals developed.

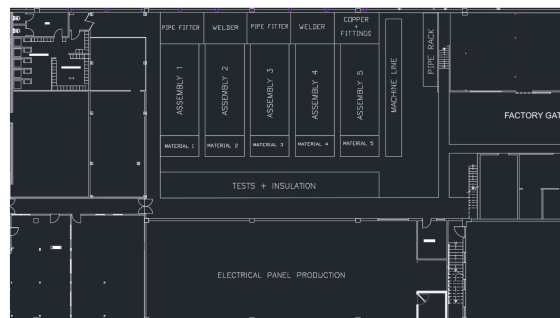


Figure 3.5: Previous Layout.

To better understand the figure, a complementary legend with a brief description of each of the mentioned sectors is necessary:

- **Factory Gate:** Main entrance for receiving and shipping materials;
- **Material:** Shelf where the materials necessary for the assembly of the unit are organized;
- **Pipe Fitter:** Work area where the pipe fitter prepares the pipes;
- **Machine Line:** Section where the machines used for pipe processing are located;

- **Pipe Rack:** Support structure for storing the pipes needed for the construction of the unit;
- **Welder:** Work area where the welder constructs the piping;
- **Copper + Fitting:** Work area dedicated to the operator assembling the copper piping and the worker responsible for constructing the necessary supports for the unit;
- **Assembly:** Area designated for the final assembly of all unit components;
- **Tests + Insulation:** Area reserved for pressure testing and insulating the unit.

After a careful analysis of the production system, it was possible to identify some inefficiencies and limitations in the existing distribution. As a starting point, a detailed analysis of the production processes was carried out, as well as the movements of materials and workers within the factory unit. This assessment revealed critical issues directly affecting operational efficiency, allowing the identification of the main limitations of the current model, among which the following stand out:

- **Material Flow:** There was no continuous material flow, and workers often faced multiple obstacles in their movements and in handling loads.
- **Pipe Fitter:** The pipe fitter requires materials located in the "Material" area, which results in significant movement between this area and their workstation, "Pipe Fitter," often necessitating constant passage through the "Assembly" area where the unit is being constructed.
- **Copper:** This task involves frequent movement between "Assembly" and "Copper + Fittings." When the assembly occurs in "Assembly 1," the distance between these stations becomes considerable.
- **Fittings:** This worker primarily handles carbon steel, which, upon contact with the steel pipes of the unit, causes contamination. Therefore, it is advisable for this worker's bench to be as far as possible from the "Pipe Fitter" and "Welder."
- **Unit Movement:** Due to its dimensions, moving the unit to the testing area is challenging.
- **Testing Area:** In this area, the unit is subjected to very high pressures. For safety reasons, it is recommended that this area be located in an isolated and protected space.
- **Insulation:** This stage did not have a specific designated location, often leading to the unit being insulated in the "Assembly" area. This caused disorganization, and the insulation was frequently damaged due to the fragility of the material.

In addition to all these limitations, it is important to note that construction work in the industrial pavilion resulted in the demolition of two walls, thereby increasing the available space for the new configuration.

Starting from this situation and with a clear objective to make the factory floor more organized, with a smoother and more efficient material flow, it was necessary to make changes to the existing layout. For this purpose, the SLP method was used, providing a structured approach to formulating a new solution.

Chapter 4

Improvements Implemented

This chapter presents the improvements implemented in the production process, focusing on increasing efficiency and addressing challenges identified in previous stages. It details the changes made in aspects such as organization, pipe construction, compressor installation, metallic structure, insulation, and the introduction of a pipe bending machine, highlighting their impact on the production flow.

Additionally, the chapter discusses the modifications made to the production layout, explaining the reasons behind these changes. Different layout alternatives are analyzed, aiming to optimize space and resources, as well as improve operational efficiency and reduce production time. The following sections detail how each improvement and adjustment contributes to the ongoing optimization of the process.

4.1 Improvements Implemented in the Process

After a detailed and thorough study of all stages of the production process, it is now possible to identify and implement improvements that prove advantageous for enhancing this process. The in-depth analysis not only allowed for an understanding of how the different phases function, but also identified critical points and areas with the greatest potential for effective interventions.

In this section, the implemented improvements will be presented, properly supported and justified, with the aim of increasing process efficiency, reducing cycle time, and improving the use of available resources. Additionally, specific metrics that play a fundamental role in performance evaluation and quantifying the results achieved will be examined.

4.1.1 Process Organization

With the aim of making production management clearer and more efficient, ensuring that the work is sequenced and standardized, a detailed organization of the entire production process was developed.

Through the analysis of cycle times, it was possible to carry out a concrete evaluation of each phase of the process, allowing the calculation of capacity utilization rates. This indicator enables

the evaluation of production capacity, determining the number of resources effectively used in each unit of time and identifying situations of underutilization or resource overload.

Additionally, it is expected that 52 units will be sold this year, as shown in Appendix C. To meet this demand, an average production of 1 unit per week will be required. Appendix D was then prepared, providing a detailed analysis of the labor required to meet the future production demand. This document serves as an essential reference for planning and appropriately sizing the work teams, ensuring the optimization of available resources.

After systematizing all the collected information, it was concluded that the required production cadence would be approximately one unit per week. To meet this pace, it would be necessary to ensure the simultaneous production of two units, adjusting all required times and operators. As shown in Appendix D, it was observed that at certain points in the production process, the number of workers performing tasks simultaneously reaches 9. Therefore, it was concluded that this would be the number of employees needed to meet the forecasted sales.

It is important to note that, until now, the production team consisted of **7 permanent employees**, with **2 additional workers** often subcontracted to cover occasional needs. However, considering the continuous increase in production requirements, it has now become both possible and essential to hire 2 additional permanent employees. This measure will enable a more stable and efficient response to all production demands.

Once the total number of operators was determined, it was decided to divide them into teams with clearly defined roles and tasks to ensure the smoothness and efficiency of the production process. This approach would provide each operator with a clear understanding of their responsibilities, avoiding ambiguities and maximizing overall productivity. The team division was structured as follows:

- **Team 1** (1 Welder, 1 Pipe Fitter, 1 Assistant): Responsible for the construction and assembly of the steel piping for one of the units.
- **Team 2** (1 Welder, 1 Pipe Fitter, 1 Assistant): Responsible for the construction and assembly of the steel piping for the other unit.
- **Team 3** (2 Assistants): Responsible for preparing the rack material, pre-insulation, preparing the structure, assembling components, and executing thermal insulation.
- **Team 4** (1 Copper Pipe Operator): Responsible for the construction and assembly of copper piping and support during the finishing stages of the units.

After analyzing the existing structure, it was found that the team was composed of **1 Welder, 1 Pipe Fitter, 1 Copper Pipe Operator, and 4 Assistants**. It was identified that there was a need to strengthen the team with an additional Pipe Fitter and Welder to meet production demands. However, it is important to note that one of the assistants was already in training to take on the role of welder, which eliminated the need to hire someone for this position. Therefore, it was decided to hire **1 additional Pipe Fitter and 1 Assistant**, adjusting the team to meet production needs and ensuring greater capacity to respond to the increased demand.

This organized and detailed division ensures task standardization, balanced distribution of work, and more efficient production, allowing for the achievement of established goals and optimization of available human resources.

4.1.2 Pipe Construction

In the first phase, the entire process was organized. However, to achieve a reduction in cycle time, it was essential to intervene at the bottlenecks, as these are the critical points that slow down the process and where improvements will have the greatest impact.

This section focuses on pipe production. A detailed analysis was conducted of all the times associated with the different activities at this stage. Several alternatives were evaluated, starting with the current situation and then considering two proposals, with the goal of optimizing the process and reducing cycle time. These alternatives were analyzed in terms of efficiency, task distribution, and impact on team productivity to determine the best approach to be implemented.

The times mentioned throughout this section were the result of the average of three measurements taken for each of the operators performing the mentioned tasks.

- **Initial Process**

The construction of the piping required for the plant was carried out by two people: a pipefitter and a welder. To create a production timeline, it was essential to analyze the structure of this stage. It was observed that all the plant's piping was divided into 17 2D drawings, corresponding to 17 distinct parts, which were constructed separately and independently.

Following this analysis, it was concluded that the process followed a well-defined sequence of steps. Table 4.1 enumerates and describes these steps, also indicating who was responsible for executing each of them.

Table 4.1: Tasks for pipeline construction.

Task	Description	Responsible
Verify drawings	The 2D drawings are analyzed to understand the specific construction needs.	Pipefitter
Separate materials	Materials necessary for the construction are separated.	Pipefitter
Measure and cut	Pipe sections are cut according to the specified measurements.	Pipefitter
Clean	The ends of pipes and valves are chamfered and cleaned.	Pipefitter
Position	Tack welds are applied to position the pipes as defined in the drawings.	Pipefitter Welder
Weld	Weld beads are applied to the previously positioned piping.	Welder

Finally, a schedule was developed to provide a clear overview of the times involved in the pipeline production stage, as well as the productivity rate of each operator. In Appendix E.0.1, an illustrates the results of this study, offering a detailed analysis of the workflow and resource allocation. This enables the identification of potential areas for improvement and optimization in the production process.

Table 4.2 presents important information regarding the labor utilization rate and the total time required for this stage of the process.

Table 4.2: Productivity in the initial situation.

	Time (h)	% Utilization
Pipefitter	63,25	99,6
Welder	35	55,1
Total	63,5	-

From the analysis of the table, it is evident that while the pipefitter has a utilization rate close to 100%, the welder's utilization is significantly below the expected level. This imbalance indicates that the pipefitter is overburdened compared to the welder. To address this issue, two alternatives were proposed, which will be presented below, with the objective of optimizing task distribution and improving the utilization rates of both operators.

Finally, it is important to note that the total production time for the piping in this situation is 63.5 hours.

• Heuristic 1

In this alternative, the goal was to reduce the idle times of the Welder. To achieve this, it was proposed to add a second **Pipefitter** to the team, thereby increasing the number of pieces sent for welding within the same period. The schedule resulting from this change is available in Appendix E.0.2.

The analysis of this heuristic is presented in Table 4.3, which displays the results obtained from implementing the proposed solution. This table shows the execution times and utilization rates of the operators, enabling an assessment of the impact of adding a second pipefitter on task distribution and team productivity.

Table 4.3: Productivity Heuristic 1.

	Time (h)	% Utilization
Pipefitter 1	32	78,5
Pipefitter 2	31,25	76,7
Welder	35	85,9
Total	40,75	-

From the analysis of the results, a reduction of 22.75 hours in the total pipeline production time was observed, decreasing from 63.5 hours to **40.75 hours**, which represents a significant improvement. Additionally, there was an increase in the welder's utilization rate, indicating a better distribution of tasks. However, there is a negative aspect to highlight: the welder ends up being overloaded. Although the pipefitters finish their tasks more quickly, the welder still has a large amount of piping left to weld, creating an imbalance in the process. This workload imbalance negatively affects the pipefitters' productivity rates, as they finish their tasks earlier and become idle while the welder is still working on their part.

• Heuristic 2

This approach was developed to address the issues identified in the previous methodologies by balancing the utilization of the Welder and the Pipefitter. After a detailed analysis of the process steps, it was concluded that some tasks did not require a high level of specialization and could be performed by an operator with lower qualifications. Therefore, a new member, designated as **Assistent**, was added to the team, initially composed of the **Pipefitter** and the **Welder**.

This new team member will be responsible for performing the tasks of Separating materials and Cleaning, allowing the pipefitter and the welder to focus exclusively on activities that require more technical expertise. With this redistribution of duties, it was possible to optimize the execution time and improve the overall productivity of the team. The schedule resulting from this heuristic is available in Appendix E.0.3.

To facilitate understanding of the data, Table 4.4 was created, presenting the results obtained from this alternative.

Table 4.4: Productivity Heuristic 2.

	Time (h)	% Utilization
Pipefitter	35,75	94,7
Assistent	27,5	72,9
Welder	35	92,7
Total	37,75	-

By analyzing the values presented in the table, we observe a slight reduction in the total pipeline construction time, which decreased to **37.75 hours**. Additionally, there is a significant improvement in the utilization rates of both the Pipefitter and the Welder, with values exceeding 90%, which are considered very positive. However, the utilization rate for the Assistant is not as favorable, but it is important to note that this operator can be redirected to other tasks once no longer needed in the pipeline production process, allowing for better resource management.

Thus, after analyzing the three situations, Heuristic 2 was chosen, as it clearly demonstrated the best results. This choice leads to a reduction of **25.75 hours** in the pipeline production time compared to the initial situation and ensures a balanced utilization rate of resources.

4.1.3 Compressor installation

In this step, a new method for installing the compressors onto the structure was developed. Until then, the installation process was done using an industrial strap, as illustrated in Figure 4.1. In this method, the compressor was secured to the strap, lifted, and moved into the correct position on the structure.



Figure 4.1: Old Transportation Method.

This process caused some instability in the compressors, making both movement and correct fixation difficult. Additionally, the connection that attaches the strap to the forklift also posed challenges, as it was not always easy to ensure its safety and make sure the strap was the right size.

Another identified problem was the difficulty in ensuring that the strap was the correct size and that the fixation between the strap and the forklift was secure. This issue also made the transport and precise installation of the compressor challenging, as the strap did not maintain the necessary stability during the process.

Along with these issues, there were frequent **errors in the installation process**, preventing it from being done correctly. Figure 4.2 illustrates a situation where difficulties occurred during this process.

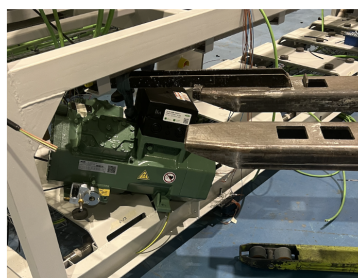


Figure 4.2: Errors in Installation.

The knot of the strap often became insecure, requiring rework, which led to inefficiencies and, consequently, wasted time. Furthermore, the distance between the transport arm and the compressor was also a challenge, as the available space to install the compressor in the plant was limited. As seen in the figure, the strap needed to be adjusted to the shortest possible length to ensure proper fitting, but this adjustment was often not ideal, resulting in an excessive distance between the arm and the compressor. This required repeating the entire process, increasing the installation time.

To address the identified problems, a support was developed using materials already available in the factory. This support was designed to ensure greater stability and safety during the transport and installation of the compressors. In Figure 4.3, an image can be seen illustrating the transport of a compressor using the new equipment.

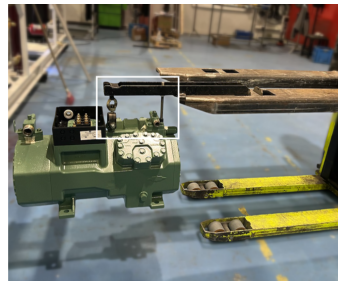


Figure 4.3: New Transport Equipment.

To describe the equipment, it can be highlighted that an eye bolt was attached to the front end of an additional forklift arm, connected to a small U-shaped plate bent in an inverted form. This component was designed to facilitate transportation and ensure that the distance between the arm and the compressor was clearly defined, providing greater precision. Additionally, this solution offers a shorter distance compared to the use of the sling, which provides greater freedom of movement during the installation process.

A bolt was added to this plate, passing through from one side to the other, functioning as a fastening pin. This set of elements forms the connection point between the compressor and the arm, allowing the equipment to be suspended safely and controlled.

Furthermore, in the intermediate section of the transport arm, a strategic stopper was installed to prevent the compressor from swinging during transport. This element significantly reduces the risk of accidents and improves efficiency both in transportation and in the installation of the compressor.

With the solution presented, the previous problems were completely resolved. The fixation between the compressor and the arm became simple, through the insertion and threading of a bolt. Furthermore, the distance between the transport arm and the compressor was minimized and maintained consistently throughout all installations, ensuring uniformity and efficiency in the process.

With the implementation of this solution, the installation time for each compressor was reduced from **20 to 10 minutes**, the result of the average of three measurements. Considering that a

plant has between 3 to 9 compressors, this reduction leads to significant time savings throughout the entire process. It is also important to highlight that, previously, two people were needed to perform the installation, but with the new approach, only one operator is required to carry out the task efficiently. Therefore, it can be concluded that this improvement results in a significant optimization of resources, contributing to greater efficiency in the production process.

4.1.4 Metallic Structure

During the assembly phase, several problems related to the metallic structure were identified, causing delays in the process. These issues mainly arose from inadequate fastening or construction solutions that hindered the flow of the assembly.

After a detailed analysis, it became clear that these difficulties were related to decisions made during the design phase. During the drawing of the metallic structure, some fastening and assembly issues were not sufficiently considered, which led to situations requiring adjustments during the execution phase, thus delaying the process.

To resolve these issues, specific changes were proposed to the design of the metallic structure, aiming to eliminate the identified difficulties and ensure a more efficient assembly process.

- **Threaded Holes:**

Until the time of the analysis, the structure arrived at the factory without the necessary holes for threading being fully threaded. Figure 4.4 illustrates an example of how the holes arrived at the factory.



Figure 4.4: Threaded hole with excess paint.

This happened because, during the painting process of the metal structure, paint residues would accumulate in the holes, obstructing the threads that had been made earlier. This problem resulted in a significant loss of time during the preparation of the plant, as it was necessary to use a thread tap in all the holes to remove the paint and ensure that the bolts were properly screwed in.

To solve this issue and avoid rework, a new practice was implemented. It was decided that, before the structure was painted, a set of bolts would be sent to the metal workshop to be

placed in the holes. This way, the holes were properly threaded, without the risk of being blocked by the paint. The final result with this implementation can be seen in Figure 4.5.



Figure 4.5: Result after implementation.

As shown in the image, this procedure ensured that the threads remained intact, resulting in a significantly faster plant preparation, eliminating the need to redo the threads.

Threading the holes was the main task in the unit preparation stage, so with the implemented change, a significant reduction in execution time was expected. By analyzing the process time, we can see that there was a reduction in time from 4 hours in the initial situation to **2 hours** after the change was implemented, the result of the average of three measurements.

- **Oil Separator Positioning:**

One of the changes implemented in the process aimed at reducing the installation time of components. Initially, the structure arrived at the factory with only one hole, used as a guide for positioning the oil separator. However, to fix this component to the structure, three holes are required. Figure 4.6 presents an image illustrating the initial situation.

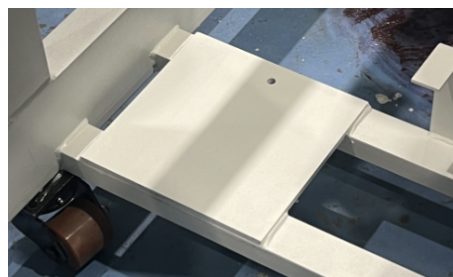


Figure 4.6: Base for fixing the oil separator.

Until that point, the remaining two holes were marked and drilled directly at the factory during the installation of the components. However, this process was time-consuming, as the available material was not ideal for the task. Since it is a standardized component, it is possible to accurately determine the exact locations where the oil separator brackets should be fixed.

Based on the dimensions of the separator, it became feasible to include the two additional holes in the structure's design, so that the manufacturing company could carry out the drilling during the production process. With this change, the structure arrives at the factory with all three necessary holes, as shown in Figure 4.7, eliminating the need for additional drilling during assembly.

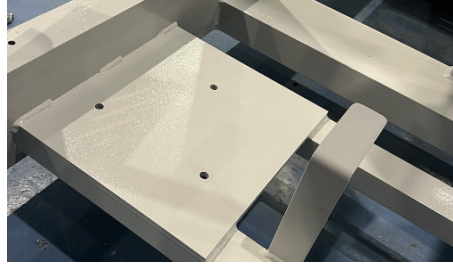


Figure 4.7: Base fixing with improvement.

From the analysis of the image, it is clear that the structure is now ready to receive the oil separator, with no further adaptations required. This change will result in a reduction in the time needed for the installation of this component.

By accounting for the time spent on this step, it was concluded that there is a reduction of about **45 minutes**, the result of the average of three measurements, which will have a positive impact on reducing the overall time in this phase of the process.

- **Cable Tray Supports:**

Another alteration in the metal structure relates to the supports required for the installation of the cable tray, which allows for the passage of electrical cables. Until then, the supports had to be manufactured to fix the cable tray. These supports were produced in a somewhat outdated manner and required considerable time for their fabrication. In Figure 4.8, we can see an example of one of the supports that were used to support the cable tray.

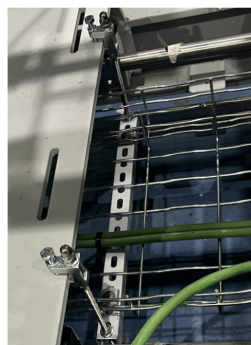


Figure 4.8: Initial Cable Tray Support.

This support, in addition to having an unappealing design, often caused difficulties during installation. Its fixation was made to the compressor support base, a structure that, due to

its sensitivity, needed to be kept as simple and functional as possible. These complications not only increased the time required to complete the installation but also posed a risk to the integrity of the base, potentially compromising the stability of the equipment. For these reasons, it became clear that a more efficient solution was needed, one that would ensure both ease of installation and preservation of the base structure.

The solution found was to develop and incorporate supports directly into the design of the metal structure, thus eliminating the need for rework later on. These new supports were designed to meet the demands of functionality and simplicity. In Figure 4.9, we can see an example of these types of supports, already integrated into the structure, highlighting their adaptation to the rest of the assembly and contributing to a more uniform finish and a more aesthetically pleasing result.

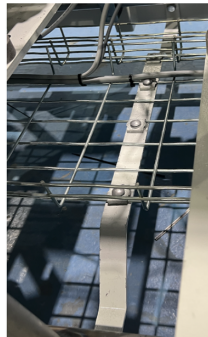


Figure 4.9: Implemented Cable Tray Support.

The analysis of the figure highlights the numerous advantages achieved with this procedure. First, the possibility of potential friction on the compressor support base was eliminated, preserving its integrity and functionality. Furthermore, a structure was developed to support and allow the leveling of the metal tray uniformly across all plants. This adjustment not only enhances the aesthetics and uniformity of the installation but also simplifies and significantly speeds up the implementation process.

Although it is not a critical point of the process, the reduction of approximately **2 hours** in the total cable tray assembly time, the result of the average of three measurements, contributes to a substantial optimization of labor resources. This gain allows efforts to be redirected to higher-value tasks, thereby increasing the overall efficiency of production.

- **Adjustable Moving Connections:**

At this stage of the process, the primary goal was to minimize rework during the pipe installation. Often, the dimensions indicated in the 2D drawings did not align with the final required measurements for installation, which led to adjustments during the process. When discrepancies were significant, it was necessary to redesign the entire pipe line. However, in cases of smaller adjustments, such as those frequently encountered at the connections to the heat exchangers, adaptations could be made. The issue, however, lay in the base that

supported the heat exchangers, which did not allow any freedom of movement, complicating these adjustments. In Figure 4.10, an example of a modification that had to be made is visible.

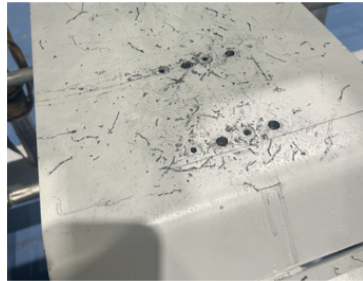


Figure 4.10: Positioning Adjustment.

The piping and the heat exchanger were misaligned by approximately 10 mm, requiring them to be brought closer together. To fix this, it was necessary to move the heat exchanger slightly forward. However, since the heat exchanger was connected to the structure through pre-existing holes, this movement required re-drilling the structure to reposition the heat exchanger, ensuring the piping was properly aligned.

To resolve this issue, a support for the heat exchanger was designed with slots instead of fixed holes. This allows the heat exchangers to be adjusted as needed, with a maximum movement of 12 mm in one direction and 30 mm in the other, as illustrated in Figure 4.11. This new support provides freedom of movement in two directions, allowing the heat exchanger to be brought closer or moved away from the end of the pipe.

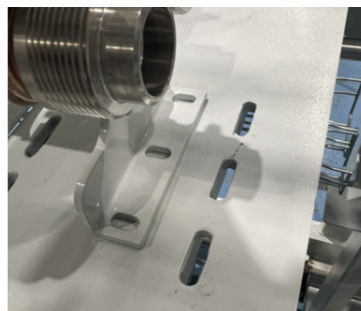


Figure 4.11: Positioning with Slot.

This new fixation model was implemented in all connections requiring relative movement between the parts, providing greater flexibility during installation. With the application of this system, it became possible to make adjustments more quickly and efficiently, without the need to modify the structure or cut or add piping. Additionally, this solution contributed to simplifying the assembly process, as adjustments can be made directly on-site, ensuring a more precise installation without the need for rework.

These changes to the production process of the metal structure have facilitated a smoother and more efficient production flow. By addressing and eliminating errors and the need for rework during the assembly process, significant improvements have been achieved. The removal of these inefficiencies has allowed the production process to proceed without interruptions, reducing the time and resources spent on fixing mistakes.

As a result, the overall assembly process has become faster and more reliable, contributing to higher productivity and lower operational costs. Additionally, the streamlined process has led to better quality control, as fewer errors occur, and the risk of defects is minimized.

4.1.5 Insulation

Analyzing one of the final stages of the production process, it is clear that the completion of the process is directly dependent on the finalization of the insulation of the unit. Until this phase is completed, it is impossible to proceed with the packaging of the structure. However, excessively long cycle times in this task were identified, which negatively impacted the flow of the process.

To mitigate this issue, in addition to defining an exclusive space for this stage, specific solutions were also developed and implemented. These solutions aimed not only to reduce execution time but also to simplify the operations related to insulation, thus improving efficiency while ensuring greater uniformity and quality in the final results.

- **Cutting Table:**

The insulation process for the unit required precise cutting of all insulation materials, adapting them to the specific dimensions of each component. However, a recurring problem arose during this stage due to the wear and tear of the knives used. Work frequently had to be paused for knife sharpening, disrupting the workflow and process efficiency.

Initially, it was believed that the excessive knife wear was solely due to the properties of the insulation material. However, a more detailed analysis revealed that while the material did contribute, another significant factor, which could be addressed, was also at play.

The cutting table used had a metal surface with a certain degree of roughness. During the cutting process, the friction between the knife blade and the rough metal surface caused constant damage to the blade, reducing its efficiency and necessitating frequent sharpening. This factor proved to be critical to the premature wear of the knives.

To verify whether the excessive knife wear was related to abrasion, a practical test was conducted. The table surface was covered with a layer of cardboard to minimize friction and, consequently, blade wear.

The results confirmed the method's effectiveness: insulating the table surface with cardboard significantly reduced knife wear, decreasing the frequency of necessary sharpening. This simple solution proved to be a practical and effective approach to mitigating the problem and improving the durability of the blades used for cutting insulation. However, while

it resolved the issue in the short term, the cardboard covering lacked durability and needed replacement at the end of the production of each unit.

To definitively resolve this problem, a more permanent solution was devised, which, though not yet fully implemented, is already in production. A new table model with a wooden surface was designed. This surface aims not only to eliminate excessive knife wear but also to include various compartments for storing the tools needed for the insulation process. This approach provides a long-lasting solution to the blade wear problem while also contributing to workspace organization and optimization, making the task more efficient.

The unique feature of the new table design is that it significantly simplifies the measurement and cutting process for insulation. A graduated ruler was incorporated into the top of the table, along with a cylinder that serves as a guide for a second graduated ruler positioned at a 90-degree angle to the first. This configuration allows for precise marking of two dimensions with a single measurement, streamlining the cutting process and increasing efficiency. Figure 4.12 illustrates the table model, clearly showing how these features help optimize measurement and cutting tasks in the insulation process.

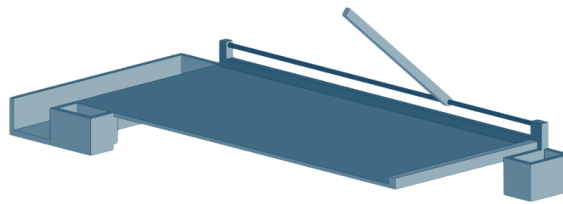


Figure 4.12: Insulation table model.

This model was designed with two closed compartments intended for storing smaller tools, such as knives and sharpeners, providing practical and accessible organization. Additionally, it includes a larger compartment, ideal for storing bulkier items such as glue cans and other materials required for the insulation process.

A key feature of this model is the inclusion of a stop mechanism, which allows for the simultaneous measurement of two dimensions, simplifying the cutting process and enhancing precision. This stop mechanism significantly optimizes work efficiency, making the process faster and more accurate while minimizing the likelihood of errors. The combination of these functionalities contributes to a more organized insulation process with a reduced margin for mistakes.

- **Cutting Tools:**

Another significant challenge related to insulation was the cutting of circular shapes. Initially, these were drawn using a compass, and then, based on the manual outline, the circle

was cut by hand with a knife. While this method was functional, it was time-consuming and prone to errors, often leading to rework and inefficiency.

During the process analysis, it was identified that several components required circular cuts with a specific diameter of 150 mm, particularly the filter covers. Cutting these circles was therefore a critical step that demanded both precision and speed.

To improve this process and reduce the execution time, a more efficient solution was developed, as illustrated in Figure 4.13. This new approach aims to perform circular cuts more quickly and accurately, eliminating the need for manual compass drawing and knife cutting.



Figure 4.13: Circular Cutting Tool.

This tool consists of an aluminum tube with a diameter of 150 mm, equipped with a handle to facilitate the cutting process. The tool operates using rotational movements, enabling the quick and precise cutting of circles with the desired diameter without the need for markings or the time-consuming manual cutting process.

The implementation of this solution primarily aimed to increase productivity while enhancing the quality of the work. With this tool, cuts become more consistent, eliminating inaccuracies that could arise with the traditional method. Furthermore, reducing errors in the insulation process contributes to more efficient production, with less need for rework. This results in a faster process with improved quality control.

- **Molds**

One of the improvements implemented in the insulation phase was the introduction of molds to optimize the process of cutting polyethylene insulation used beneath the unit tanks and heat exchangers. This insulation needed to be cut to specific dimensions matching the component bases, a task that was previously performed manually and lacked standardization.

Previously, the process began with direct measurements of the components. After taking these measurements, the polyethylene was cut, but the dimensions were not recorded for reuse in future productions, requiring the repetition of the same procedure for each new unit. This method was particularly labor-intensive in the case of tanks, which required marking eight holes for bolt passages. Marking these holes was a demanding and time-consuming

task, as it involved finding the center of the base and then drawing the diameters with an angular spacing of 45°.

To address this issue, molds were developed, as illustrated in Figure 4.14. A specific mold was created for each of the different tanks and heat exchangers commonly used in the units.



Figure 4.14: Mould for cutting polyethylene from a tank.

The molds were made of durable material, suitable for prolonged use without significant wear. This improvement enabled the polyethylene dimensions to be delineated quickly and practically, eliminating the need for constant manual measurements or additional calculations, making the process much more efficient.

In addition to removing the need for repeated measurements, the molds ensure high precision in cuts and hole markings, guaranteeing that each piece of insulation is produced with exact dimensions and characteristics, perfectly adapted to each component. This systematic approach significantly reduced the time required for insulation preparation, directly contributing to the efficiency of the production process.

Finally, this method not only simplified the cutting process but also promoted uniformity and quality, ensuring that insulation pieces are consistently produced with greater speed and less effort, optimizing available resources and reducing material waste.

- **Pre-Insulation**

During the detailed analysis of the process and the organization outlined in **Chapter 3, Section 3.5**, it was observed that, in the initial stages of production, some operators faced idle periods. These periods represented moments where operators were not directly engaged in productive activities.

To address this lack of work, methods were devised to allow for the preparation of insulation even before the components or piping arrived at the factory. Previously, insulation tasks were performed based on direct measurements of all components and piping—a time-consuming process that could only commence once the materials had arrived.

To eliminate this dependency and expedite the process, technical catalogs containing standardized dimensions of components were utilized. Using this information, it became possible to pre-plan the insulation elements, as illustrated in Figure 4.15.

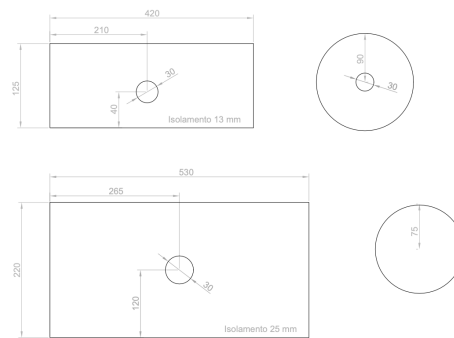


Figure 4.15: Insulation Planning for Filters.

These pre-planned templates enabled the cutting of insulation material without the need for direct measurements or contact with the components. This brought a significant additional advantage: the reduction of errors and waste. Previously, measurement errors in insulation were common, often requiring the entire material to be discarded. By using predefined and standardized dimensions, such issues were virtually eliminated.

For piping insulation, the process followed a similar approach. Existing 2D drawings of the piping were used to determine the necessary dimensions for the insulation. This allowed for precise and preemptive cutting of the insulation material to the required specifications.

This initiative enabled the pre-insulation phase to commence early in the production process, effectively eliminating the previously identified idle periods for operators. Furthermore, it significantly improved the efficiency and speed of the final insulation phase, contributing to overall productivity gains.

4.1.6 Pipe Bending Machine

This subsection will discuss an ongoing study, as it involves a significant investment that is being evaluated by the management. However, a cost-benefit analysis has been conducted, along with a study of the potential advantages associated with implementing this solution.

The proposed improvement consists of replacing the machine currently used for tube bending. The equipment currently in operation is quite old, exhibiting several weaknesses both technically and operationally. The existing limitations include:

- **Limited diameter capacity:** The machine can only bend tubes with a diameter between 1 and 2 inches, limiting flexibility for working with different pipe sizes.
- **Manual angle setting system:** The process of setting the bending degrees is done manually, which can be inaccurate and time-consuming, affecting consistency and productivity.
- **Distortion of bend diameter:** The bend produced by the machine has an excessively elongated diameter, about twice the diameter of the tube, which is not ideal for many applications and can compromise the quality of the installation.

- **Time-consuming die change:** Replacing the dies to accommodate different pipe sizes is a laborious and time-consuming process, resulting in frequent stoppages and reducing operational efficiency.

After a detailed market research, a machine was selected that is highly competent for the required functions, meeting the production demands. To verify the production advantages of this machine, a practical case related to a Series 3 type plant was analyzed.

In this study, the number of bends that could be made if the new machine were implemented was calculated. With this data, Table 4.5 was created, showing the number of bends that can be made based on their dimensions.

Table 4.5: Number of Bends Made by the Machine.

Diameter	Number of Bends
$\frac{1}{2}$ "	10
$\frac{3}{4}$ "	12
1"	8
$1\frac{1}{4}$ "	14
$1\frac{1}{2}$ "	9
2"	3
Total	56

Although the current machine can bend pipes of some of the mentioned diameters, it cannot achieve the necessary curvature to meet the specific dimensions required. Based on the analysis of the data, it was found that with the new machine, it would be possible to make a total of **56 bends** that would currently need to be purchased commercially.

Upon analyzing the production process, it was noted that each bend made internally eliminates the need for several additional operations. For each bend that could be produced on the new machine, we are avoiding the time spent cleaning 4 pipe ends, applying 2 unions, and welding 2 joints. This simplification of the process contributes to a significant reduction in production time.

With the current method, producing the piping with 56 bends would take around **8 hours of production**. With the introduction of the new machine, a significant reduction in production time is expected. This reduction, coupled with the elimination of additional steps, would result in a substantial improvement in productivity.

As expected, a new piece of equipment has a significantly higher operational performance. However, it is crucial to assess, from an economic standpoint, whether the replacement will bring real benefits and identify what those advantages will be. In Appendix F, a simplified analysis of the economic benefits related to the machine replacement is provided, along with the potential break-even point, which is the moment when the investment will become justifiable and financial returns will begin to be visible.

4.2 Layout Changes

In this section, an approach aimed at improving the factory layout will be presented. To achieve this, the SLP method will be used, which is a structured and systematic approach to developing efficient layouts. As described in **Chapter 2, Section 2.3.2**, its implementation follows a methodological sequence composed of five main steps that, when applied in an integrated manner, result in a well-founded solution aligned with the project's objectives.

These steps encompass everything from the initial analysis of flows and relationships between work areas to the final layout configuration, ensuring that all decisions are based on data and objective criteria.

As a starting point for applying the method, it was established that assembly would take place in "Assembly 1", as it was the production box most frequently used by the workers.

In the first stage, a complementary analysis of the production process was conducted to thoroughly understand all the relationships between operations and operators. With this data, it was possible to map the flow of each operator and material based on their location and tasks. Figure 4.16 illustrates a graphical representation of this flow.

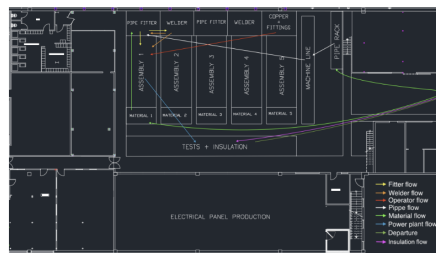


Figure 4.16: Flow of Materials and Workers.

By carefully observing the layout configuration, it is possible to identify several intersecting flows, generating interferences that potentially impact process efficiency. Additionally, some movements occur over areas designated for other activities, creating disruptions in workflow and compromising the overall organization of the space.

The second step of the SLP method aims to deepen the data already collected, incorporating specific information about the production system under study. In this context, it was essential to identify the areas with the highest interaction, considering the frequency and intensity of movements and communications between them.

To achieve this, a detailed analysis of the stages and interactions occurring during the central production process was conducted. This information is systematically organized in Table 4.6, which describes the production process stages, the existing connections between different areas, and the frequency of each interaction.

Table 4.6: Interconnections in the Production Process.

Stage	Description	Interconnections	Frequency (per unit)
Material Entry	Entry of pipes and preparation of the rack Material 1 for constructing the central	Entry - Pipe rack ; Entry - Material 1	Pippe rack (1) Material (1)
Copper Piping Construction	The operator in the Copper + Fittings area builds copper piping and details required by the unit	Copper + Fittings - Material 1	4
Pipe Preparation	The Pipe Fitter is responsible for preparing all pipes and valves based on 2D drawings	Pipe Fitter - Machine line - Material 1	15
Piping Construction	All previously prepared piping is welded	Pipe Fitter - Welder	17
Arrival of Components and Structure	At this stage, the metal structure and necessary components arrive at the factory floor	Entry - Assembly 1	9
Assembly	Workers gather around the structure to assemble all components onto it	Assembly -Pipe fitter; Assembly — Welder; Assembly — Fittings; Assembly — Copper.	Pipe fitter (17) Welder (17) Fittings (7) Copper (10)
Testing	The unit undergoes a pressure test	Assembly 1 - tests + insulation	1
Insulation	Thermal insulation is applied to the piping	Movements between the unit and the insulation cutting table	30
Finishing	The unit is finalized and prepared for shipping	Copper + Fittings - Tests + Insulation	1

After collecting all this data, it was organized into a proximity matrix, as illustrated in Figure 4.17. The interpretation of this matrix assumes the existence of a scale that clarifies the importance of the relationship between sectors, as follows:

- **A** - Absolutely Necessary;
- **E** - Especially Important;
- **I** - Important;
- **O** - Ordinary Closeness OK;
- **U** - Unimportant.

This interaction scale between sectors was used as a basis; however, to simplify the comparison between layouts, the importance of the connections was defined by the number of interactions occurring during the process. Sectors that connect more than 10 times have an interaction of type A, those connecting between 5 and 10 times have an interaction of type E, sectors connecting fewer than 5 times have an interaction of type I, while sectors with no connection are classified as type O interactions. Finally, sectors that must be separated are identified with a type U interaction.

It is also important to note that when two rows of the matrix intersect, a cell is formed where the vowel corresponding to the connection between sectors is inserted.

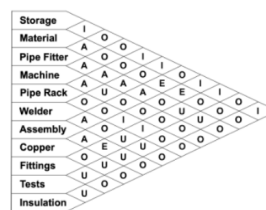


Figure 4.17: Activity relationship chart.

With this representation, it becomes possible to sketch an initial layout of the workstations, positioning them closer or farther apart based on the identified relationships. For example, the **Pipe Fitter** and the **Welder** are expected to be physically close, given that the relationship between them is classified as **type A**. This initial step serves as the foundation for the next stage of the SLP method.

The next step involves the spatial organization of the work areas, ensuring that areas with stronger relationships are placed near one another. Simultaneously, it is necessary to ensure that stages requiring separation—due to specific requirements or potential interferences—are positioned appropriately to meet these conditions.

For this stage, a relationship diagram was created, connecting the work areas that need proximity using a legend that defines the line styles based on the importance of the relationships. The result of this diagram is illustrated in Figure 4.18.

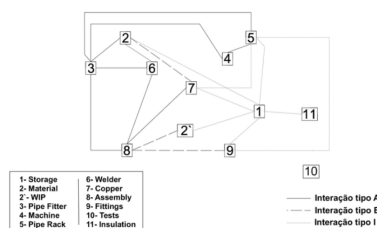


Figure 4.18: Relationship diagram.

To arrive at this design, several conditions were considered. Beyond ensuring the proper relationships between workspaces, it was essential to avoid line crossings. However, this condition was violated in the interactions between Storage and Material (1-2) and between Pipe Rack and

Copper (5-7). These are low-frequency interactions that occur at different stages of the process, making the crossings less problematic.

It is also worth noting that a material shelf (2') was added to store all materials required for assembly in the Assembly area. This addition will be implemented in the next step of the method.

In the fourth phase, the distribution of workstations was determined, taking into account the space required for each section and the dimensions of the factory floor. The fifth step involves analyzing the block diagram created in the previous phase and adapting it to the available infrastructure. Since these two steps are complementary, they were carried out simultaneously.

During this process, meetings were held with the responsible parties, and visits to the factory floor were conducted to ensure that all variables were analyzed, aiming to explore as many alternatives as possible. As a result, it was observed that:

- There were enough shelves to add a support shelf for the Assembly area;
- Special care was needed for the movement of the unit, as it is a rigid structure of large dimensions;
- There was a door providing access to the warehouse that had not been used until now;
- The available space was now larger due to renovations;
- A container was acquired to perform pressure tests in a safe and controlled environment;
- Four assembly zones and two pipe production zones were required.

Finally, a meeting was held with the Safety Department to ensure that all necessary requirements were met and that all changes complied with applicable regulations.

With all details finalized, two alternatives for the block diagram were developed, shown in Figures 4.19.



Figure 4.19: Alternative block diagram.

Starting from this point, a detailed analysis of both proposals was conducted to select the most suitable option for implementation on the factory floor. Additionally, the impact of each proposal on daily operations was evaluated, including aspects such as ergonomics, accessibility, and the potential for future expansion. Based on these criteria, the layout that best meets the operational and strategic needs of the factory will be developed.

In the next section, the strengths and limitations of each proposal will be outlined. From this discussion, the final decision on the selected model will be presented, along with the rationale behind this choice.

- Isolated and properly protected testing area;
- Defined space for the insulation zone.

Once all these issues are resolved, it is worth noting that centers with a length of less than 8 meters, representing 78% of the production, could be moved to the testing area without the need for rotation.

Even so, this alternative does not fully solve all existing problems and introduces new challenges, such as:

- The WIP rack has limited accessibility for the operator responsible for organizing it;
- The pipefitter is located farther from the unit;
- The machinery area is very dispersed, making the pipefitter's work less efficient and requiring unnecessary movements;
- The machinery area lacks space for any new machines that may be acquired in the future;
- For units longer than 8 meters, moving them to the testing area becomes more challenging;
- Difficult movement between the testing area and the insulation area.

Thus, although this solution offers notable advantages compared to the initial state, it still presents some limitations. Alternative 2 will aim to address these issues while maintaining the improvements already implemented.

4.3.2 Alternative 2

In the design of this alternative, a physical separation between the assembly area and the finishing area was once again established, thereby maintaining the advantages that result from this arrangement. Figure 4.21 illustrates the proposed layout.

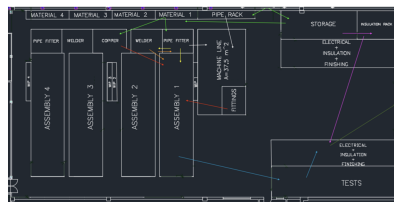


Figure 4.21: Layout - Alternative 2.

In this alternative, the lateral warehouse entrance was once again used to direct materials to an intermediate zone, allowing for the creation of a continuous flow of entry and exit. This contributed to the improvement of internal workflow. By implementing specific pathways for feeding the material racks, it was possible to optimize the movement of materials and workers, ensuring circulation occurred in a single direction.

Figure 4.21 illustrates the operational flow required for the production of a unit. This flow will be analyzed specifically for production at Assembly 1, although the overall evaluation will consider all Assemblies in an integrated manner, ensuring a comprehensive view of the production process.

After careful observation, an analysis can be made highlighting the strengths and some limitations of this proposal. The positive aspects include:

- Continuous material flow;
- Dedicated space for a small storage area for frequently used components;
- Pipe fitter with quick access to the material rack;
- Pipe fitter's and material movement zones located outside the assembly area;
- Copper workstation positioned closer to the assembly zone;
- Fittings positioned away from the pipe fitter and welder;
- Pipe machine located in a designated area with room for future expansion;
- Flexibility to add a new production box due to the available space;
- Isolated and properly secured testing area;
- Defined space for insulation activities.

We can see that most of the limitations of the initial layout have been addressed with the proposed changes, resulting in significant improvements in space organization and workflow efficiency. However, some limitations still remain that need to be considered to achieve optimal performance in the production environment. The main limitations identified include:

- One of the pipefitters is somewhat far from the machine area;
- The WIP rack has difficult access for the operator organizing it;
- Fittings are a bit far from Assemblies 1 and 2;
- For large units, there may be some difficulty in moving them.

A new proposal will still be developed, with the main objective of addressing the limitations identified in the previously presented alternatives. This new approach will aim to integrate the positive aspects already recognized, while addressing the weaknesses in order to maximize the efficiency and functionality of the system. Therefore, it is expected that this proposal will provide a more balanced solution, closer to an optimal solution, tailored to the identified needs and the context under analysis.

Chapter 5

Analysis of Results

This chapter presents the analysis of the results achieved after the implementation of improvements in the production process. The goal is to evaluate the effectiveness of the changes made, highlighting their impacts on process efficiency, cycle time, and resource utilization. The first section focuses on analyzing the improved process, providing a detailed view of the implemented improvements and their effects on overall performance.

Next, the analysis of the layout is presented, with an emphasis on the results obtained from the changes in the production layout. The evaluation of the new layout aims to determine whether the changes have contributed to optimizing space usage, reducing transportation times, and improving the flow of the process. The chapter concludes with an overview of the results achieved and perspectives for future improvements.

5.1 Analysis of the Improved Process

After the implementation and description of all the improvements made, it is essential to evaluate the impact of these changes on the production process as a whole. This analysis is crucial to understand to what extent the changes have contributed to the efficiency, quality, and speed of the process.

To carry out this evaluation, some **KPI's** will be analyzed to provide an objective comparison between the previous situation and the new reality after the improvements. The goal is to identify the gains achieved, highlight the areas with the most significant positive impact, and, if necessary, identify areas that could still be improved further.

The main focus is the reduction in cycle time. To analyze the effects of this indicator, the Excel file developed in **Chapter 3, Section 3.5** will be adapted. In Appendix B.0.3, this analysis is presented for the process with the implemented improvements. The model of the plant being analyzed is the Series 3 type.

Table 5.1 summarizes this analysis, showing the times before and after the steps where improvements were applied. Finally, the total cycle time is presented, from the arrival of the drawings at the factory floor to the completion of the plant.

Table 5.1: Cycle time.

Stage	Time before (hours)	Time after (hours)
Construction of Piping	63,50	37,75
Installation of Components	8,25	6,75
Structure Preparation	4,00	2,00
Installation of cable trays	10,50	8,50
Insulation	26,00	20
Total Process	114	92

It is important to highlight that, in the case of insulation, the time difference is not only due to the reduction in time but also to the restructuring of the stages. With the creation of the pre-insulation step, the final insulation stage now requires less time.

Additionally, during the execution of these stages, other activities occur simultaneously. Therefore, the total hours for each improvement do not directly reflect the overall reduction in final production time, but only a portion of that reduction.

The improvements implemented, which had a direct impact on cycle time, resulted in a reduction of approximately 19%, surpassing the initial 15% target, with a savings of 23 production hours per plant.

Another important metric is labor productivity. With the organization of production stages and the formation of work teams, it became possible to clearly define each operator's role, eliminating friction and ensuring efficiency.

Table 5.2 shows the utilization values for each operator before and after the improvements, considering the time needed for the simultaneous construction of two plants. Initially, subcontracting a pipe fitter and a welder was necessary.

Table 5.2: Utilization Rate.

Operator	Work Time Before (hours)	Work Time After (hours)	% Utilization Before	% Utilization After
Pipe Fitter 1 and 2	63,25	35,75	99,61%	94,70%
Welder 1 and 2	35,00	35,00	55,12%	92,70%
Copper Operator	70,00	70,00	70,00%	81,46%
Assistent 1 and 2	73,00	37,50	66,97%	82,85%
Assistent 3 and 4	73,00	77,00	66,97%	82,80%

The analysis of Table 5.2 shows that the organization of the process resulted in a significant improvement in operator utilization, with rates exceeding 80%, which is considered very satisfactory compared to the initial process. These rates were calculated by dividing the hours worked by the total hours assigned to each task.

For the pipefitters and welders, the assigned hours included both the pipe construction and its installation. For Assistants 1 and 2, the operational time was counted from the start of construction until the pressure test. The copper operator and Assistants 3 and 4 performed tasks throughout the entire process.

- **Pipefitters**

As described in **Chapter 4, Section 4.1.2**, there was a reduction in the total work time of the pipefitters due to the addition of an assistant to the team. Despite a slight decrease in the utilization percentage of the pipefitters, the tasks performed by them became exclusively specialized, ensuring greater efficiency in task execution.

- **Welders**

For the welders, there was a significant increase in the percentage of utilization. This increase stems from the fact that the pipefitters consistently fed the welding process, eliminating unnecessary downtime.

- **Assistants**

Initially, the assistants did not have clearly defined tasks, which resulted in significant time losses. The reorganization of the process and the clear definition of work teams led to a substantial increase in the utilization of these operators, directing their productive hours to truly necessary activities.

In general, we observed that the labor utilization percentage increased, making the stages more efficient and reducing waste by eliminating unnecessary steps.

Thus, we conclude that, in addition to the 19% reduction in cycle time, it was possible to rely on a more complete and integrated team, capable of producing two units simultaneously. This fact allows for a significant increase in annual productivity, meeting the company's requirements and aligning with sales forecasts.

5.2 Analysis of the Improved Layout

In this section, an objective comparison will be made between the three layout proposals. The distances traveled by each operator during the production process will be measured, considering all the necessary stages. The average distances traveled in the Assembly areas will be calculated, reflecting the performance of each proposal.

A score will also be assigned based on the relationship between the degree of interaction defined by the SLP method and the distance between the sectors. This will assess the efficiency of the layout in meeting the proximity needs between areas with higher interaction.

Based on these objective indicators, it will be possible to determine which proposal performs best both in operational terms and spatial efficiency, contributing to a well-founded and strategic choice.

In Table 5.3, the tasks and the distances traveled by the operators in each proposal are described.

In the last part of the table, the stages in which the movement of the metal structure or the unit occurs are detailed, requiring planned actions to ensure its safety and integrity.

Table 5.3: Comparison of Distances for Each Proposal

Task	Distance Proposal 1	Distance Proposal 2	Distance Proposal 3
Pipefitter			
Prepare piping	400 m	330 m	300 m
Assemble unit	210 m	180 m	180 m
Total:	610 m	510 m	480 m
Welder			
Build piping	30 m	30 m	30 m
Assemble unit	150 m	150 m	150 m
Total:	180 m	180 m	180 m
Assistent			
Prepare material	22 m	32 m	22 m
Assemble unit	35 m	35 m	35 m
Insulate	9 m	9 m	9 m
Total:	66 m	76 m	66 m
Copper			
Build piping	34 m	30 m	30 m
Assemble piping	90 m	50 m	50 m
Adjust unit	15 m	15 m	15 m
Total:	139 m	95 m	95 m
Fittings			
Build supports	100 m	110 m	60 m
Total:	100 m	110 m	60 m
Unit			
Structure arrival	38 m	30 m	20 m
Move to tests	35 m	30 m	20 m
Move to insulation	15 m	15 m	15 m
Total:	88 m	75 m	55 m

The data presented in the table allows for an objective comparative analysis between the different proposals. Proposal 3 stands out in most aspects, offering a slight advantage in the decision-making process. The distance traveled by the **Pipefitter** is particularly noteworthy, as pipe construction is a critical point in the process analysis.

When analyzing the movement of the **Structure**, Proposal 3 also presents additional benefits. Although all proposals show less satisfactory results in this aspect compared to the initial situation, this is justified by the need to install the testing area in a separate and protected zone.

This reduction in the distances traveled contributes to greater efficiency, reducing the time required for pipe assembly and the efforts involved in moving the structure.

The second part of the analysis involves assigning a score based on the proximity and interaction between sectors, as defined by the SLP method. Table 5.4 presents the scores assigned to each connection, considering proximity and the type of interaction.

Table 5.4: Table of scores.

Interaction	Distance (meters)					
	3	4	5	6	7	8+
A	5	4	3	2	1	0
E	4	3	2	1	0	0
I	3	2	1	0	0	0
O	0	0	0	0	0	0
U	-5	-4	-3	-2	-1	0

In calculating the total score, the distancing connections, of the "U" type, between the testing area and the other areas, were not considered, as the testing area is already isolated and protected, eliminating the need for additional distancing.

To make the understanding easier, the SLP method's proximity matrix format was adopted to distribute the scores between the relational sectors. In Appendix G.0.1, it is possible to observe the result of this analysis applied to Alternative 1.

The maximum score would be 76 points, achievable only if the alternative obtained the maximum score in all parameters. In practice, this is impossible due to **capacity reasons**, such as the fact that there is only one copper operator for the four assemblies, and **relationship reasons**, such as between the welder and the machine line, since the pipefitter needs to be close to both. Therefore, a score around 60 points is more representative of an ideal real scenario.

Although this alternative has a satisfactory score in several aspects, it was penalized by 7 points due to the difficulty of ensuring the necessary distancing between sectors that require separation. This impacted the overall evaluation, resulting in a total score of 32 points.

The same analysis was conducted for Alternative 2, with the corresponding score matrix presented in Appendix G.0.2. This allows for a comparative basis between the layouts for a more detailed evaluation.

In this proposal, the distancing issues were corrected, which contributed to the score approaching an ideal solution. Additionally, the fact that it presents a more organized machine and storage area also favored the improvement of the score, allowing it to reach 46 points.

Finally, Alternative 3 was analyzed in detail, and, as in the previous proposals, the corresponding matrix was created. Appendix G.0.3 presents the result of this implementation, clearly demonstrating the characteristics and organization of the proposal.

The entry of materials at the beginning of the production flow, making it more fluid, produced noticeable results in improving the score of this proposal. On the other hand, reducing the width of the work areas related to the **Assemblies** and the **Pipe Fitter** and **Welder** zones did not compromise production and allowed the **Pipe Fitter** to be positioned closer to the **Machine Line** and **Pipe Rack**. This reorganization resulted in a higher score for this proposal, highlighting the improvements in the production process.

After a qualitative analysis, in which Alternative 3 already stood out for its ability to solve many of the production inefficiencies, the quantitative analysis confirmed this conclusion. The data obtained proves that Alternative 3 is indeed the one that best addresses the challenges related to material movement, workflow, and sector organization. Its ability to optimize the layout and resource distribution was crucial in improving production processes. This proposal consistently achieved better results in both metrics evaluated in this subchapter, showing superior performance compared to the other options. Therefore, Alternative 3 emerges as the most effective solution for the identified problems and will be the one implemented in the factory hall, contributing to a more efficient and organized work environment.

Chapter 6

Conclusion

The present study aimed to analyze and improve the production process of refrigeration units, focusing on increasing operational efficiency, reducing waste, and optimizing resources without compromising the quality of the final product. Through a systematic and integrative approach, it was possible to implement improvements that resulted in significant advances in both the organization and the overall performance of the factory.

One of the main results achieved was the reduction in total production time, which decreased from 114 to 92 hours, representing a 19% reduction in cycle time. This improvement was achieved through process reorganization, elimination of non-value-added activities, and more efficient task redistribution. Additionally, productivity increased significantly, accompanied by a more rational and optimized use of available resources.

To achieve these results, tools based on Lean Manufacturing principles, such as Value Stream Mapping and the Kaizen philosophy, were applied. These allowed for the identification of bottlenecks and opportunities for improvement at each stage of the production process. The reconfiguration of the factory layout also played a crucial role in this context, being based on detailed analyses and the use of Systematic Layout Planning. These changes resulted in a more efficient flow of materials and operators, promoting greater ergonomics, safety, and agility in production.

Throughout the project, challenges such as initial resistance to changes were overcome through meetings, training sessions, and continuous feedback with the teams, ensuring alignment among all involved and facilitating the transition to the new flows and practices. These actions were key to ensuring the success of the implemented changes.

The data collected and analyzed throughout the work provided valuable insights into critical points in the production process, helping to clarify uncertainties and propose concrete solutions. The implemented improvements contributed to making processes more organized and agile, positively impacting the company's competitiveness and market positioning.

In conclusion, this study fully achieved its objectives, bringing significant results that not only addressed specific problems but also established a solid foundation for future continuous improvements. The detailed analysis and application of structured methodologies proved essential

in transforming the production processes, promoting operational efficiency, organization, and sustainability. This work reinforces the relevance of adopting a methodical, data-driven approach to achieve concrete and lasting advancements in the industrial environment.

6.1 Future Work

As a continuation of this project, it is recommended to expand the analysis and improvement methodologies to other sectors of the company, aiming to maximize benefits across the entire production chain. This expansion will allow the identification of new optimization opportunities and promote improvements that will positively impact the overall efficiency of the organization.

Additionally, it is crucial to continuously monitor performance indicators over time. This practice will ensure the maintenance of the gains achieved, while enabling the identification of new areas for improvement and the implementation of corrective or preventive actions, always aligned with the company's strategic objectives.

Another essential aspect is the adoption of an effective stock control and order management system. This system should ensure the continuous availability of the components required for production, eliminating waiting times and disruptions in the production process. Reducing these times will contribute significantly to the agility and efficiency of the process, generating relevant advances in productivity and operational results.

Finally, this study demonstrated not only the feasibility of systematically and sustainably improving industrial processes but also established a solid foundation for future advancements and innovations in refrigeration unit production, reinforcing the company's competitiveness in the market.

Bibliography

- [1] D. R. James P. Womack, Daniel T. Jones, *The machine that change the world*. Simon Schuster, 2011.
- [2] K. Institute, “Compreender lean manufacturing - guia kaizen.” <https://kaizen.com/pt/insights-pt/compreender-lean-manufacturing-guia/>. Accessed: Oct. 07, 2024.
- [3] L. E. I. (LEI), “Lean enterprise institute.” <https://www.lean.org>. Accessed: Oct. 07, 2024.
- [4] J. A. de Sousa Barros Basto, “Gestão da produção - lean and sustainable supply chains,” 2011.
- [5] TOTVS, “Conheça 11 ferramentas de lean manufacturing.” <https://www.totvs.com/blog/gestao-industrial/ferramentas-de-lean-manufacturing/>. Accessed: Oct. 07, 2024.
- [6] E. TOTVS, “O que é a metodologia kaizen?.” <https://www.totvs.com/blog/negocios/metodologia-kaizen/>. Accessed: Oct. 09, 2024.
- [7] J. A. Faria, “Continuous improvement - kaizen.”
- [8] J. A. Faria, “Customer focus.”
- [9] N. K. Ramarapu, S. Mehra, and M. N. Frolick, “A comparative analysis and review of jit “implementation” research,” *International Journal of Operations & production management*, vol. 15, no. 1, pp. 38–49, 1995.
- [10] D. F. Lopes, “Analysis and implementation of a kanban system in a metal-mechanical company,” 2017.
- [11] L. S. da Silva, “Ferramentas da qualidade: uma aplicação do ciclo pdca e masp em micro e pequenas empresas,” *Revista de Gestão e Secretariado*, 2024.
- [12] J. A. Faria, “Introduction to the catapult workshop.”
- [13] K. Institute, “O guia definitivo para 5s e o treino 5s.” <https://kaizen.com/pt/insights-pt/guia-definitivo-5s-treino/>. Accessed: Nov. 15, 2024.
- [14] A. A. M. dos Santos, “Gestão da qualidade: conceito, princípio, método e ferramentas,” *Revista científica INTERMEIO*, 2013.
- [15] G. Forlogic, “Diagrama de ishikawa.” <https://ferramentasdaqualidade.org/diagrama-de-ishikawa/>. Accessed: Nov. 15, 2024.

- [16] K. V. V. S. Shravan E. R., Sourav Dharmanand1 and D. K. K. R., “Implementation of lean manufacturing in a small and medium enterprise using value stream mapping,” 2024.
- [17] H. V. L. Yang-Hua Lian, “An application of simulation and value stream mapping in lean manufacturing,” 2002.
- [18] M. A. . A. G. Sisay G. Gebeyehu, “Production lead time improvement through lean manufacturing.” <https://www.tandfonline.com/doi/full/10.1080/23311916.2022.2034255#abstract>. Accessed: Nov. 15, 2024.
- [19] Lucidchart, “Símbolos e ícones de mapeamento de fluxo de valor.” <https://www.lucidchart.com/pages/pt/simbolos-e-icone-de-mapeamento-de-fluxo-de-valor>. Accessed: Nov. 18, 2024.
- [20] L. F. P. Branco, “Aplicação do lean management na produção de unidades de ventilação da riox,” 2011.
- [21] M. eco online, “Lean management tools.” <https://www.mangolive.com/lean-management-tools-bottleneck-analysis>. Accessed: Nov. 18, 2024.
- [22] R. G. Ferreira, “Definição e monitorização de indicadores chave de desempenho (kpi) para controlo de operações na indústria corticeira,” Master’s thesis, Faculdade de Engenharia Universidade do Porto, 2019.
- [23] S. Bell, “Smart goals.” <https://www.mindtools.com/a4wo118/smart-goals>. Accessed: Nov. 19, 2024.
- [24] B. A. O. T. Montijn van de Ven, Paola Lara Machado · Alexia Athanasopoulou, “Key performance indicators for business models: a systematic review and catalog,” 2023.
- [25] W. KENTON, “Capacity utilization rate: Definition, formula, and uses in business.” <https://www.investopedia.com/terms/c/capacityutilizationrate.asp>. Accessed: Nov. 19, 2024.
- [26] L. E. Institute, “Cycle time.” <https://www.lean.org/lexicon-terms/cycle-time/>. Accessed: Nov. 19, 2024.
- [27] C. ARC, “Conheça os 7 principais indicadores de produção.” <https://controlarc.com.br/conheca-os-7-principais-indicadores-de-producao/>. Accessed: Nov. 19, 2024.
- [28] S. C. Rei, “Melhoria operacional e redução dos tempos de setup em processos de transformação de cartão canelado,” Master’s thesis, FEUP, 2021.
- [29] S. Phipps, “Quais são os melhores kpis da supply chain?.” <https://www.slimstock.com/pt/blog/kpis-supply-chain/>. Accessed: Nov. 20, 2024.
- [30] “Indicadores kpi a adotar para avaliar o projeto-piloto 1 – aperfeiçoamento da tarifa de acesso às redes em mat, at e mt.” <https://www.erse.pt/media/wqymfffj/anexo-4-manual-kpi.pdf>. Accessed: Nov. 20, 2024.
- [31] A. B. R. V. F. Araújo, “Desenvolvimento e aplicação de uma metodologia de suporte ao planeamento estratégico baseada na tela de análise estratégica,” Master’s thesis, Universidade do minho - Escola de Engenharia, 2018.

- [32] B. T. Tompkins, White, *Facilities Planning*. Wiley, 2002. Pages 298–309.
- [33] J. A. de Sousa Barros Basto, “Gestão da produção - facility layout,” 2011.
- [34] H. A. F. Steffan M. Werner, Fernando A. Forcellini, “Re-layout in a study environment to increase their capacity based on the slp,” Master’s thesis, Universidade Federal de Santa Catarina, 2016.
- [35] F. R. G. R. Rodrigues, “Princípios lean manufacturing aplicados à definição de um layout de uma unidade de produção,” Master’s thesis, Universidade do minho - Escola de Engenharia, 2022.
- [36] Managementguru, “Objectives and principles of plant layout.” <https://pt.pinterest.com/pin/objectives-and-principles-of-plant-layout-management-guru--11660107>. Accessed: Nov. 25, 2024.
- [37] Y.A. and M. B. Çengel, *Thermodynamics: An Engineering Approach*. McGraw-Hill Higher Education ISBN: 978-0-073107-68-4, 2006.
- [38] B. P. e Silva, “Projeto do sistema de ejeção de líquido para uma central a co2 transcrito, com vista ao funcionamento em evaporadores inundados,” Master’s thesis, FEUP, 2021.
- [39] C. Afonso, *Sistemas Frigoríficos*. Porto: Efeitos Gráficos ISBN: 978-989- 54350-1-2, 2019.
- [40] A. T. Hundy, G.F. and T. Welch, *3.1 Introduction, in Refrigeration, Air Conditioning and Heat Pumps (5th Edition)*. Elsevier, 2016.
- [41] M. Kutz, *13.4.2 Refrigerant Selection for Closed Cycle, in Mechanical Engineers’ Handbook, Volume 4 - Energy and Power (4th Edition)*. John Wiley Sons, 2014.
- [42] Y. Ge and S. Tassou, “Thermodynamic analysis of transcritical co2 booster refrigeration systems in supermarket. energy conversion and management.” <https://doi.org/10.1016/j.enconman.2010.11.015>. Accessed: Nov. 26, 2024.
- [43] I. Dinçer and M. Kanoğlu, *2.11 Thermophysical Properties of Refrigerants, in Refrigeration Systems and Applications (2nd Edition)*. John Wiley Sons, 2010.
- [44] D. Z. Bahman, A.M. and E. Groll, “A generalized moving-boundary algorithm to predict the heat transfer rate of transcritical co2 gas coolers. international journal of refrigeration.” <https://doi.org/10.1016/j.ijrefrig.2020.05.021>. Accessed: Nov. 26, 2024.
- [45] A. Pamitran, “Evaporation heat transfer coefficient in single circular small tubes for flow natural refrigerants of c3h8, nh3, and co2. international journal of multiphase flow.” <https://doi.org/10.1016/j.ijmultiphaseflow.2011.02.005>. Accessed: Nov. 26, 2024.
- [46] R. M. M. Ornelas, “OtimizaÇão da estrutura de centrais frigoríficas pelo método de elementos finitos,” Master’s thesis, Instituto Superior de Engenharia do Porto, 2021.

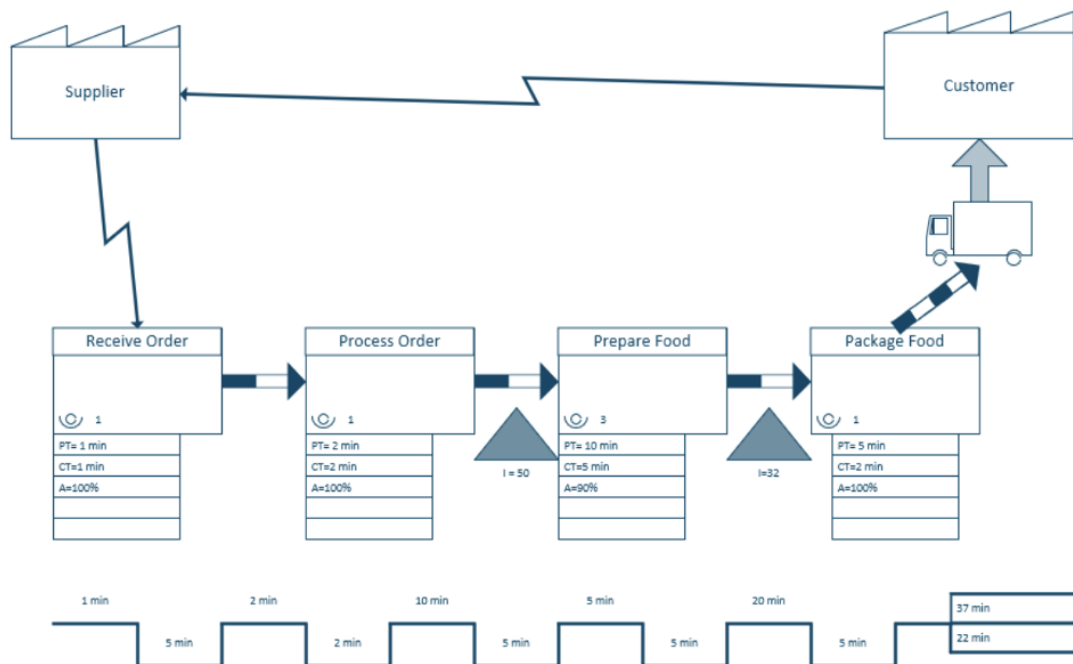
Appendix A

VSM Symbols and Example

A.0.1 VSM Symbols

Process Symbols											
Material Symbols											
Information Symbols											
General Symbols											
Extended VSM Symbols											

A.0.2 VSM Example



Appendix B

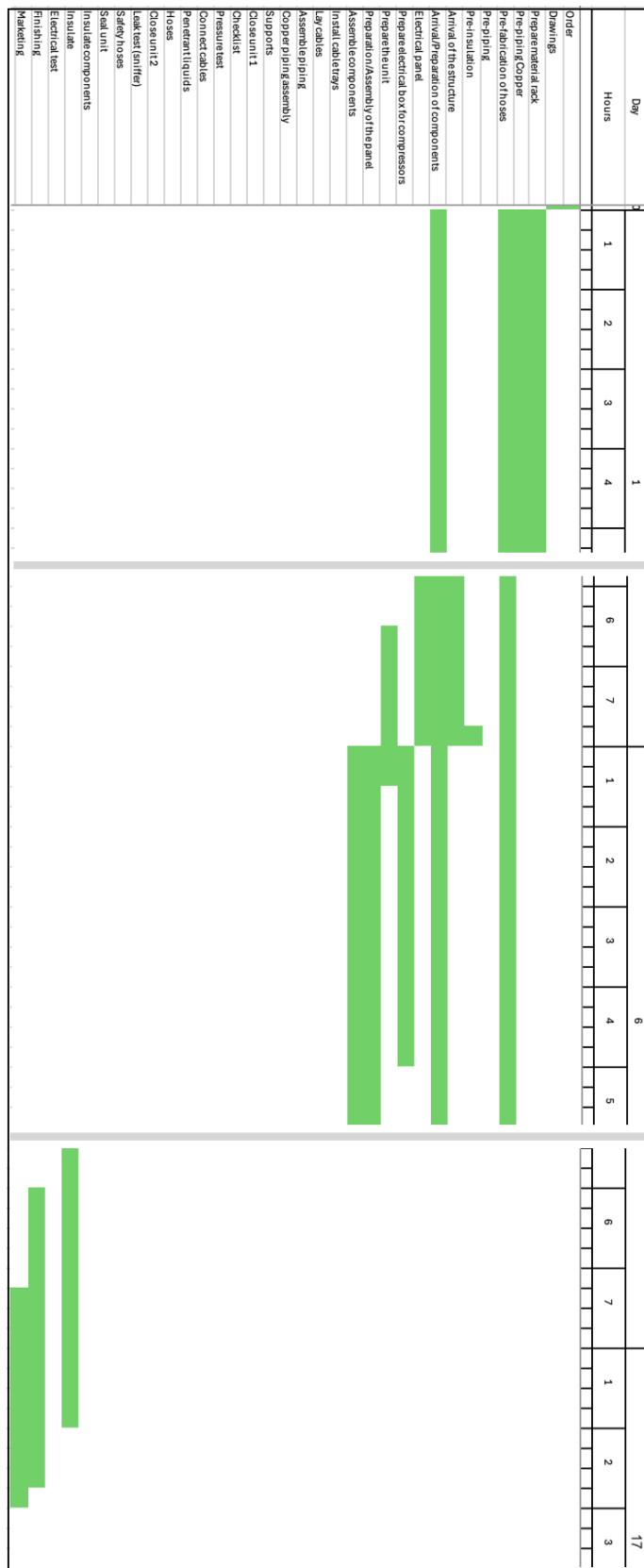
Process Time

B.0.1 Process Time Analysis

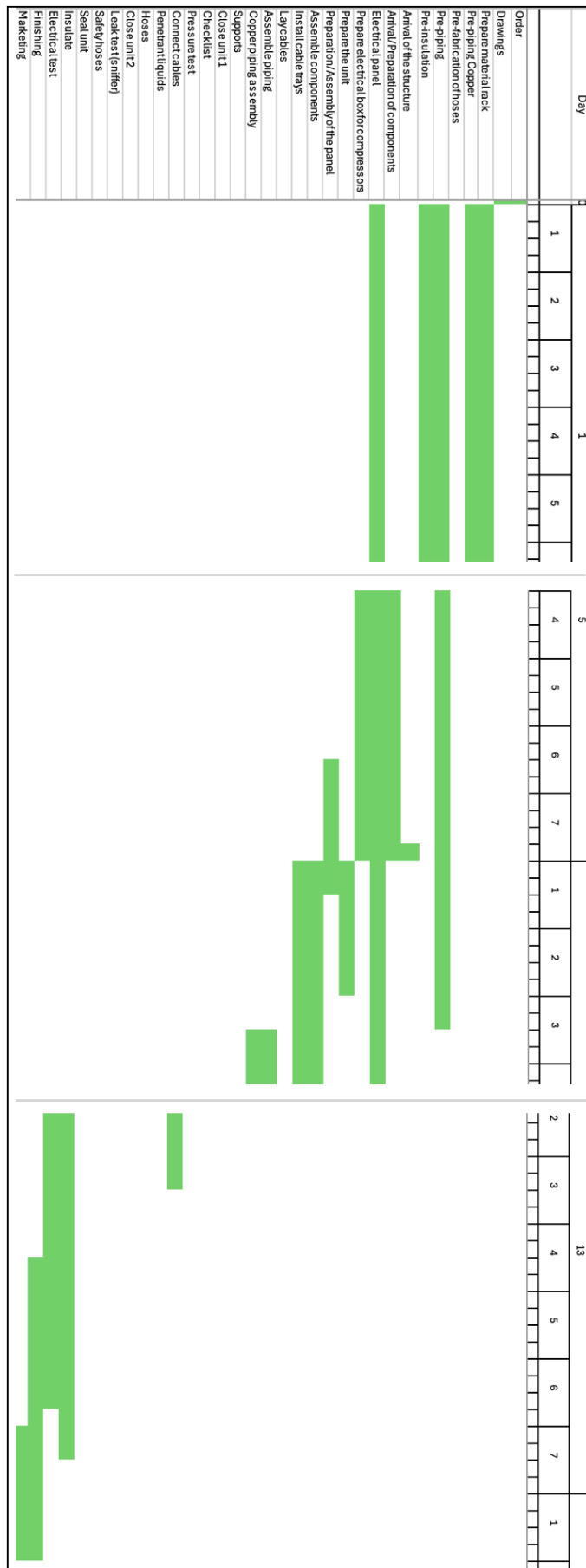
Preparação dos componentes				Tempo min	Tempo com melhorias		Antes	Depois
Compressores								
	N° compressores		Separar parafusos/anilhas/porcãs	5	5			
			Preparação e montagem reguladores	13	13			
	4		Coletar comp c/ coletores	10	10			
						total	97	97
Preparação de filtros								
Tempo por ponta	N° filtros	N° pontas a limpar	Abriir filtro	15	15			
2	3	6	Limpeza e chanfro	5	5			
						total	60	60
Preparação de permutadores								
	n° permutadores		ir buscar	10	10			
			cortar reline	15	5			
	2		colar reline	10	10			
						total	70	50
Preparação depósitos								
Tempo por ponta	N° Depósitos	N° pontas a limpar	Separar parafusos	5	5			
2	2	10	Desembalar	5	5			
			Limpar conexões	20	20			
			cortar rilene	30	15			
						total	120	90
Separador oleo								
Tempo por ponta	N° Separadores	N° pontas a limpar	Separar parafusos	5	5			
2	1	2	Desembalar	5	5			
			Limpar conexões	4	4			
			Furar estrutura	30	0			
						total	44	14
			total				405	315
Dias até chegarem os componentes				0	total em min	0		
Preparação rack material (horas)				7	total em min	420		
Entregados desenhos dias				0	total em min	0		
Dias até chegar a estrutura				5	total em min	2100		
Preparação central (horas)				4	total em min	240	120	
Construção da tubagem				Tempo min	Tempo com melhorias			
Kit transcritica								
tempo de medire cortar	tempo limpar	Tempo soldar/cordão	Conferir desenhos	30	30			
10	3	6,5	Separar materiais necessarios	5	5			
			Limpar acessórios (curvas, Tês, Valv)	150	150			
Tempo pingar/cordão	n° Tubos para medir	tamanho do tubo	Medir e cortar tubagem	80	80			
3	6	1 1/4"	Pingar	78	78			
n° pontas a limpar	N° cordões solda/pingar	n° picagens/furos	Soldar	169	169			
50	26	2				total	345	188
Kit flash gas								
tempo de medire cortar	tempo limpar	Tempo soldar/cordão	Conferir desenhos	30	30			
10	3	6,5	Separar materiais necessarios	5	5			
			Limpar acessórios (curvas, Tês, Valv)	138	138			
Tempo pingar/cordão	n° Tubos para medir	tamanho do tubo	Medir e cortar tubagem	80	80			
3	8	1 1/4"	Pingar	69	69			
n° pontas a limpar	N° cordões solda/pingar	n° picagens/furos	Soldar	149,5	115			
46	23	0				total	330	179
Kit Filtro LT								
tempo de medire cortar	tempo limpar	Tempo soldar/cordão	Conferir desenhos	30	30			
10	3	6,5	Separar materiais necessarios	5	5			
			Limpar acessórios (curvas, Tês, Valv)	78	78			
Tempo pingar/cordão	n° Tubos para medir	tamanho do tubo	Medir e cortar tubagem	60	60			
3	6	1 1/4"	Pingar	39	39			
n° pontas a limpar	N° cordões solda/pingar	n° picagens/furos	Soldar	84,5	84,5			
26	13	0				total	225	129
Kit Filtro MT								
tempo de medire cortar	tempo limpar	Tempo soldar/cordão	Conferir desenhos	30	30			
10	3	4	Separar materiais necessarios	5	5			
			Limpar acessórios (curvas, Tês, Valv)	90	90			
Tempo pingar/cordão	n° Tubos para medir	tamanho do tubo	Medir e cortar tubagem	60	60			
3	6	3/4"	Pingar	45	45			
n° pontas a limpar	N° cordões solda/pingar	n° picagens/furos	Soldar	60	60			
30	15	2				total	240	135
Kit Filtro Liquido								
			Conferir desenhos	30	30			

Pré fabrico Isolamento				Tempo min	Tempo com melhorias		Antes	Depois
Isolamento		Separar material necessário		60	60			
		Medir		115	0			
		Cortar isolamento		120	620	total	295	610
Pré fabrico mangueiras				Tempo min	Tempo com melhorias			
Mangueiras		Ir buscar		0,5				
		Medir e cortar e cravar mangueiras	10	5		total	0	60
Preparação Painel				Tempo min	Tempo com melhorias			
Painel		Montar manifold		40	40			
		Aplicar manifold		35	35			
		Montar painel na estrutura		45	45	total	120	120
Montagem dos componentes				Tempo min	Tempo com melhorias			
Componentes		Alinhar compressores		5	5			
		Montar Filtros		20	20			
		Montar Separador		30	30			
		Montar depósitos		30	30			
		Montar permutadores		30	30			
		Colocar comp na estrutura		20	10	total	355	285
		Furar estrutura separador		30	0			
Montar esteiras						total	630	510
Checklist 1					1	total	60	60
Montagem da tubagem cobre				Tempo min	Tempo com melhorias			
		Tubagem GE		180	180			
		Injeção de Gás		90	90			
		Injeção de Óleo		90	90			
		Injeção de Líquido		90	90			
		Tubagem Água		90	90	total	540	540
Montagem da tubagem				Tempo min	Tempo com melhorias			
		Kit Transcritica		120	120			
		Kit Flash Gas		90	90			
		Kit Filtro LT		90	90			
		Kit Filtro MT		60	60			
		Kit Filtro Líquido		60	60			
		Linha Aspiração LT - (Azul Escuro)		110	110			
		Linha Aspiração MT - (Azul Claro)		115	115			
		Linha IT Gas - (Laranja)		60	60			
		Linha IT Líquido - (Laranja)		60	60			
		Linha Retorno GC - (Roxo)		60	60			
		Linha Descarga HP - (Vermelho)		82	82			
		Coletor Óleo		90	90	total	1455	1455
		Ligação separador / gas cooler		90	90			
		Coletor paralelos		90	90			
		Coletor de descarga de segurança		90	90			
		Ligações injetor		120	120			
		tubagem água		60	60			
Fecho da central 1				Tempo min	Tempo com melhorias			
fecho central (1)		4 Colocar válvulas 3V		2,5	2,5			
		6 Colocar detetores de nível		2,5	2,5			
		13 Colocar válvulas de acesso (1/4 SAE)		2,5	2,5			
		10 Colocar Tacos		1	1			
		3 Fechar tampas de filtros		10	10			
		4 Verificar e apertar válvulas Compr.		2	2			
		2 Fechar CCMT		2	2	total	135	135
Teste Pressão				Tempo min	Tempo com melhorias			

B.0.2 Times Before Improvements



B.0.3 Times After Improvements



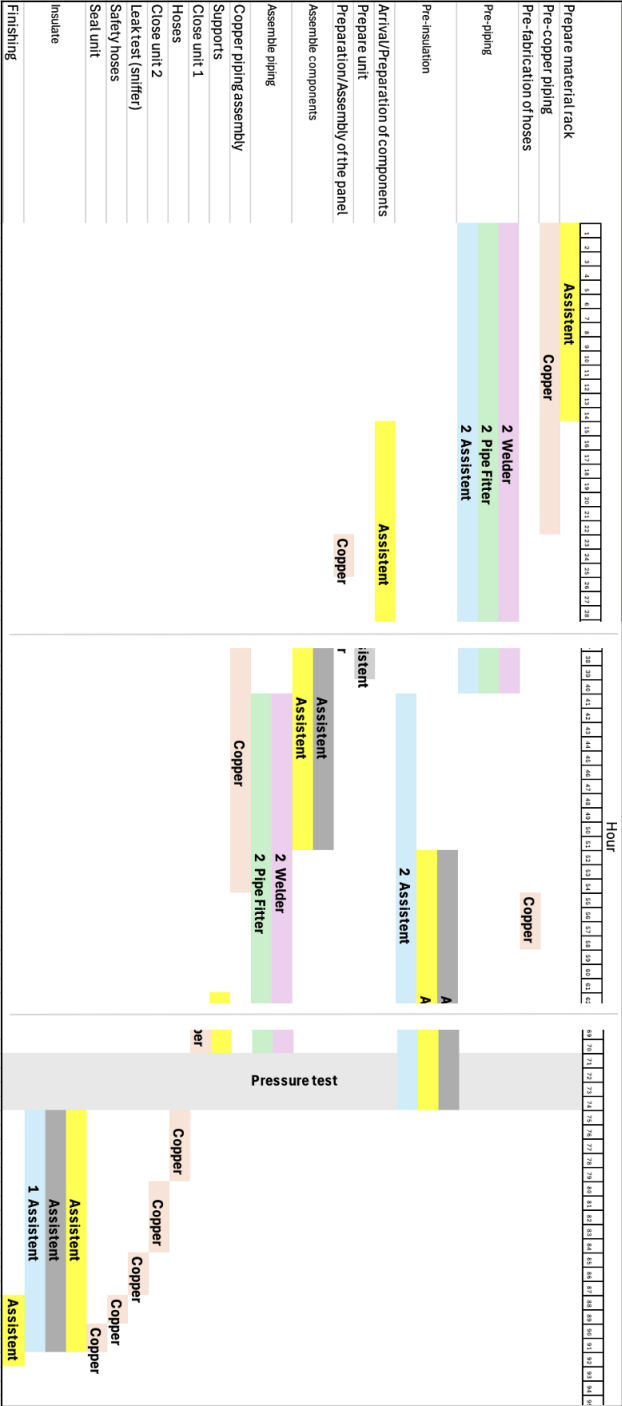
Appendix C

Sales Forecast

	2023	2024	2025 (Forecast)
Serie 1	20%	18%	14%
Serie 3	44%	35%	33%
Serie 5	21%	23%	23%
Serie 7	10%	15%	19%
Serie 9	5%	9%	11%
Total number	18	34	52

Appendix D

Process Organization

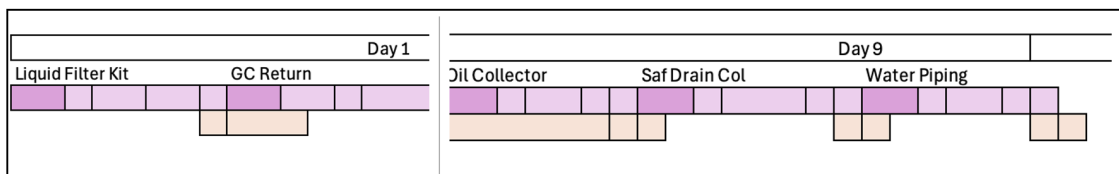


Appendix E

Heuristics for pipeline construction

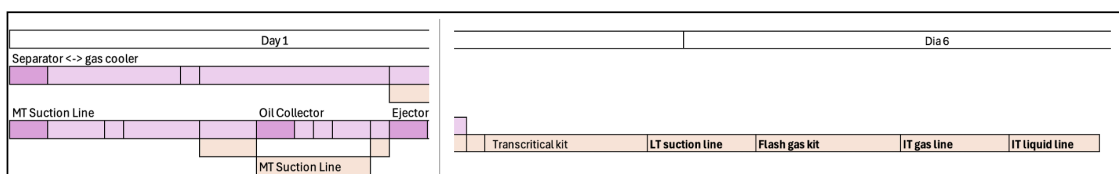
E.0.1 Pipe Fitter and Welder

	Time (h)	% utilization
Pipe Fitter	63,25	99,61%
Welder	35	55,12%
Total	63,5	-



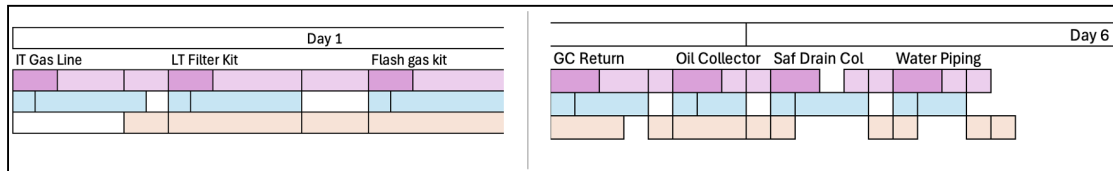
E.0.2 2 Pipe Fitter and Welder

	Time (h)	% utilization
Pipe Fitter 1	31,25	76,69%
Pipe Fitter 2	32	78,53%
Welder	35	85,89%
Total	40,75	-



E.0.3 Pipe Fitter, Assistant and Welder

	Time (h)	% utilization
Pipe Fitter	35,75	94,70%
Assistant	27,5	72,85%
Welder	35	92,72%
Total	37,75	-



Appendix F

Pipe Bending Machine Analysis

F.0.1 Data Analysis

Nº de curvas a evitar		Custos
1/2"	10	30
3/4"	12	36
1"	8	32
1 1/4"	14	70
1 1/2"	9	54
2"	3	27
Total	56	249

Custos sistema atual	-	-	Custo/ central
Discos	2,5	€/disco	€2,50
Luz rebarba	1,5	KWh	€2,80
Bengalas feitas com a atual	7	Unidades	€1,17
Material desperdiçado	10%	das curvas são desperdicio	€2,10
Total	-	-	€8,57

Tempos	min
Trocar matriz	150
Tempo perdido a limpar	560
Tempo perdido a pingar	336
Tempo perdido a soldar	486
Tempo a mais de fazer bengalas	35

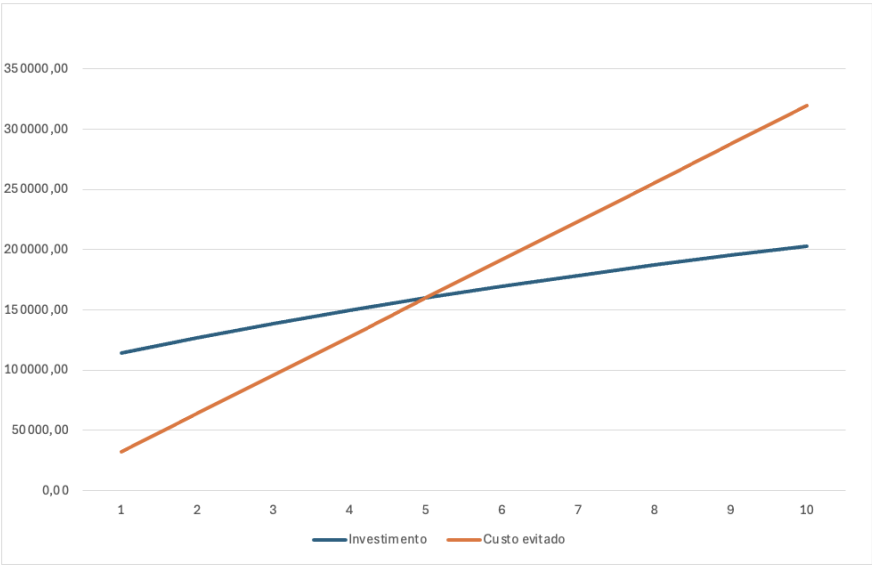
Ganhos com maquina	Tempos (min)	Custos
Tubista	521	173,67
Soldador	822	274,00
Ajudante	560	93,33
Total	972	541,00

Custo total por central	€798,57
Horas de produção ganhas/ central	11,53333333

Custo maquina (NOVA)	€100 000,00	
Desvalorização/ano	10,00%	
Energia eletrica (KWh)	5	0,2€/KWh
Manutenção/ano	€3 375,00	

F.0.2 ROI Analysis

Nº centrais a produzir/ ano											
	Ano 0	Ano 1	Ano 2	Ano 3	Ano 4	Ano 5	Ano 6	Ano 7	Ano 8	Ano 9	Ano 10
Investimento	€100 000,00	-	-	-	-	-	-	-	-	-	-
Desvalorização	-	€10 000,00	€9 000,00	€8 100,00	€7 290,00	€6 561,00	€5 904,90	€5 314,41	€4 782,97	€4 304,67	€3 874,20
Valor da máquina	€100 000,00	€90 000,00	€81 000,00	€72 900,00	€65 610,00	€59 049,00	€53 144,10	€47 829,69	€43 046,72	€38 742,05	€34 867,84
Custos anuais	-	€13 775,00	€12 775,00	€11 875,00	€11 065,00	€10 336,00	€9 679,90	€9 089,41	€8 557,97	€8 079,67	€7 649,20
Custo evitado	-	€31 942,67	€31 942,67	€31 942,67	€31 942,67	€31 942,67	€31 942,67	€31 942,67	€31 942,67	€31 942,67	€31 942,67
Poupança anual	-	€18 167,67	€19 167,67	€20 067,67	€20 877,67	€21 606,67	€22 262,77	€22 853,26	€23 384,70	€23 862,99	€24 293,46
Poupança acumulada	-€100 000,00	-€81 832,33	-€62 664,67	-€42 597,00	-€21 719,33	-€112,67	€22 150,10	€45 003,36	€68 388,05	€92 251,05	€116 544,51
ROI	-	18,17%	19,17%	20,07%	20,88%	21,61%	22,26%	22,85%	23,38%	23,86%	24,29%



Appendix G

Score Matrix

G.0.1 Alternative 1

[illegible]

Reflection on the Sustainable Development Goals

The presented dissertation aligns with several of the Sustainable Development Goals (SDGs) established by the United Nations, demonstrating the integration of sustainable practices in engineering and production management. Specifically, this work contributes to the following aspects:

SDG 8 – Decent Work and Economic Growth: By proposing improvements in the production process and factory layout organization, the study emphasizes the importance of safer and more efficient working conditions, optimizing the flow of materials and operators. The adoption of practices such as Lean Manufacturing and targeted employee training underscores a commitment to enhancing productivity and worker well-being.

SDG 12 – Responsible Consumption and Production: The reduction of waste in the production process and the improved use of resources are directly aligned with the goal of promoting more sustainable consumption and production patterns. By prioritizing efficiency and eliminating low-value-added steps, the study contributes to minimizing the environmental impact of industrial operations.

SDG 11 – Sustainable Cities and Communities: The reconfiguration of the factory layout and the implementation of ergonomic and safety solutions improve working conditions in the industrial environment, promoting practices that can be replicated to strengthen sustainability and inclusion in urban production systems.

Additionally, this work emphasizes the importance of performance indicators, which are essential for monitoring the effectiveness of actions and ensuring long-term sustainability. By adopting practices that balance environmental, social, and economic aspects, the study highlights the crucial role of engineering in developing innovative and sustainable solutions.