



Application of Lean Principles in Maintenance Management: A Case Study

Gustavo Ventura Ferreira de Abreu

Thesis submitted to the School of Technology and Management of the Polytechnic Institute of Bragança (Portugal) with the Federal Center for Technological Education Celso Suckow da Fonseca (Brazil) to Fulfil the Requirements for the Double Degree program to obtain the degree of Master in Mechanical Engineering.

Supervisors:

Prof. Maria Clara Rodrigues Bento Vaz Fernandes

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Concluding this work would not have been possible without the companionship and support of all the people around me. I am deeply grateful to everyone who has been part of my journey from the very beginning until now.

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Abstract

This work presents the application of Lean principles in maintenance management through a case study supported by a company that provided its data and procedures for analysis. The study was conducted following the DMAIC cycle (Define, Measure, Analyze, Improve, and Control), enabling a detailed evaluation of maintenance processes, identifying failures, developing improvement actions, and controlling maintenance performance indicators.

Each DMAIC phase was structured with Lean and Quality tools. In the ‘Define’ phase, the project scope, objectives, and limitations were established using a Project Charter and a SIPOC diagram, which studied 6 processes in the maintenance system. In ‘Measure’, the history of maintenance orders and performance indicators was studied. The ‘Analyze’ phase identified the causes of inefficiencies using the Ishikawa Diagram, and in ‘Improve’, an Impact x Effort matrix was developed to select the causes that should be prioritized, enabling the creation of an action plan, using the 4W1H tool, to address these causes.

The ‘Control’ phase introduced the ‘Maintenance Failure Profile’, which enables the monitoring of performance indicators, tracking equipment failure modes, and assessing the maintenance team’s efficiency. This tool provides leadership with a detailed view of the maintenance status, enables historical comparisons, and supports data-driven decisions.

The project demonstrates that the analysis performed, along with the proposed improvements, has the potential to significantly enhance the efficiency of this company’s maintenance management, without requiring financial investments or structural changes.

Keywords: Maintenance; Lean; DMAIC; Process Improvement.

Resumo

Este trabalho apresenta a aplicação de princípios Lean na Gestão de Manutenção, por meio de um estudo de caso suportado por uma empresa que disponibilizou seus dados e procedimentos para análise. O estudo foi conduzido seguindo o ciclo DMAIC (Definir, Medir, Analisar, Melhorar e Controlar), permitindo avaliar os processos de manutenção, identificar falhas, elaborar ações de melhoria e controlar indicadores de performance.

As fases do DMAIC foram estruturadas com ferramentas Lean e da Qualidade. Na fase ‘Definir’ o escopo, os objetivos e as limitações do projeto foram estabelecidos em um Project Charter e um diagrama SIPOC, que avaliou 6 processos presentes no sistema de manutenção. Em ‘Medir’, o histórico de ordens de manutenção e dos indicadores de performance foi estudado. A fase ‘Analisar’ identificou as principais causas de ineficiências, utilizando o Diagrama de Ishikawa, em ‘Melhorar’ uma matriz de Esforço x Impacto foi desenvolvida para selecionar as causas que deveriam ser priorizadas, permitindo a criação de um plano de ação, com a ferramenta 4W1H, para tratar as causas identificadas.

A fase ‘Controlar’ introduziu o ‘Perfil de Perdas da Manutenção’, que permite monitorar indicadores de desempenho, rastrear modos de falha e avaliar a eficiência das equipes de manutenção. Essa ferramenta fornece à liderança uma visão detalhada do status de manutenção, permite comparações históricas e suporta decisões baseada em dados.

O projeto demonstra que as análises realizadas, junto as melhorias propostas, tem a capacidade de aumentar significativamente a eficiência da gestão de manutenção desta empresa, sem exigir investimentos financeiros ou alterações estruturais.

Palavras-chave: Manutenção; Lean; DMAIC; Melhoria de Processos.

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Chapter 1

Introduction

Maintenance plays a fundamental role in competitiveness and performance among companies and it is evident that process optimization and the gains related to continuous improvement are no longer applied exclusively to production stages.

According to Kardec and Nascif, [1], successful companies demonstrate a heightened awareness of the relationship between maintenance and quality, while also seeking cost reduction. They also emphasize that for a company to achieve the established improvements and planned goals, it is essential to implement an action plan across the entire organization that incorporates best maintenance practices. These practices focus not solely on technical advancements but on strategic approaches encompassing Maintenance Management, Quality Control, and process optimization. In this context, the Lean methodology becomes a valuable ally within the philosophy described by Deming [2] in ‘Out of the Crisis’: “When quality is poor, blame the system, not the people, and management is the system.”

Considering an approach within Maintenance Management and Lean Concepts, there are plenty of tools and different methods that can be applied to achieve waste reduction and process optimization. In this context, the present thesis uses a lean perspective to analyze and conduct a study on the maintenance processes of a real company.

The study will analyze the current state of maintenance and, based on Lean tools and best practices in Maintenance Management, it aims to identify inefficiencies, failures, and

improvement points. This evaluation enables the development of a specific action plan tailored to the company's reality, focusing on improving maintenance reliability, control of performance indicators, failure traceability, and creating a culture of continuous process improvement.

Initially, Lean was commonly dedicated to improving production areas. However, it can be applied in all departments of a company, including the maintenance sector [3], always with the same purpose: to enhance performance, efficiency, and competitiveness, eliminate waste, and standardize processes.

1.1 Objectives

The case study conducted within the maintenance sector of the company under study aims to develop a detailed analysis of the current state of maintenance utilizing DMAIC methodology (Define, Measure, Analyze, Improve, and Control). This approach will enable the identification of failures, improvement opportunities, and waste points that impact the performance of the maintenance department and, consequently, the overall organization.

In this context, Lean tools will be selected to handle process issues, enabling the development of a viable and tailored action plan aligned with the company's specific needs. Furthermore, critical maintenance performance indicators will be defined and monitored.

The proposed improvements will aim to ensure enhanced data quality and accuracy, optimize procedural workflows, and strengthen the traceability of failures. Additionally, the development of a Maintenance Failure Profile, focused on stratifying maintenance data, will provide more precise measurement and management capabilities for the maintenance sector. This approach is designed to generate a positive impact on the company's processes, extending beyond theoretical analyses to support more accurate strategic decision-making and significant optimization of maintenance management processes.

1.2 Thesis Structure

This document is structured into six main chapters. Chapter 2 provides a literature review, concerning the main topics of this work: Maintenance Management, Lean Principles, and the application of Lean methodologies specifically focused on maintenance processes. Chapter 3 offers an overview of the company studied, describing the current state of the maintenance department and identifying both the main challenges and positive aspects.

Chapter 4 conducts a detailed analysis of the company's maintenance processes using the DMAIC methodology, where the steps of Define, Measure, and Analyze will be developed. Based on the findings of this chapter, the subsequent chapter (5) will conduct the Improve and Control phases, proposing an action plan to address the identified gaps and opportunities while respecting the company's reality and conditions. Additionally, this chapter includes the development of the Maintenance Failure Profile, ensuring the stratification of the collected data, and the mechanism to control the performance indicators. The last chapter consolidates the results and presents the conclusions drawn from the research.

Chapter 2

Literature Review

This chapter aims to provide an overview of the key concepts related to Maintenance Management, Lean Principles, and the Lean approach focused on maintenance. Its objective is to establish a solid knowledge base on best maintenance practices, the definition of Lean methodology, its main objectives, and the Lean perspective on Maintenance Management. Throughout the chapter, the literature review will also address the main tools and methods used in both Maintenance and Lean Management, with particular emphasis on areas where these two fields intersect.

2.1 Maintenance Management

Maintenance management is a set of planned activities to preserve the functional capacities of equipment and systems in operation or to restore them to this condition [4]. Maintenance decisions should be based on technical and economic justification, and the leadership must use a solid process to determine what needs to be done, and when it has to be done to ensure the reliability, availability, and performance of a company's assets [5]. According to [4] "Global competitiveness has increased exponentially and maintenance has to be seen not as a loss, but as an asset to business management."

The failure in the maintenance process conduces the company to several factors that

affect the production, and consequently the profitability and competitiveness of a company. The main impacts can be observed in costs, due to emergency repairs, and a stoppage or reduced production flow. Bad quality is also a negative effect that inefficient maintenance can induce, causing rework, a long lead time, and customer dissatisfaction. Last but not least, the safety of employees is strongly connected to the working conditions, and malfunctioning of machinery can result in an unsafe workplace [4], [5]. There are numerous techniques to increase maintenance performance and reliability, such as focusing on failure identification, and preventive activities, to avoid unplanned repairs [6].

2.1.1 Strategies and Types of Maintenance

Understanding the main strategies and the different types of maintenance commonly found in an organizational environment is essential to advancing the study of maintenance processes. The most usual strategies for guaranteeing the Maintenance Department's great performance include Maintenance Engineering, Reliability-Centered Maintenance (RCM), and Total Productive Maintenance [1], [7], and these strategies are presented below.

- **Maintenance Engineering:** It is the technical support for maintenance, and its main goal is to identify and eliminate root causes of failures. Focusing on continuous improvement, it has the attribution to enhance reliability, equipment availability, and reduce costs and waste. Effectively implementing this approach requires time, a solid database, and collaboration between maintenance and engineering teams, as well as high investment in training people and in new analysis tools, software solutions, and devices for equipment monitoring, aiming at a solid understanding of maintenance processes that allows the development of problem solutions and improvements proposals [1].
- **Reliability Centered Maintenance (RCM):** It aims to determine the most effective maintenance tasks to guarantee an asset's performance and reliability at the lowest cost possible. It focuses on studying an asset in detail to determine potential

failure modes and their consequences, in order to prevent them from occurring or minimize the chances [1], [8]. This approach also confers optimization of maintenance plans and better resource allocation, though it requires great communication between maintenance and operation teams, demands time to implement, a solid database, and it is a costly investment [5].

- **Total Productive Maintenance:** TPM is a maintenance methodology designed to maximize equipment effectiveness, eliminate breakdowns, and promote autonomous maintenance by operators through their daily activities. The primary objectives of TPM are to ensure the maintainability and reliability of equipment, reduce maintenance costs over equipments lifecycle, and systematically improve maintenance processes. TPM is supported by key pillars, which include focused improvement, autonomous maintenance, planned maintenance, training operators, initial control of new equipment, and quality maintenance. TPM also extends its principles to administrative and support areas, to enhance overall operational efficiency [1], [7].

Looking in an operational context, the most common types of maintenance include Emergency Corrective Maintenance, Preventive Maintenance, and Predictive Maintenance. Each type has its distinct characteristics and associated advantages and disadvantages [1], [4]. It is also important to emphasize that new studies consider more types of maintenance beyond the 3 most common, which are Planned Corrective Maintenance [1], and Detective Maintenance [1].

Management is responsible for determining the most appropriate type of maintenance for each situation, ensuring the desired performance is achieved at the lowest possible cost. The most suitable type depends on various factors, including cost, safety implications, production impact, and the asset's criticality [1]. This requires a well-defined decision-making process and a reliable measurement and monitoring of performance indicators. The main types of maintenance will be described below:

- **Emergency Corrective Maintenance:** The failure is addressed after it occurs,

generating higher repair costs, potential safety risks, and unplanned downtime [1].

- **Preventive Maintenance:** This approach consists of scheduled component replacements to prevent failures. Anticipating potential problems helps reduce unplanned downtime and extend an asset's lifespan, although if it is not carefully planned, components can be replaced earlier than necessary, wasting components and skilled labor [1], [5], [9].
- **Predictive Maintenance:** Utilizing condition monitoring techniques, this method aims to predict failures before they occur. It minimizes downtime and maximizes asset availability. However, predictive maintenance requires high investments in sensors, data analysis, and specialized expertise. Due to its costs, it is commonly applied to high-critical equipment only [1].
- **Planned Corrective Maintenance:** This type of maintenance is an extension of Emergency Corrective Maintenance, with the main distinction being that the failure has either occurred or been identified before causing a complete equipment breakdown. This allows the maintenance team a minimum lead time to prepare for the execution of the activity, preventing a production line stoppage [1].
- **Detective Maintenance:** It is performed to identify hidden or non-perceptible failures by operational and maintenance collaborators. Specific tasks are carried out to verify the protection of a system, aiming to detect such failures. Typically, this involves conducting tests or specific inspections to identify certain types of system failures [1].

2.1.2 Measuring and Controlling Maintenance

Another critical aspect of maintenance management is establishing effective control mechanisms to measure maintenance performance. To achieve this efficiently, leadership must monitor several Key Performance Indicators (KPIs) to evaluate the performance of maintenance activities and ensure process reliability.

The use of KPIs is essential as they serve not only as performance benchmarks but also as triggers for initiating failure analysis if results are not as expected, on the other hand, performance targets can be monitored and measured through the use of KPIs. However, it is important to emphasize that the use of KPIs requires a reliable database to ensure the accuracy of indicators.

The most used KPIs for maintenance purposes are:

- **Mean Time Between Failures (MTBF):** It is defined as the average time between failures of an asset. A high MTBF indicates greater asset reliability [4].
- **Mean Time To Repair (MTTR):** Represents the average time is necessary to repair an asset after a failure. A low MTTR is desirable as it indicates quick repairs and reduced downtime [4].
- **Failure Rate:** This calculates the frequency that failures occur in an asset over a specific period. A low failure rate suggests good asset reliability [1], [4].
- **Equipment Availability:** Indicates the percentage of time an asset is available for operation. High availability is crucial for productivity [1], [10].
- **Overall Equipment Effectiveness (OEE):** This metric assesses equipment performance based on availability, performance, and quality. It's calculated by multiplying availability, performance, and quality [4], [10].
- **Maintenance Schedule Compliance:** This measures the percentage of maintenance orders completed as scheduled or in a determined period. A high compliance rate implies good maintenance planning and execution [10].

The measurement of KPIs enables performance control in maintenance processes, which is essential for efficient management, and it is aligned with Lean practices for process improvement. As emphasized in ISO 9001:2015 [11], it is important to note that different indicators may be relevant depending on the company's specific needs and goals.

The selection of indicators should be aligned with the strategic objectives of each department, they must be relevant to the measured process and determined by the organization [11].

2.2 Lean Thinking

Lean Management is a leadership approach aimed at identifying and eliminating waste, which is defined as everything that does not add value to the customer. Lean's goals include improving quality, enhancing productivity, reducing costs, and shortening production times, in order to deliver value to the customer [12], [7].

2.2.1 Lean Principles

Five principles form the foundation of Lean Thinking. These principles are applied across organizations, regardless of their industry segment, to drive cultural transformation aimed at achieving greater efficiency, reducing waste, and optimizing processes [13], [14].

The five principles are:

- **Specify Value:** It states that Value is defined by the customer, making it essential to understand what the client considers valuable. This is crucial to eliminate activities that do not add value to the product.
- **Identify the Value Stream:** This encompasses all the steps needed to deliver a product to the customer.
- **Flow:** It seeks a fluid and waste-free process, by eliminating bottlenecks and interruptions in the value stream.
- **Pull:** It states the production must be triggered by customer demand. Producing only what is needed, when it is needed.
- **Pursue Perfection:** It represents the continuous improvement process, always seeking to enhance and optimize the system.

Throughout this chapter, the Lean principles described above will be adapted to the context of Lean Maintenance, in order to detail how each principle is applied from the perspective of maintenance management.

2.2.2 Types of Waste

The principles of Lean are based on the definition that every activity should add value to the final product or service, from the customer's point of view. If there is an activity that does not add value, it is considered waste and should be eliminated [15]. According to this philosophy, waste can manifest in seven principal ways [13], but recently the eighth waste type started being considered [16]. The eight kinds of waste are described below:

- **Overproduction:** Producing more than customer demands. Causing high stock levels, storage costs, and obsolescence risk.
- **Waiting:** Time wasted by people or equipment waiting for the availability of resources, information, or the previous process steps.
- **Transportation:** Unnecessary movement of materials, parts, or products being transported, inside or outside the company.
- **Over-processing:** Using overly complex processes, exceeding customer's needs, and adding costs without adding value.
- **Motion:** Unnecessary movement of people or equipment during the execution of tasks.
- **Inventory:** Immobilized capital of material, parts, or finished products waiting to be utilized or shipped.
- **Defects:** Errors in production that require rework, generating material waste, additional costs, and customer dissatisfaction.
- **Underused Staff Skills:** Failure to use employee's skills and creativity.

2.2.3 Application of Lean Principles and important Tools

Applying Lean Principles in companies aims for long-term development combined with a cultural transformation. For the effective implementation of this management approach, different Lean and Quality tools must be applied simultaneously, according to the necessity of each company and process, but always emphasizing process improvement, collaboration among employees, continuous learning, and the pursuit of perfection [4], [16]. Another aspect to be considered is how Lean must be implemented in companies, addressing both its conceptual and practical aspects, for all employees. This includes training and empowering employees to engage in continuous improvement efforts [14].

A wide range of tools and different approaches can be applied based on the specific needs of each organization. The DMAIC methodology will be the main approach for this project, its application will help define the steps and the identification of the most useful tools for each stage.

The acronym **DMAIC** stands for “Define, Measure, Analyze, Improve, and Control”. It is a systematic approach used to identify and address process inefficiencies, aiming to improve process control and performance [15], [17]. This methodology is highly effective for process analysis and will serve as the basis for the case study conducted in this thesis. It will be utilized to analyze the current maintenance state and identify improvement opportunities. Each stage of DMAIC methodology will be explained below.

- **Define Stage:** In this step, the problem is defined, and its boundaries are clearly established. The project objectives, including its scope and the customer’s needs and expectations, are documented. There are different tools such as SIPOC diagrams, Project Charters, and Value Stream Mapping to define and visualize the problem [15], [17].
- **Measure Stage:** The focus is on collecting appropriate data using metrics and indicators that quantify the current state of the process. Reliable and accurate data collection is essential to ensure the truthfulness of subsequent analyses [15], [17]. If the available data is not reliable enough to conduct an analysis, it must

be considered as a great failure in the process. Thus, it must be addressed as a potential root cause of process issues during the “Analyze” stage.

- **Analyze Stage:** The collected data is analyzed to reveal the root causes of the problem defined. Statistical and process analysis tools, including the Ishikawa Diagram, 5 Whys, and Pareto Analysis, are used to identify root causes, process inefficiencies, or bottlenecks [15], [17]. If the analyzed data is insufficient or inaccurate, a fundamental issue with the data collection process itself is highlighted. This issue must be corrected in subsequent stages to ensure effective process improvement.
- **Improve Stage:** This phase focuses on developing and implementing solutions to address the problem, based on the analysis of root causes defined in the previous steps. The goal is to develop a feasible action plan that optimizes the process, increases efficiency, and minimizes waste. Different approaches are useful for developing high-potential solutions, such as brainstorming, Kaizen, testing, and simulations [15], [17].
- **Control Stage:** This stage ensures that the implemented improvements will be sustained over time. New indicators and control procedures are established to monitor the process and prevent the recurrence of the problem. Control charts, performance dashboards, and audits are utilized to monitor the process performance and maintain the achieved improvements [15], [17].

According to the stages of DMAIC, concentrated on maintenance processes, this work will focus on tools that integrate lean thinking and quality within maintenance management, such as 5S, Kaizen, Root Cause Analysis, Pareto Analysis, SIPOC Diagram, and Project Charter. Those tools are described below.

5S is a set of principles focused on improving the workplace organization to create a clean, organized, and efficient work environment. The five 5S are Sort, Set in Order, Shine, Standardize, and Sustain. This tool is usually combined with different tools to enhance productivity [4].

Kaizen is a Japanese word that means ‘improve for better’. It is a term that represents continuous improvement, which means small and constant improvements that help a company pursue perfection. In the Kaizen perspective, all employees must be involved in process improvement, identifying issues, developing solutions, and implementing them [13].

There are different Root Cause Analysis tools to define the origin of issues in an organization or in a specific process, such as Ishikawa Diagram where the potential causes of a problem are grouped [17], [18]; 5 Whys, which is a simple technique of questioning “Why?” 5 times repetitively to understand the root cause of a problem [1], [17].

Pareto Analysis is a graphical representation that permits identifying the most frequent problems or primary causes of failures [4]. It is based on the principle that 80% of effects come from 20% of causes. In a maintenance department, it could mean that 80% of problems are caused by 20% of failure modes.

SIPOC is an acronym for Suppliers, Inputs, Processes, Outputs, and Customers. The aim is to provide a clear overview of the complete process and define the key elements involved in the production system or in a specific process [15], [17].

The Project Charter represents a tool that outlines critical information and draws a guideline for a project. It includes the project description, scope, objectives, deliverables, risks, assumptions, background, and the used indicators. It is used in the preliminary phase of the project to outline its complete scope and goals [19], [20].

2.3 Maintenance under a Lean Perspective

After understanding the key concepts of Maintenance Management and the principles of Lean Management, it becomes evident that combining these two approaches is feasible and profitable. This integration aims to optimize company performance by producing more with fewer resources [4].

The concept of Lean Maintenance, introduced in the late 20th century, focuses on

minimizing resource consumption during maintenance activities, while ensuring the highest possible level of equipment availability [21]. It means that Lean, when applied to maintenance management, shifts the focus from purely technical issues to a management perspective, applying Lean principles adapted to a maintenance context, with an emphasis on identifying and eliminating root causes of problems, avoiding and reducing waste [18].

The main challenges in maintenance routines are acknowledged. According to [4], the majority of these challenges include a lack of proactive maintenance, recurring failures, poor activity planning, insufficient failure monitoring and traceability, ineffective prioritization of activities, and inefficiencies in the implementation of new resources and equipment. As highlighted by [22], significant progress has been made in maintenance management in recent years. However, there remains considerable room for improvement. Some potential solutions involve process optimization, the application of Lean principles, better resource and effort allocation, operational efficiency enhancements, and improved activity planning.

As discussed in the previous section, Lean thinking is built on five core principles, which are highly effective in analyzing processes to address the customer's needs [21]. In the context of the maintenance department, the "customers" are the other areas of the company that depend on reliable and available equipment to ensure uninterrupted production while avoiding unnecessary costs. By leveraging these principles, it is possible to adapt Lean principles to Lean Maintenance, as detailed below [14].

- **Specify Value:** What the company expects from the maintenance department, is reliable and available equipment, zero accidents, and low costs.
- **Identify the Value Stream:** Identify which steps of the maintenance process deliver value to the "customer", it means which steps do not waste any resources and are indispensable for maintenance.
- **Flow:** To establish a continuous flow of information (Maintenance Orders, Procedures, and KPIs monitoring), material (Spare Parts), and labor (Workflow) within

maintenance processes, in order to accelerate operations and eliminate waste and misinformation during these activities.

- **Pull:** Performing tasks according to the real necessity of companies, with the correct prioritization of activities, and following well-structured maintenance planning.
- **Pursue Perfection:** Develop a culture of continuous improvement in the maintenance department, reducing waste, and empowering employees to improve their workplace and increase their effectiveness.

2.4 Relevant Studies and Their Contributions to This Thesis

The combination of Lean and Maintenance Management, applied to a real case study conducted using the DMAIC methodology, with a focus on process improvement, KPI development, and control, is not commonly addressed in scientific studies. For this reason, the development of this thesis was guided by references that addressed some of these characteristics, and some of the techniques and methodologies used in these references inspired the development of the present work. These studies focus on the application of Lean tools in maintenance across different companies or situations, analyzing how the performance and efficiency of maintenance are impacted.

Youssef [15] uses a different methodology as its foundation, Lean Six Sigma, but its analysis of maintenance through the DMAIC approach presents significant opportunities for a real case study. It highlights the use of tools associated with the DMAIC methodology to achieve process improvement, cost reduction, and enhancements in both performance and quality. In the Define stage, a SIPOC diagram was used to map key elements of the process, identifying suppliers, inputs, processes, outputs, and customers. During the Measure stage, a detailed process mapping was conducted to assess the current state. In the Analyze stage, an Ishikawa diagram was applied to systematically identify potential root causes of inefficiencies, while a Failure Mode and Effects Analysis (FMEA)

was performed to evaluate risks and develop mitigation strategies. This work is highly effective in the process analysis using the DMAIC methodology, but does not present consolidated results or KPIs to measure and control how a company can evaluate its gains from applying Lean to the maintenance process.

The study conducted by Dragone [14] provides an excellent parallel of what “maintenance customers” mean in an organization and how Lean principles apply to them. The analysis develops an evaluation of Lean maintenance principles, but the context of the study is not a factory, but rather the construction industry. In this study, no action plan for process improvement was developed, instead, this work focuses on an analysis of the application of Lean principles in the maintenance of a company, with each of the five principles being analyzed individually, both qualitatively and quantitatively. Although there is no direct connection between the study conducted by Dragone, [14], and the methodology used or the type of company addressed in this thesis, the work carried out by Dragone [14] makes a significant contribution regarding the adaptation of Lean principles when applied to maintenance management, highlighting that the “customers” of maintenance are internal clients, and that the value maintenance generates for a company is not directly reflected in the products the company sells, but rather in what the company expects maintenance to deliver, such as reliable and available equipment, zero accidents, and low costs. This reflection supported and facilitated the integration of Lean principles with Maintenance Management, which served as a foundation for the development of this thesis.

Pinto [4] conducted a case study in an industrial maintenance environment, aiming to optimize the process and information management, enabling the control and monitoring of maintenance indicators of a multinational company by using a Lean approach as a transformation driver. The most used tools and methods to analyze and enhance the process were 5S, the PDCA cycle, SMED, and the Pareto Diagram. This combination of tools and methods allowed the identification of root causes and the development of solutions. Another goal was the implementation of routines to automatically obtain KPIs for process control, which was successfully achieved. The controlled KPIs were MTBF,

MTTR, and OEE. These indicators were not previously calculated, and after the project implementation, an OEE of 90% was achieved.

This thesis, in addition to the previous theoretical framework, will conduct an individualized study of a company using the DMAIC methodology. The selection of tools and KPIs will be tailored to the organization's unique context, focusing on process improvement and result systematization. Furthermore, a Maintenance Failure Profile will be developed, ensuring easier identification of failures, bottlenecks, and root causes. This approach will also support decision-making and resource allocation by the leadership.

Subsequent chapters will analyze the maintenance management processes of the selected company based on the principles of maintenance management and Lean Maintenance. This analysis seeks to identify failures and bottlenecks within the current processes, enabling the formulation of effective solutions to address these issues. Additionally, performance indicators will be established to monitor and evaluate the efficiency of maintenance management.

Chapter 3

Case Study

This chapter develops a brief description of the company and the current state of the maintenance department, including planning, equipment criticality, measured indicators, maintenance flow, collected data, and associated regulatory standards.

3.1 The Company

As a worldwide organization, the company is a global leader in manufacturing and aftermarket services for comprehensive flow control systems. These systems support applications such as energy, water, and food production. The enterprise has 16,000 associates in 50 countries. The case study will occur in the plant situated in Brazil, in the state of Rio de Janeiro, which follows International Standards, specifically ISO 9001:2015 “Quality management systems — Requirements” [11] and ABNT - NBR 5462:1994 “Reliability and maintainability” [23].

The maintenance department oversees a total of 140 assets, categorized based on their criticality levels: A, B, and C, as presented in Table 3.1. Level A assets are the most critical and essential for production continuity, where failures can cause immediate and significant impacts on operations or safety. In contrast, Level C assets have lower criticality and generate minimal immediate impact on production or employee safety. Despite these differences, it is essential to recognize that the maintenance department’s

optimal performance ensures the factory’s expected productivity, product quality, and timely delivery. Therefore, all assets, whether directly linked to production or auxiliary, are important to the company’s operational efficiency and overall success.

Criticality	Number of Assets
A	17
B	12
C	111
Total	140

Table 3.1: Criticality of Assets

The most common types of maintenance in this company are Preventive, Emergency Corrective, and Predictive Maintenance. These activities are executed through Maintenance Orders (MOs), which can be either pre-planned or derived from an emergency. This report will primarily focus on preventive and emergency corrective actions, as predictive maintenance is performed seasonally by a specialized partner company and it is limited to two machines.

3.2 Planned Maintenance

At the end of each year, the Annual Preventive Maintenance Plan is developed for the following year. This plan outlines all the preventive maintenance tasks to be performed on each asset throughout the upcoming year. The maintenance schedule is based on each equipment’s criticality level and specific maintenance requirements, respecting the manufacturer’s recommendations. Every asset is identified using exclusive tag IDs to ensure an individualized approach. This works in agreement with an internal procedure.

To conduct this study, an analysis was performed on the planning and execution of preventive maintenance tasks for the year 2024. The results are presented below in Table 3.2. In eight months the completion rate of preventive maintenance orders fell below expectations, which are at least 80% of maintenance orders’ fulfillment, even though the planning was carried out several months in advance. This discrepancy is attributed to

unexpected priorities faced by the maintenance team, materials shortages, insufficient manpower, or due to productivity needs, which resulted in the rescheduling of preventive maintenance orders. The data provided by the company did not include detailed descriptions of the reasons for these postponements.

Month	Planned	Realized	Rescheduled	Fulfillment
Jan	21	21	0	100,00%
Feb	16	12	4	75,00%
Mar	22	20	2	90,91%
Apr	19	19	0	100,00%
May	15	16	0	106,67%
Jun	19	22	0	115,79%
Jul	25	16	9	64,00%
Aug	38	31	7	81,58%
Sep	20	14	6	70,00%
Oct	20	13	7	65,00%
Nov	20	13	7	65,00%
Dec	4	1	3	25,00%
Total	239	198	45	82,85%

Table 3.2: Preventive Maintenance - 2024

According to the internal procedure, if a preventive activity needs to be rescheduled, it must be highlighted in the control sheet. The production team must also agree to define a new date.

The Table 3.2 highlights that in May and June, the number of completed maintenance tasks exceeded the planned values. This indicates that maintenance activities originally scheduled for different months were also performed during May and June, in addition to the tasks initially planned.

3.3 Corrective Maintenance

According to the company’s internal procedure, corrective maintenance is defined as “any unplanned stoppage of machines, facilities, and/or equipment that occurs unexpectedly during the manufacturing process.” In line with this definition, unexpected failures

must be promptly reported and addressed to restore normal operational performance in the production environment. In order to report failures, Corrective Maintenance Orders (CMO) are used.

A CMO is a structured document that contains all the necessary information for repairing or maintaining equipment. The primary purpose of a CMO is to formally communicate the need for a specific maintenance task on an asset.

To ensure an effective and efficient process, three key steps must be followed:

1. **Request:** Identifying the need for a maintenance intervention, the employee must request the maintenance service through a CMO.
2. **Execution:** The CMO is assigned to the responsible team. In this stage, the necessary resources, such as spare parts, tools, and a skilled workforce, are mobilized to execute the maintenance task.
3. **Registration and Conclusion:** When the service is done, information about what was executed and the time spent must be reported to the responsible planner. Then the CMO is concluded, and the data is incorporated into maintenance statistics.

3.3.1 Corrective Maintenance Orders Description

The company follows an established workflow for creating corrective maintenance orders. The flow starts when an employee diagnoses the need for a maintenance intervention, so the requester must describe the preliminary information in a form that will be automatically sent to the maintenance team.

The information present in the form is:

- **Equipment:** Describe which equipment or machine has presented a failure or decrease in its performance.
- **Tag:** It is used to specify machines. It is commonly used to differentiate equal equipment by using a specific code.

- **Description:** A brief overview of what is happening to the machine. It is a simple description of the preliminary symptoms presented by the equipment, or in which system the maintenance team should focus.
- **Requester:** Identify the collaborator that requested the maintenance team intervention.
- **Priority:** The importance degree of the maintenance intervention, defined by the requester. The maintenance team revises this definition according to the equipment criticality, production needs, and in comparison to other requests.
- **Attachments:** Any kind of attachments like photos, short films, or documents that might help the maintenance team diagnose the failure.

The maintenance receives the form and adds some important information. Firstly, the maintenance team confirms the need to create an order, it might be a repeated order or a misoperation, in this context, the order is canceled and the requester receives feedback informing the reason.

If the order is executed, the maintenance informs the conclusion date and the start/end time. When the order is concluded, the requester is also notified. All the information trade occurs by email automatically, and the data of orders are saved in an electronic sheet.

3.3.2 Execution of Corrective Maintenance Orders

The company has provided data on the completion rate of corrective maintenance orders for the year 2024, comparing the total number of requests with the number of concluded orders. These details are presented in the Table 3.3.

According to the company, the established goal regarding corrective maintenance orders is at least 80% of fulfillment by month. In case it is not achieved, it is necessary to develop an action plan tailored to the issues faced in the month.

Months	Requests	Executed	Fulfillment (%)
Jan	193	142	73,58%
Feb	163	104	63,80%
Mar	163	117	71,78%
Apr	162	106	65,43%
May	150	115	76,67%
Jun	139	106	76,26%
Jul	156	117	75,00%
Aug	168	131	77,98%
Sep	189	156	82,54%
Oct	111	91	81,98%
Nov	99	86	86,87%
Dec	65	57	87,69%
Total	1758	1328	75,54%

Table 3.3: Corrective Maintenance Orders Conclusion

From the table above, it is evident that the completion rate of maintenance orders remained below 80% for most of the year, despite an improvement in the last four months. However, it is important to highlight that October, November, and December recorded the lowest number of maintenance requests for the year, which directly impacts the maintenance team's ability to meet work order demands.

The annual analysis shows an average fulfillment of 75,54%, which does not achieve the indicator of the completion rate of corrective maintenance.

3.4 Key Performance Indicators Used

According to ISO 9001:2015, [11], an organization must determine the inputs and the expected outputs for each process in a company, obviously it includes the maintenance process. To measure processes is necessary to define criteria and methods to ensure process control, which requires the choice of key performance indicators attached to each process's needs.

Regarding maintenance processes, there are several KPIs commonly used to measure maintenance performance, addressed to the entire department or to specific assets [23],

in order to evaluate if the main goals of the maintenance system are being met.

Despite following these rules, the company studied does not have consolidated KPIs in the maintenance department. The sole performance indicator monitored is the monthly completion rate of both preventive and corrective maintenance orders, and this metric is general for all assets.

Corrective maintenance orders must have at least 80% of fulfillment in a month, or an action plan should be developed. Preventive maintenance orders that are not completed must be immediately rescheduled in agreement with the production team.

3.5 Considerations

It is essential to acknowledge that no process is perfect, as there is always room for improvement. This company is no exception, despite having several positive aspects that should be highlighted, such as compliance with specific regulatory standards for the quality management system, as well as maintenance and equipment reliability. The categorization of equipment based on its criticality, along with the implementation of an annual preventive maintenance plan tailored to each asset and its specific requirements, is also a strong point. Additionally, the establishment of a structured corrective maintenance workflow, from order generation to its systematic conclusion, represents a necessary control measure for a reliable and effective maintenance management system. Another positive aspect is the monitoring of maintenance orders' fulfillment, both preventive and corrective.

However, some deficiencies in the maintenance process can be observed, along with opportunities for improvement, even in areas where procedures are already effectively implemented. The key areas requiring attention are outlined below:

- There is no standardized and systematic procedure for classifying equipment criticality.

- The Preventive Maintenance and Corrective Maintenance procedures do not differentiate maintenance strategies based on the criticality of each asset. This lack of differentiation impacts maintenance planning, rescheduling of preventive orders, and prioritization of corrective orders.
- The Preventive Maintenance procedure does not define any trigger related to order completion rates, nor specify corrective actions if the target is not fulfilled.
- Preventive tasks can be rescheduled, and the procedure states that such rescheduling must be recorded in the control spreadsheet and approved by the production team, though the reason for rescheduling is not documented, creating a gap in process control.
- The monitoring of key performance indicators (KPIs) is incomplete. The only metric tracked is the fulfillment rate of maintenance orders (both preventive and corrective). More comprehensive analyses related to equipment availability, failure modes, failure recurrence, mean time between failures (MTBF), and mean time to repair (MTTR) are not conducted.
- Every asset is assigned a unique TAG, but it applies only to the machine as a whole. For deeper analysis, equipment should be subdivided so that maintenance orders can specify both the equipment and the component that failed.
- This equipment subdivision is also crucial for resource traceability. The purchase of replacement components should be linked to these subdivisions to improve inventory control and maintenance planning.

This section presented some preliminary considerations regarding the current state of the maintenance process. In the next chapter, the entire study will be structured using the DMAIC methodology. This methodology allows for an in-depth analysis aimed at identifying the main gaps and process deficiencies. Solutions and new control strategies will also be proposed to address the identified challenges effectively.

Chapter 4

Methodology

This chapter will focus on the development of the DMAIC methodology, specifically adapted to the company's current reality. The primary objective is to develop the "Define, Measure, and Analyze" stages, analyzing the current situation in order to define the root causes of maintenance issues.

The study will be conducted based on the company's current state, as described in Chapter 3. It is also important to highlight that the company's lack of information collection is a significant issue, which will be discussed in the next pages.

4.1 Define

The 'Define' stage is the first phase of the DMAIC methodology and, according to many authors, the most important, as it establishes the project's direction and foundation [24]. At this stage, it is essential to identify the characteristics that impact customers, have a clear definition of the project scope, and establish its primary objective [25]. This phase is fundamental to ensuring a precise and concrete understanding of the current state, setting well-defined goals, and delineating the project's area of focus. A well-structured problem statement helps prevent errors that could occur throughout the project's development [20].

Some tools are indispensable to achieve the required level of information and develop

a solid and effective ‘Define’ phase, ensuring that this stage effectively guides the project [17]. In this report, the Project Charter and the SIPOC Diagram will be utilized.

The Project Charter (Figure 4.1) will be developed to align expectations and objectives, define project limitations, specify which KPIs will be controlled, and establish the key stakeholders involved. This step is crucial at the beginning of the project to ensure a clear direction from the outset, allowing the subsequent phases of DMAIC to be conducted in a structured, efficient, and objective manner.

The other tool utilized in this study is the SIPOC Diagram (Figure 4.2), which is commonly employed to map a process systematically. This tool provides a clear overview of who is involved in each step, simplifying the understanding of the maintenance order flow, and identifying the key suppliers, inputs, process steps, outputs, and customers. Using SIPOC, it is possible to identify process gaps, improve communication between related departments by clarifying the workflow and responsibilities, and establish a foundation for subsequent analyses in the later phases of DMAIC.

Both the Project Charter and the SIPOC Diagram are developed in the next pages.

PROJECT CHARTER		
PROCESS IMPROVEMENT IN THE MAINTENANCE MANAGEMENT OF A COMPANY		
PROJECT OVERVIEW		
PROBLEM DESCRIPTION	The maintenance process exhibits deficiencies in the standardization of activities, in the definition of clear performance triggers and goals regarding equipment availability, as well as a significant lack of control and measurement of KPIs.	
PRIMARY OBJECTIVES	The project aims to analyze the maintenance processes using DMAIC, identify gaps, define performance indicators, enhance data accuracy, and improve failure traceability. Develop a Maintenance Failure Profile to control the maintenance performance and triggers.	
BACKGROUND	The maintenance process faces several issues, including the absence of a systematic method for classifying equipment criticality, which limits tailored maintenance strategies, and, the Preventive and Corrective Maintenance procedures do not consider asset criticality, affecting planning, rescheduling, and prioritization of maintenance orders. The Preventive Maintenance procedure lacks triggers for order completion and does not define corrective actions for unmet targets, additionally, undocumented rescheduling reasons create control gaps. KPI monitoring is insufficient, focusing only on order fulfillment. The lack of detailed component-level tracking traceability hampers analysis, affecting overall maintenance efficiency and equipment reliability.	
SCOPE		
INCLUSIONS	EXCLUSIONS	LIMITATIONS
<ul style="list-style-type: none"> · Corrective and Preventive Maintenance Processes; · Definition of Performance Indicators; · Definition of Triggers and Control Methods (KPIs and Failure Profile); · Proposal for Improvement in Work Order Descriptions, and Procedures. 	<ul style="list-style-type: none"> · Maintenance performed by third parties will not be addressed; · Predictive maintenance will not be covered; · Building and utility maintenance will not be addressed. 	<ul style="list-style-type: none"> · The implementation of the action plan is solely dependent on the company; · The provision of data for analysis is dependent on the company; · The control, using the Failure Profile created, is dependent on the company; · No costly improvements will be proposed as actions.
SCOPE DESCRIPTION	This project focuses on improving the maintenance management system, aiming to enhance equipment reliability, traceability, and performance monitoring by the implementation of KPIs and process optimizations. The improvements will be aligned with best practices in maintenance management and Lean methodologies, using DMAIC methodology.	
DELIVERABLES AND ADDITIONAL INFO		
EXPECTED DELIVERABLES	MILESTONES	
<ul style="list-style-type: none"> · Identify the main process failures in data collection, maintenance procedures, and performance indicator monitoring; · Proposal of a Preventive and Corrective Maintenance procedures revision, including triggers for actions and differentiation based on asset criticality; · Define performance indicators and enable their calculation and monitoring; · Develop a tailored action plan addressing identified process gaps and proposing solutions to enhance efficiency, and improve the maintenance process; · Develop a detailed stratification of failure data, enabling precise analysis of failure modes, recurrence, and associated impacts. (Maintenance Failure Profile - MFP). 	<ul style="list-style-type: none"> · Define Scope and Objectives - Jan/2025 · Measure Data and Current KPIs - Feb/2025 · Analyze Failures and Gaps - Mar/2025 · Develop the Action Plan - Apr/2025 · Develop the MFP for process controlling - May/2025 	
EXPECTED BENEFITS	The project aims to enhance the Maintenance Management Systems by optimizing maintenance planning, defining and standardizing maintenance triggers and KPIs, and improving process control through better traceability and data-driven decision-making. It will reduce downtime, minimize costs, improve efficiency, and strengthen stakeholder alignment for continuous improvement.	
RISKS	The principal risks include resistance to change, data accuracy issues, lack of information, and stakeholder misalignment. Another important aspect is the challenge of integrating updated processes and procedures with existing systems, delaying progress.	
STAKEHOLDERS IMPACTED	Maintenance Team / Engineering Team / Quality Team / Production Areas / Finance Department.	

Figure 4.1: Project Charter

From the Project Charter represented in Figure 4.1, the objectives and limitations of the project are clearly established. To avoid misaligned expectations, it is essential to differentiate between the company’s responsibilities and the scope of this thesis.

This study focuses on analyzing the maintenance process, using data, metrics, and information provided by the company. However, the implementation of the proposed actions will be the sole responsibility of the organization. The role of this work is to develop and propose theoretically grounded solutions for process improvement, resource optimization, and enhanced control and measurement of maintenance indicators.

Additionally, the ‘Control’ phase of DMAIC will depend on the company’s adoption of the suggested improvements. To structure this control and enable the monitoring of performance metrics and indicators, the Maintenance Failure Profile will be developed. This system will allow for data stratification, analysis of failure modes, identification of recurrences, and support decision-making.

S	I	P	O	C
SUPPLIER	INPUT	PROCESS	OUTPUT	CUSTOMER
Production Operators and Maintenance Technicians	Information about machine failures and performance issues	Corrective Maintenance Work Order Creation (A)	Recorded maintenance execution data	Maintenance Team
Maintenance Technicians and Planners	Work Orders, asset criticality classification, and maintenance schedules	Corrective & Preventive Maintenance Execution (B)	Equipment repaired or serviced	Productivity Areas
Maintenance Leads	How an equipment affects the company about, productivity, safety, costs, and its redundancy in the process	Equipment Criticality Assessment (C)	Prioritization of equipment based on criticality and defined maintenance triggers	Maintenance Team / Quality Team
Maintenance Planners	Maintenance requirements for each equipment according to manufacturer specifications and prioritization based on criticality	Preventive Maintenance Planning & Scheduling (D)	Annual preventive maintenance schedule	Maintenance Team
Maintenance Team	Collected work order data and performance metrics	Performance Monitoring & KPI Tracking (E)	Control of performance indicators and measures of availability and reliability of equipment	Maintenance Leads
Maintenance Team / Quality Team	Historical data, current failure status, and equipment condition	Failure Analysis and Root Cause Investigation (F)	Root Cause identification, and corrective actions recommendations	Maintenance Team / Quality Team / Productivity Areas

Figure 4.2: SIPOC Diagram

The SIPOC diagram presented in Figure 4.2 selects key activities that represent critical processes present in the maintenance management system. These selected processes are essential for ensuring the effectiveness and performance of the company's maintenance operations. To simplify the nomenclature, each process studied in the SIPOC diagram will be designated by letters from A to F.

Through the SIPOC diagram, it is possible to realize that the selected processes are not necessarily continuous or directly dependent on each other. However, deficiencies in the execution of any of these processes can directly or indirectly impact others, and compromise the results of the maintenance department entirely, affecting the company's overall results. For this reason, an assertive evaluation of all of them is essential for a clear and accurate understanding of the company's maintenance operations.

The SIPOC diagram shows the expected outputs for each process labeled from A to F, which compose the maintenance management system, and also shows the inputs required to generate each of them. This structure highlights which stages need improvement to achieve more efficient outputs aligned with the management plan and expected results.

One key area identified in the diagram concerns the criticality of equipment, especially in process (C), as the analyzed procedures do not provide clear instructions for defining the criticality of the assets. Furthermore, there are no distinctions in maintenance strategies and trigger definitions based on criticality, which could impact prioritization and resource allocation. An incorrect criticality classification also affects both processes (B) and (D). This is not the only factor capable of impacting these two processes. Although other inputs related to (B) and (D) are being performed in the company studied, the quality of these inputs will also be evaluated throughout this chapter.

Another critical issue is the lack of detailed descriptions in maintenance work orders, process (A), which affects KPI monitoring (Process E) and root cause investigations (Process F). The maintenance collected data lacks in-depth information about the performed tasks, mainly due to the absence of component categorization. Implementing this classification would improve failure traceability, enabling more precise and targeted performance measurements and a failure mode analysis.

In addition to the preliminary analyses carried out through the SIPOC, more in-depth verifications, with a detailed study of the processes described in Figure 4.2, will be conducted throughout this chapter.

With the scope established from the Project Charter, along with the alignment of expectations, definition of objectives, and project limitations, with the insights gained from the SIPOC diagram, the ‘Define’ phase of the project is concluded. In the next section, the collected data will be examined to assess the current state of the complete maintenance process, marking the beginning of the ‘Measure’ phase.

4.2 Measure

In the ‘Measure’ phase, the objective is to identify relevant data and key performance indicators that align with the critical characteristics of the maintenance process, allowing for an accurate diagnosis of the initial process state [20]. Building on the established foundation in the ‘Define’ phase, this stage focuses on understanding the complete maintenance management process and its workflow, except for maintenance costs analysis, respecting the company’s policy of not sharing financial reports.

The ‘Measure’ stage provides a broad and precise view of the current state of the entire maintenance department, without identifying root causes yet [26]. To develop this phase, it is essential to collect data, evaluate existing performance indicators, assess process inputs, define and analyze measurement systems, measure current process performance, and understand the operational workflow [27].

4.2.1 Operational Workflow Structure

An effective way to evaluate the initial state of a process and understand its stages within the overall system, is through the use of a business process workflow, based on the collected data [19].

A workflow diagram is a graphical tool that simplifies the visualization of operational

activity sequences, from the beginning to the completion. A workflow helps identify critical points, making it a fundamental tool for both initial process planning and continuous improvement [25].

Figure 4.3 presents the operational workflow of the company's maintenance department under study, which includes processes A, B, and D, described in the SIPOC diagram, in Figure 4.2.

It is important to highlight that the company does not have a standardized workflow defined by formal procedures. The workflow, presented in Figure 4.3 was developed based on information provided by the maintenance coordinator and manager, allowing for a detailed representation of the current state of the maintenance processes.

However, the lack of a standardized procedure for describing maintenance processes can lead to potential errors, gaps in knowledge, and variations in execution depending on the technician's experience, training level, and familiarity with the process.

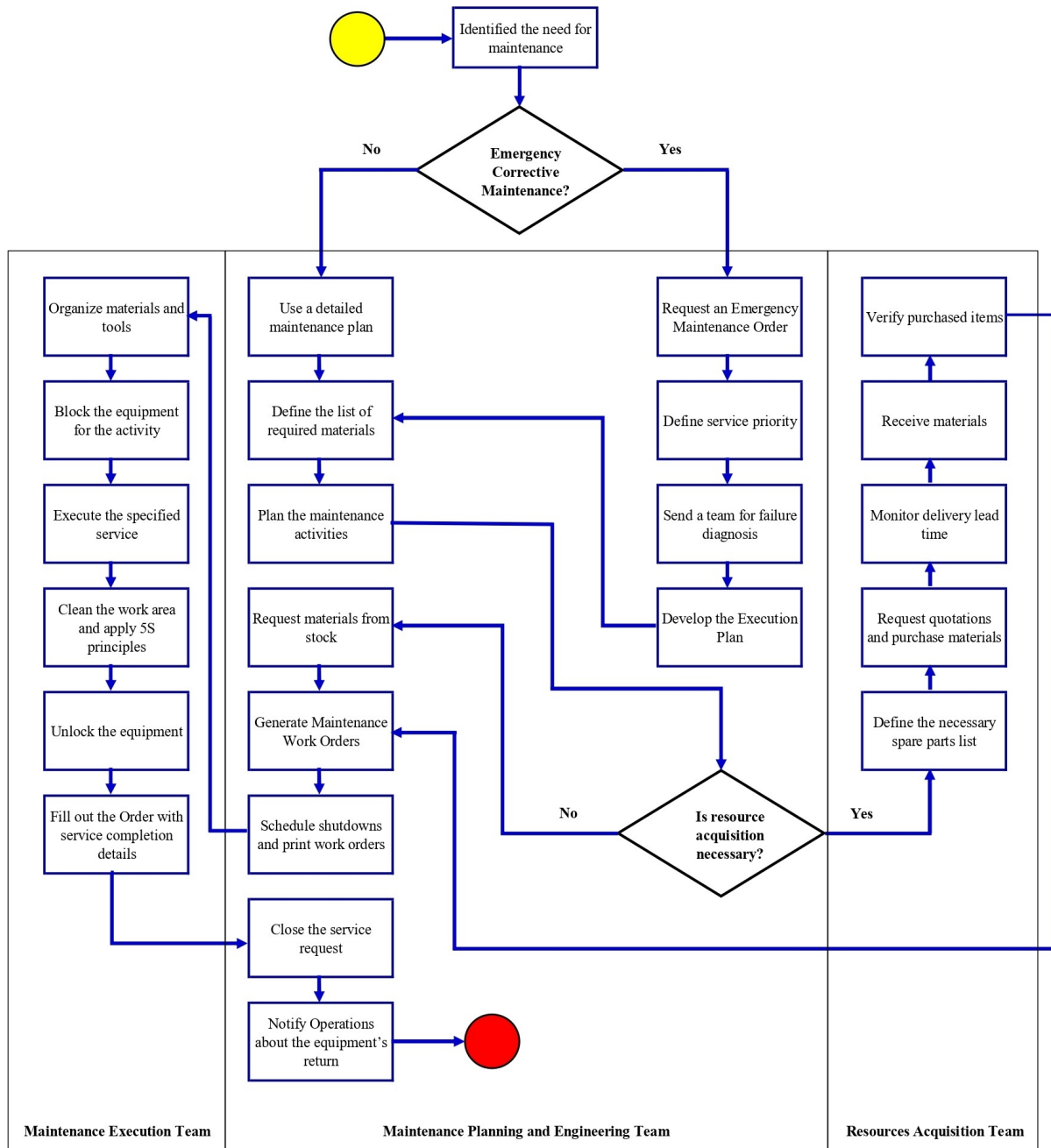


Figure 4.3: Operational Maintenance Workflow

The operational map shows the sequence of corrective and preventive maintenance execution (SIPOC Process B, Figure 4.2). It also presents the preventive maintenance planning (SIPOC Process D), the steps of creating a corrective maintenance order (SIPOC Process A), and how the tasks are distributed within the maintenance department. The operational flow begins when a maintenance need is identified and ends after the work order is completed.

Corrective maintenance requires additional steps compared to preventive activities, but its main challenge is not just the number of tasks involved. The major issue lies in aspects that cannot be fully represented in the workflow, due to the unexpected nature of equipment failures, which often lead to production stoppages. Additionally, emergency component acquisition might be required, increasing costs due to fast purchases and shipping fees. Another critical factor is lead time, as many machine components are either custom-made or imported, resulting in long delivery periods that the company does not anticipate. A common approach to mitigate this issue is maintaining spare parts in stock; however, low-utilization components stored for long periods represent tied-up working capital, storage costs, and inventory maintenance expenses, generating one of the wastes identified in Lean Thinking. Those issues are directly related to the SIPOC processes B and A.

When well-planned, preventive maintenance allows for the advanced procurement of components, ensuring lower material costs and optimized delivery times. Furthermore, it enables maintenance scheduling close to the component arrival date, eliminating the need for excessive inventory storage. However, for preventive maintenance to be effective, a comprehensive Initial Equipment Control must be established, which means that the company must be prepared to receive new assets, allowing for an effective execution and planning of maintenance tasks, and criticality definition. Another key aspect is to enable the creation of preventive maintenance plans based on the specific requirements of each asset before it starts operating. Lastly, proper equipment tagging and subdivision must be implemented to ensure traceability of maintenance activity. If there was no efficient equipment commissioning, or those tasks were not carried out following established rules

and procedures it influences the SIPOC process D.

The company studied does not have standardized procedures for the activities related to Initial Equipment Control. As a result, the activities required for the effective commissioning of equipment may have been realized differently over the years, depending on the collaborator's expertise.

Although there is no procedure, specific maintenance plans exist for each machine, aligned with the manufacturer's technical specifications, and the equipment is identified through TAGs. However, there is no subdivision by systems and components, which restricts traceability and reduces accuracy in the description of maintenance plans and work orders.

4.2.2 Preventive Orders and Corrective Orders

Some of the key metrics used to evaluate maintenance performance include the completion rate of maintenance tasks, which is typically divided between preventive and corrective tasks. According to the maintenance coordinator, the company under study expects 80% of completion rate for corrective maintenance activities. However, no specific objective has been defined for preventive tasks. For comparison purposes, the same target of 80% will be applied to preventive maintenance to assess effectiveness and compliance over the past year. The rates of preventive and corrective compliance are presented in Figures 4.4 and 4.5. Throughout this section, the processes presented in the SIPOC diagram (Figure 4.2), which are related to maintenance orders, will be studied.

It is important to emphasize that the performance targets are not standardized through formal procedures.

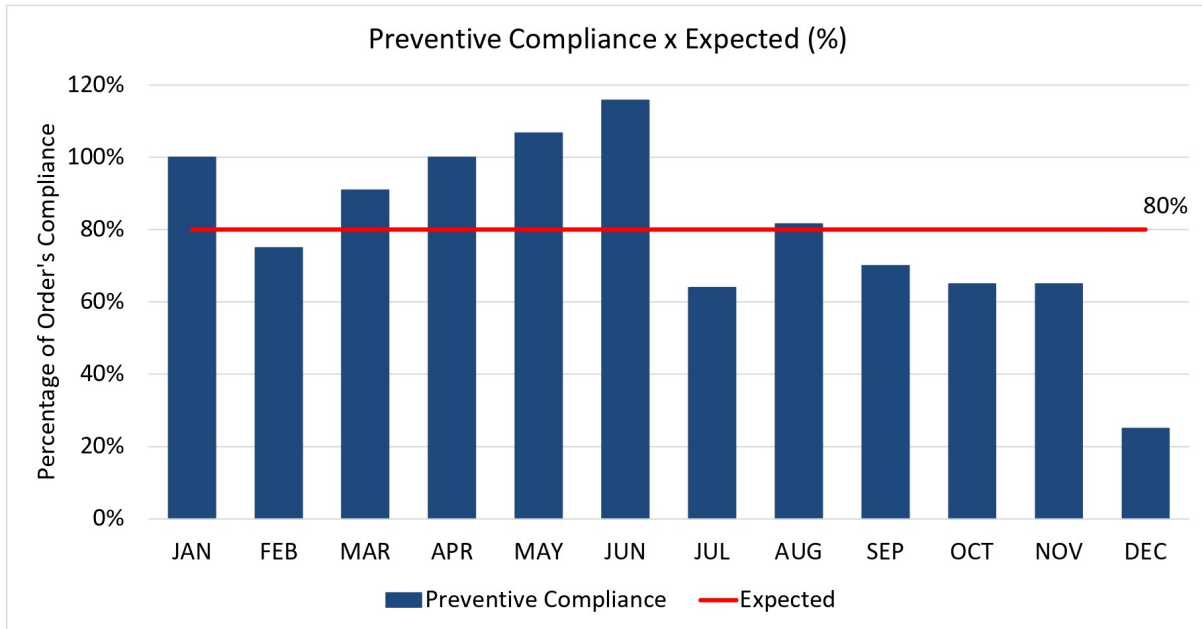


Figure 4.4: Preventive Orders Compliance

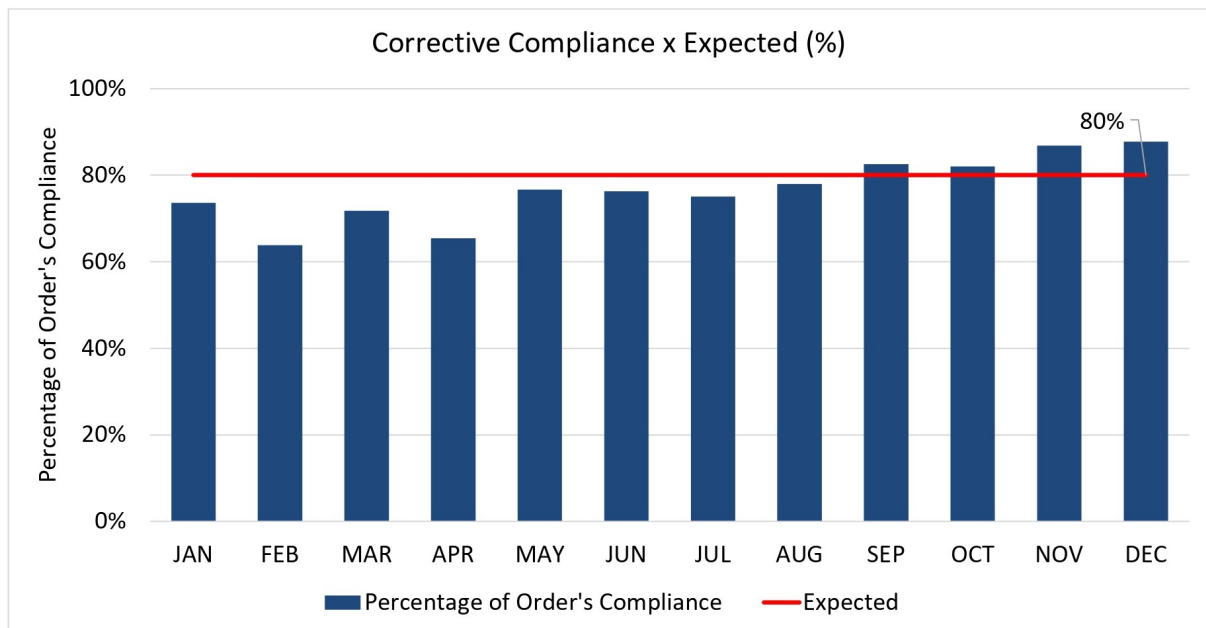


Figure 4.5: Corrective Compliance

In the charts above, the completion rate is shown separately for each type of maintenance order. In Figure 4.4, it can be observed that preventive maintenance achieved

the target in only six months of the year, indicating that the planning and execution of preventive maintenance (SIPOC Processes B and D) are not being fully effective. Meanwhile, corrective maintenance performed worse, as shown in Figure 4.5, where the 80% goal was only achieved during the last four months of 2024, highlighting that the SIPOC Processes A and B are not fully meeting the established targets. Furthermore, current maintenance procedures, both preventive and corrective, lack clear definitions of the actions to be taken in cases where maintenance work orders are not completed. Currently, this is the main indicator used to assess maintenance performance.

Monitoring the fulfillment of maintenance orders provides a good overview of maintenance execution. However, this is the unique metric controlled in the maintenance system, indicating that there are notable gaps in maintenance control, which directly affect SIPOC Processes E and F. The main gaps identified include that maintenance is not prioritized and measured according to the criticality of the asset; There is no specific tracking by equipment or component division; Availability and performance indicators such as MTBF (Mean Time Between Failures) and MTTR (Mean Time to Repair) are not monitored. One objective of this study is to enable the measurement of these indicators. To achieve this, data collection regarding maintenance activities must be improved.

As a complement to Figures 4.4 and 4.5, the Figures 4.6 and 4.7, visually represent the compliance between planned and executed work orders for preventive tasks, as well as between requested and completed work orders for emergency corrective maintenance. In both Figures, it is evident that, for most months, there is a clear discrepancy between the number of completed work orders and the total number of requested orders.

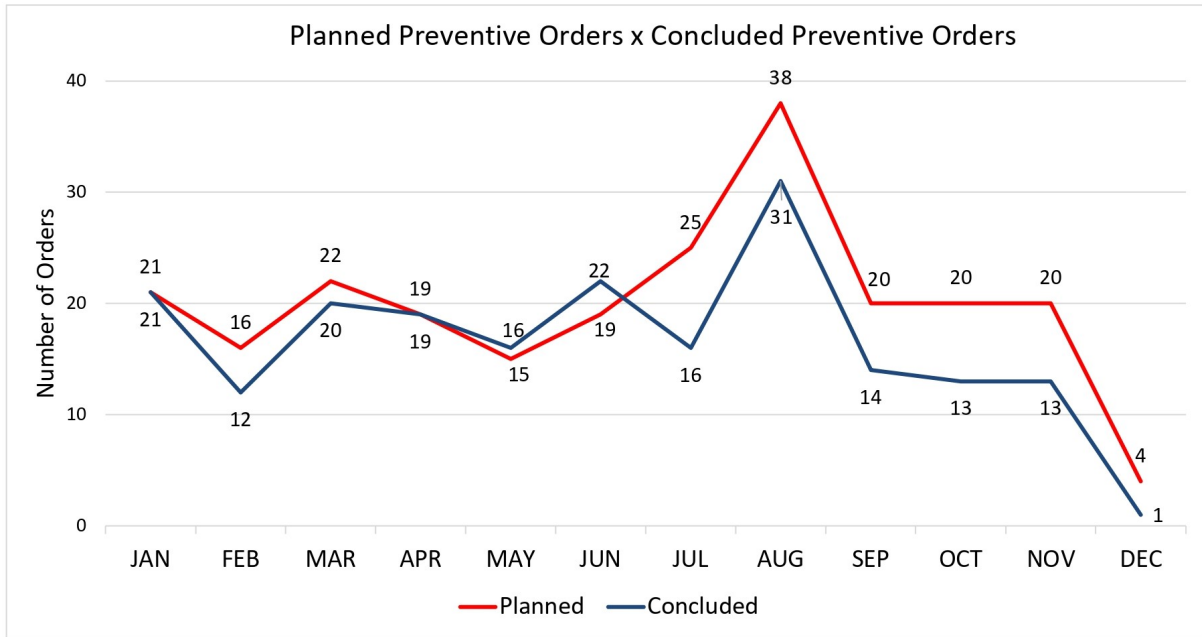


Figure 4.6: Planned Preventive Orders x Concluded Orders

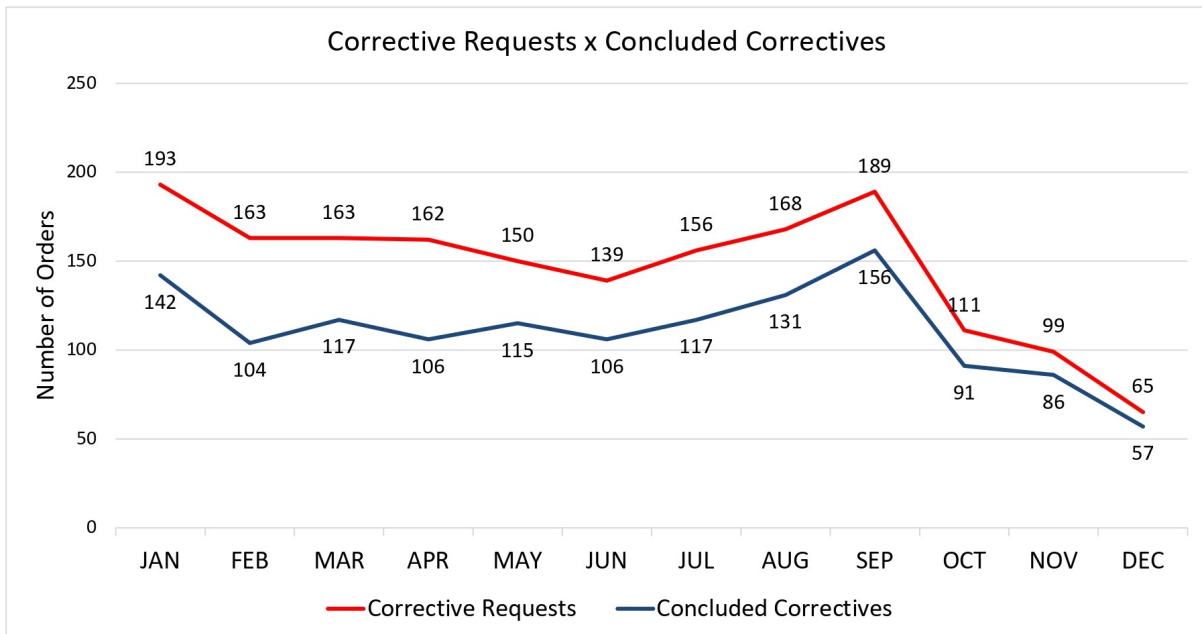


Figure 4.7: Corrective Requests x Concluded Orders

Additionally, in the Figure 4.8, there is a comparison between the total number of corrective orders requested, preventive orders completed, and preventive orders rescheduled,

during the year 2024.

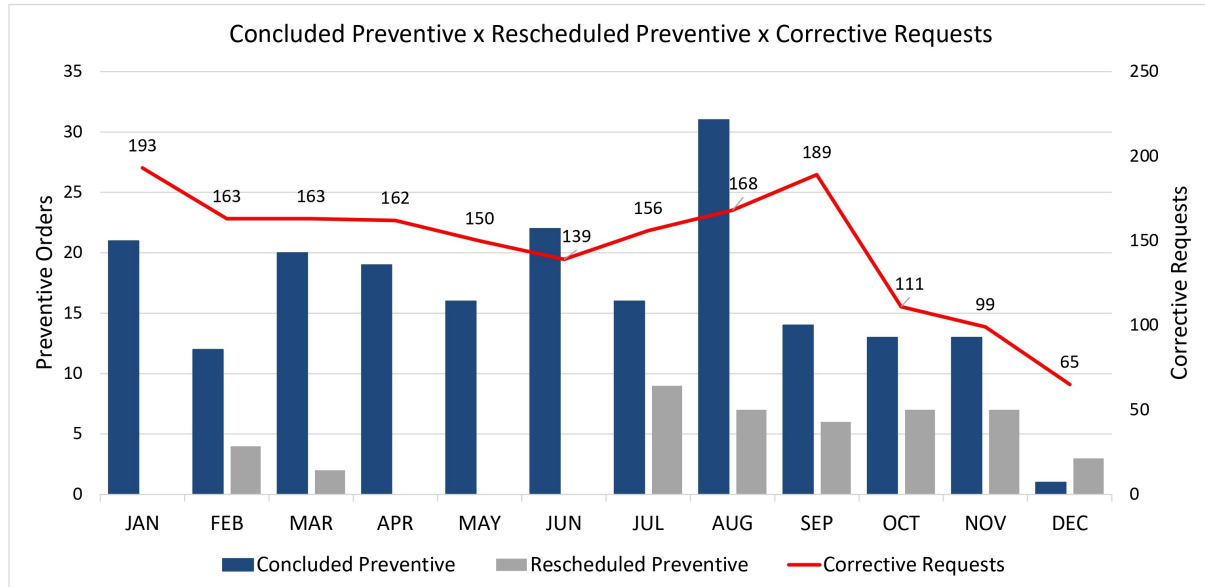


Figure 4.8: Concluded Preventive x Rescheduled x Requests

The data reveals that the last three months of the year had the lowest number of emergency corrective requests. However, the remaining months exhibited high volumes, with two months nearing 190 corrective requests.

Regarding preventive maintenance, only four months of the year had no postponed tasks, confirming that the initial maintenance planning had not been effective. In addition, there is a significant discrepancy in the execution throughout the months: for example, in August, more than 30 preventive interventions were performed, while in December, fewer than 5 were recorded.

These findings highlight the need for better maintenance planning and execution control, ensuring a more balanced distribution of preventive tasks throughout the year.

The Figure 4.8 also demonstrates that the relationship between preventive and corrective maintenance is not immediate. It is acknowledged that one influences the other, but there are additional factors that must be considered to improve the overall process.

Throughout this section, it also becomes evident that some critical maintenance performance indicators are not being measured. Additionally, the lack of detailed descriptions in

maintenance work orders hinders failure mode traceability, root cause identification, and data-driven decision-making. These two issues address the SIPOC (Figure 4.2) processes E and F.

Another important issue affecting the process is the lack of standardization in maintenance activities. There are no established procedures for key aspects such as:

- How to define equipment criticality. This issue corresponds to the SIPOC process C;
- How the criticality influences preventive and corrective maintenance strategies. This issue corresponds to the SIPOC processes A, B, and D;
- The definition and control of maintenance triggers and actions to be taken when maintenance tasks are not completed or do not reach a pre-defined trigger. This issue corresponds to the SIPOC processes E and F;
- The subdivision of equipment into systems and components, improving work order descriptions, and enabling more robust analysis. This issue corresponds to the SIPOC processes E and F;

Addressing these gaps would enhance process standardization, data accuracy, and maintenance management efficiency, leading to better decision-making and improved equipment reliability. It must be emphasized that although some maintenance procedures currently exist, new ones must be developed, and existing ones should be revised.

In the next section, the maintenance process will be analyzed in detail to identify the main causes of failures in process control and maintenance management. This analysis will be based on the objectives set in the ‘Define’ phase and the data collected during the ‘Measure’.

In the subsequent phases of DMAIC, solutions will be proposed to address the identified issues and achieve the established goals, bringing greater reliability, standardization, and control to the process. Additionally, new methods for maintenance control, failure modes, and performance indicators will be developed.

4.3 Analyze

The ‘Analyze’ phase aims to identify the sources of process variability and determine their root causes [15]. Diverse tools enable this analysis and should be selected based on the specific needs of the project [17]. This stage will conduct an in-depth analysis of the data presented in previous sections, focusing on the current maintenance process structure and metric control.

For this analysis, the Cause and Effect Diagram, commonly known as the Ishikawa Diagram, will be utilized. This tool classifies the causes of quality variation within a process and visually correlates these causes with the identified problems [25]. Additionally, a graphical analysis will be performed, including Pareto analysis due to the 80/20 principle.

4.3.1 Cause and Effect Diagram

The Cause and Effect Diagram is a visual representation of the connection between an outcome of a process and the factors capable of influencing it [28]. To construct this diagram, ensuring all potential causes are considered, a structured four-step method should be followed [29]:

1. Identify the problem.
2. Determine the main factors involved.
3. Identify possible causes.
4. Analyze the diagram.

The identified causes are structured in 6 different classes, there are [25], [29]:

- **Measurements:** Any cause related to measurement instruments or the effectiveness and accuracy of indicators and metrics;
- **People:** Causes related to the employees involved in the process;

- **Materials:** Causes associated with the materials used in the process;
- **Machines:** Causes related to all machinery and tools used in the process;
- **Methods:** The specific conditions that allow the process to exist, such as policies, procedures, rules, and regulations;
- **Environment:** Causes related to the environment and workplace conditions, including pollution, heat, dust, layout, and physical space.

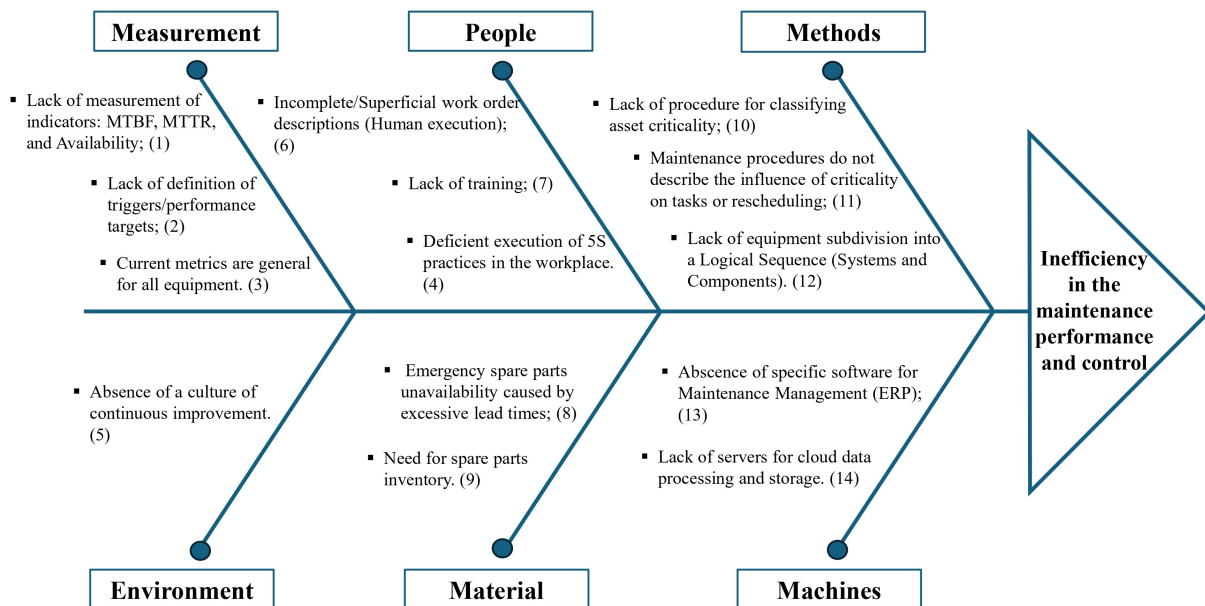


Figure 4.9: Cause and Effect Diagram

The Cause and Effect Diagram (Figure 4.9) outlines several potential causes for inefficiencies and lack of control in the company’s maintenance system. The primary common factor among these causes is the lack of measurement and process control. However, this issue is not limited to the “Measurement” category, it also includes aspects that negatively impact the overall maintenance management.

Regarding the class “People”, the incomplete and poorly detailed descriptions of maintenance work orders generate potential failures associated with the lack of reliable information for analyses and root cause investigations. Often, this occurs due to the lack of

appropriate training, combined with the absence of standardization and established procedures, as can also be observed in the “Method” class. Procedures are essential to guide the maintenance in a high-level and efficient manner, regardless of the professional responsible for performing a task, reducing process variability and resulting in more accurate and predictable results in the maintenance department.

Other aspects also influence maintenance performance, as seen in the “Machines” class. This category includes the company’s assets, which lack precise categorization to allow the traceability of failure modes, and this class also includes the absence of appropriate software tools for maintenance management, such as an Enterprise Resource Planning (ERP) system.

In addition to these, the “Environment” class highlights two factors that operate in parallel to the effective performance of the maintenance department: the absence of continuous improvement processes and the lack of effective 5S implementation in the workplace. Finally, the “Material” class issues originate from the need for inventory and long lead times for emergency parts, which represent issues that arise from the high volume of corrective actions and inefficient material procurement planning.

The accumulation of these factors leads to operational disruptions, reduced efficiency, and suboptimal maintenance performance. This results in various types of waste, such as rework, increased defects in maintenance activities, production losses due to corrective stoppages, poor failure traceability, ineffective spare parts inventory management, and excessive time spent on maintenance execution, leaving no room for continuous improvement initiatives.

In the “Improve” phase, an Effort x Impact Matrix will be developed in addition to the Cause-and-Effect Diagram to categorize the identified causes. The goal of this matrix is to prioritize which issues should be addressed first based on their impact on the process and ease of implementation. This approach enables the creation of a targeted action plan, focusing on solving the most critical inefficiencies, especially those that can be resolved with low cost and effort while generating significant impact in a short period.

4.3.2 Graphical Analysis

The first set of analyses focuses on preventive maintenance adherence and how it is related to the equipment criticality, in order to understand if the criticality influences the maintenance planning in this company. In Figure 4.10, a direct comparison is made between the number of planned preventive orders and the number of equipment units in each criticality class.

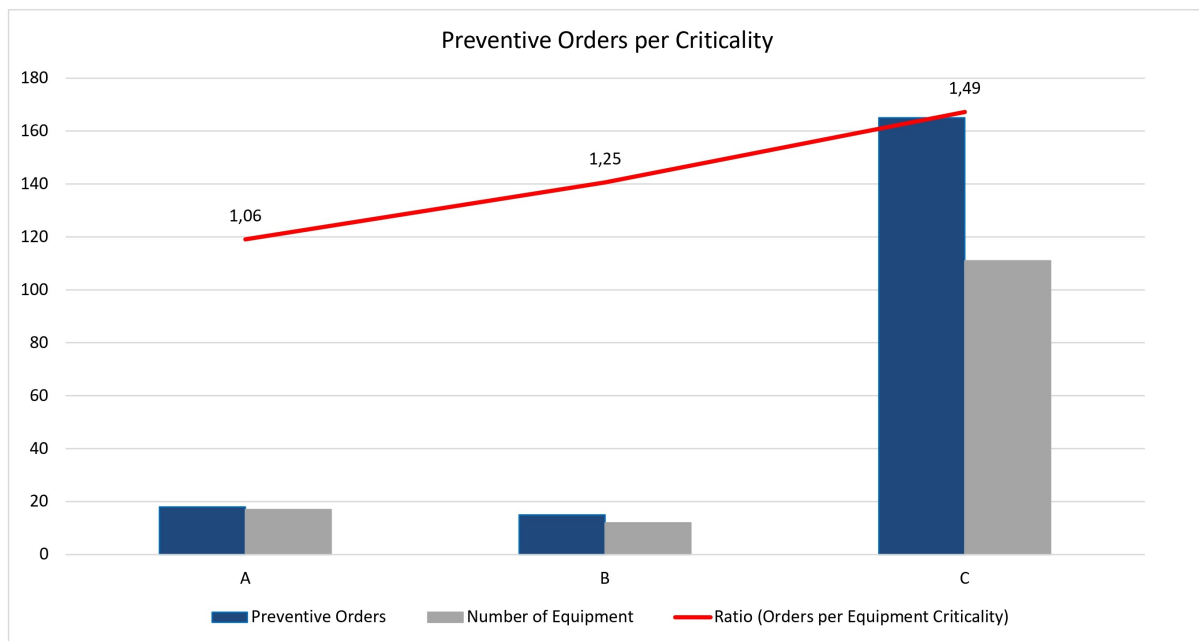


Figure 4.10: Ratio of Preventive Orders per Criticality

This initial analysis highlights the predominance of “C” class equipment in relation to the other categories. Consequently, the total number of preventive work orders is also higher for this class. However, a notable aspect is the ratio of preventive work orders per equipment unit. The “C” class exhibits a higher ratio compared to the other categories. This is an important point of concern since higher criticality equipment is typically subject to more rigorous maintenance efforts. This discrepancy may indicate a flaw in the criticality classification methodology, compounded by the absence of a formal procedure for defining equipment criticality.

In Figure 4.11, the percentage of completed preventive work orders is shown, segmented by criticality class. The results reveal that “A” class equipment has the lowest compliance rate, reaching just under 80%, while “C” class equipment achieves similar levels. In contrast, “B” class equipment shows the highest completion rate, exceeding 93%. Once again, this outcome contradicts expectations, as higher criticality equipment should, in theory, receive the most maintenance attention. This further supports the argument that the equipment classification system may not be entirely reliable. Additionally, the absence of performance metrics to assess maintenance adherence at this level of detail may distort the results for certain categories, as a result, it becomes impossible to visualize this information clearly, preventing the implementation of specific controls for each equipment category.

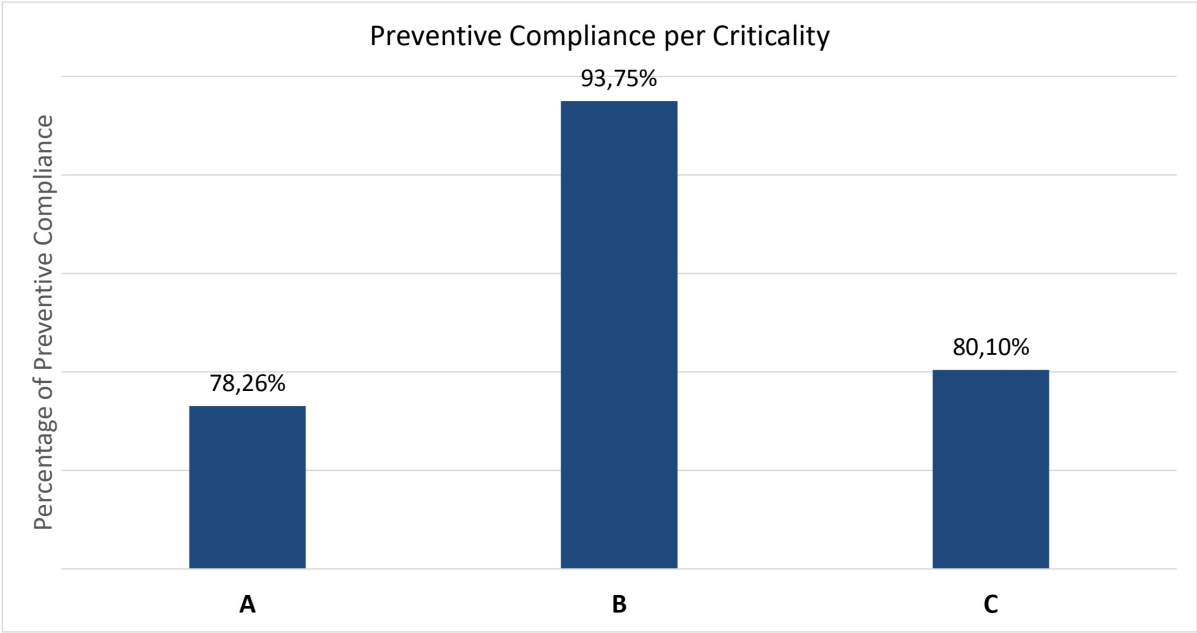


Figure 4.11: Preventive Orders Compliance per Criticality

Beyond the criticality classification, the company also categorizes its equipment into four major groups: Lifting, Machining, Transportation, and Others. Based on these groupings, further analysis has been conducted.

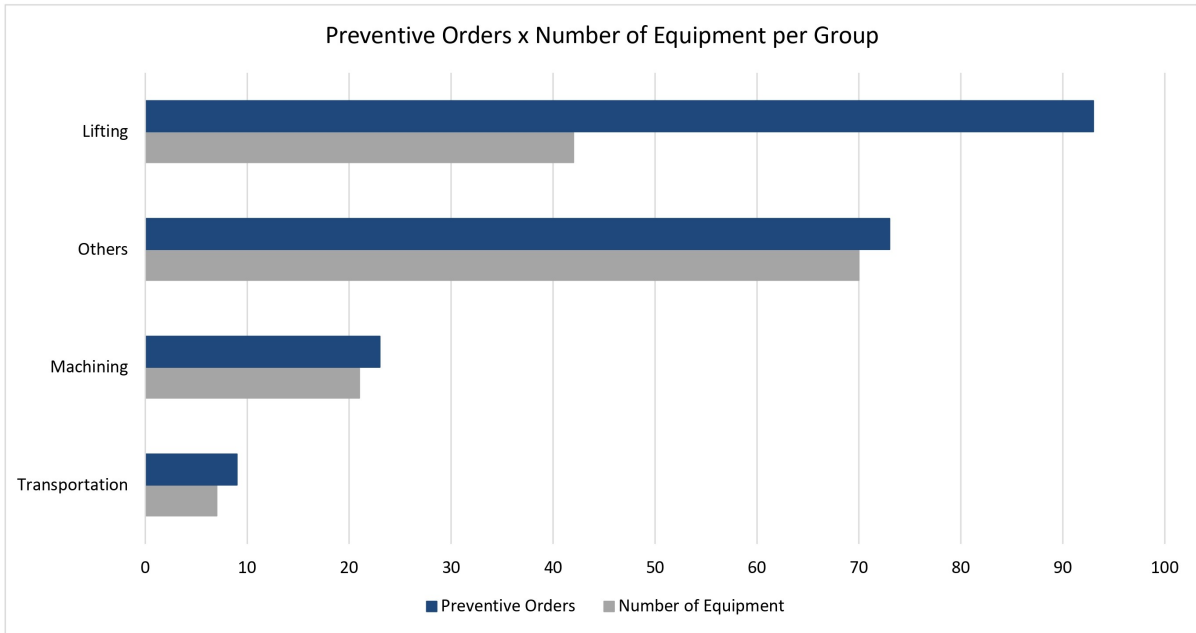


Figure 4.12: Preventive Orders compared to the number of equipment in each Group

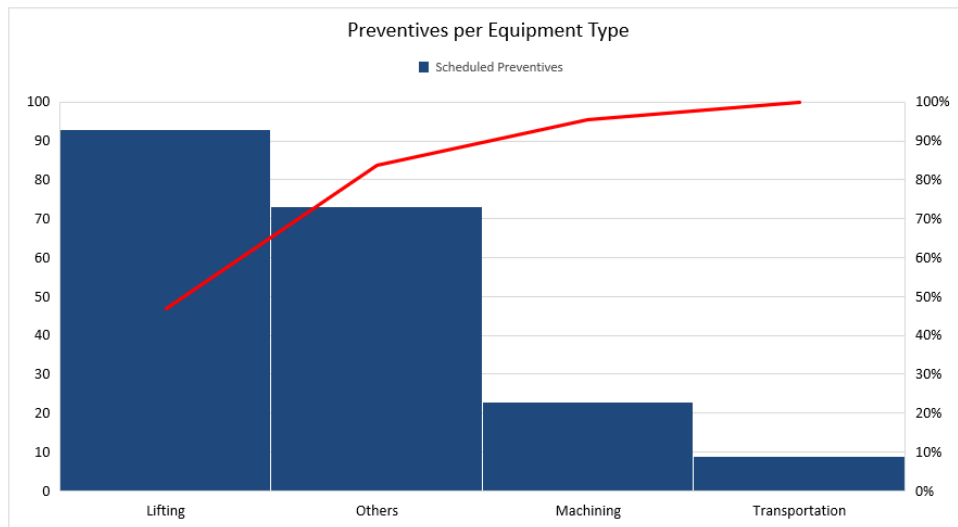


Figure 4.13: Preventive Orders per Group - Pareto Analysis

In Figure 4.12, the number of work orders is compared to the number of assets that compose each group. The results indicate a significant deviation in the “Lifting” group, where the number of preventive work orders is more than twice the number of equipment units in this group. Following this, the “Others” category presents the second highest

number of work orders, despite encompassing 70 different machines, the largest among all groups.

Additionally, Figure 4.13 shows that more than 83% of all preventive maintenance orders are concentrated in the “Lifting” and “Others” categories. The high number of assets within these groups can partly justify this concentration, as the 2 groups together account for 112 equipment units or 80% of the total asset base. However, one concerning aspect is the excessive number of machines classified in the “Others” category. Exactly 50% of the total asset base belongs to this group, which creates difficulties in conducting targeted analyses and significantly reduces traceability.

It is also important to highlight that the company does not conduct analyses using the criticality and equipment groups in the current maintenance system.

4.3.3 Corrective Maintenance Orders Analysis

The data collection process for corrective work orders, despite being standardized, has several control weaknesses and lacks critical information. In 2024, considering only corrective maintenance activities carried out by the company’s internal maintenance team, specifically those generated through the corrective maintenance request form, a total of 699 occurrences were recorded.

Despite the high number of work orders cataloged in the historical records spreadsheet, the poor data quality prevents the execution of different in-depth analyses. A significant improvement in the data collection and processing is required to enable accurate assessments, including failure mode identification, failure traceability, improved decision-making, and more precise KPI tracking.

To understand the quality of information contained in the digitally generated corrective orders recorded in the spreadsheet, several key aspects were analyzed:

- Equipment identification issues: out of 699 work orders, only 17 include the equipment name in the “Equipment and TAG” column. This means that only 2.43% of the work orders contain this crucial information, making it impossible to analyze

the most failure equipment and its impact on maintenance operations.

- Lack of equipment classification: there are no dedicated columns for equipment criticality or equipment groups, further generalizing the data and reducing the accuracy of potential analyses.
- Missing execution time data: the start and end dates of the maintenance execution, as well as the start and finish times of the work, are not recorded. This makes it impossible to calculate key maintenance indicators, such as Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR).
- Long open work order durations: the current system only records the dates for request submission, system registration, and work order closure. However, some work orders remained open for more than three months, with the longest case reaching 11 months without completion. There is no recorded explanation for these extended delays, preventing further investigation.

While not the majority, work orders that remain open for an extended period represent a management concern. Proper tracking of these delays would allow for better bottleneck identification and improved process control. Table 4.1 shows the distribution of work order durations.

Period	Number of Orders	Rate(%)
1 month or less	644	92.1%
Between 1 and 3 months	21	3.0%
Between 3 and 6 months	25	3.6%
More than 6 months	9	1.3%

Table 4.1: Order Distribution by Period

- No Material Usage Tracking: There is no control over the materials used in corrective maintenance work orders. This absence hinders critical analysis regarding which components contribute most to maintenance inefficiencies, whether due to high failure recurrence or excessive costs.

4.4 Potential Causes Mapping

In this chapter, the company's current situation was presented, and through dedicated analysis, it is possible to identify the potential causes of inefficiency in maintenance control and management. Based on the causes outlined in the Ishikawa Diagram (Figure 4.9), as well as the causes observed in the Figures 4.10, 4.11, 4.12, and 4.13, Table 4.2 compiles the main causes. In the next chapter, the causes presented in this table will be categorized according to the impact of their resolution, and the effort required to address them. For this, a matrix analysis will be performed using the Effort x Impact method, identifying the 'Vital Causes', which are the causes that should be addressed first due to their high impact combined with a low-resolution cost [25], whether financial, time-related, implementation-based or related to cultural change.

It enables the development of an action plan addressed to the vital causes, along with the creation of control methods designed to assess the optimized process.

Itens	Potential Causes
1	Lack of measurement of indicators: MTBF, MTTR, and Availability.
2	Lack of definition of triggers/performance targets.
3	Current metrics are general for all equipment.
4	Deficient execution of 5S practices in the workplace.
5	Absence of a culture of continuous improvement.
6	Incomplete/Superficial work order descriptions.
7	Lack of training for employees.
8	Emergency spare parts unavailability caused by excessive lead times.
9	Need for spare parts inventory.
10	Lack of procedure for classifying asset criticality.
11	Maintenance procedures do not describe the influence of criticality on tasks or rescheduling.
12	Lack of equipment subdivision into a Logical Sequence (Systems and Components).
13	Absence of specific software for Maintenance Management (ERP).
14	Lack of servers for cloud data processing and storage.
15	Lack of proper equipment categorization, only 4 groups to 140 equipment.
16	Limitations in data collection due to Corrective Work Order Structure.

Table 4.2: Potential Causes of Inefficiency in Maintenance Control and Management

Chapter 5

Improvement Proposals and Control Methods

In this chapter, the action plan and improvement proposals will be developed as part of the ‘Improve’ phase of the DMAIC methodology. In the first section, an Effort x Impact matrix will be used to categorize the potential causes identified in the previous chapter. This categorization will allow the prioritization of Vital Causes, meaning those that provide the greatest benefits and are relatively easy to implement.

Process improvement tasks will be developed based on the vital causes and structured using the 4W1H methodology, a widely used approach to developing action plans.

The ‘Control’ phase will be conducted in the following section by creating the Maintenance Failure Profile (MFP), enabling data stratification, improved organizational decision-making, and performance monitoring.

However, it is important to emphasize that the collection of data related to the improvements implemented will not be included in this study, as the implementation and subsequent data collection require time beyond the scope of this research. Instead, the Maintenance Failure Profile will be developed and exemplified using synthetic data to serve as a guideline for the company, allowing it to track and measure the effectiveness of process improvements after their implementation.

5.1 Improve

5.1.1 Vital Causes Definition

An Effort x Impact matrix will be used to identify the vital causes. This is a qualitative tool designed to graphically assess which corrective actions require high or low effort for implementation and the impact they generate on the process once solved. This facilitates the decision-making process regarding which solutions should be prioritized for process optimization at a low operational cost [25], [30].

The difficulty of implementing improvements is commonly associated with high investment costs, extended implementation time, cultural shifts, and employee resistance to change, difficulties that might delay the continuous improvement process.

In the categorization provided by the matrix, four groups are identified [25]:

- **Low Effort and High Impact:** These causes should be prioritized for implementation, as they offer significant benefits while requiring minimal effort.
- **High Effort and High Impact:** Although these improvements have a strong impact, their feasibility must be carefully analyzed, as they often require significant time and financial resources.
- **Low Effort and Low Impact:** These causes should be reviewed to assess their real necessity. If considered relevant, they can be implemented as secondary tasks, due to their low effort requirement.
- **High Effort and Low Impact:** These should only be addressed if strictly necessary, as they demand considerable resources while providing limited benefits to the process.

It is important to note that the assessment of “Low Impact” is based on the maintenance process under evaluation rather than its overall impact on the company.

Considering the definition of each group that composes the Effort x Impact Matrix, the potential causes described in Table 4.2 can be classified into these four categories. The

classification takes into account whether resolving a cause would positively impact the maintenance performance of the company, enabling the development of assertive actions to mitigate the main causes in maintenance processes.

In addition to the impact of transforming the maintenance system, the level of effort required to resolve each cause is also evaluated. Priority is given to causes whose resolution does not generate significant costs or require an excessively long time to implement.

If a cause requires any financial investment, it will be automatically classified as “High Effort” and will not be addressed in this study. Similarly, causes that are amplified by other causes, result from them, or are auxiliary processes in the company will be classified as “Low Impact”.

For instance, Cause 13, “Absence of specific software for Maintenance Management (ERP)”, would bring a high and immediate impact. However, it is not prioritized due to its financial investment requirements. In contrast, Cause 9, “Need for spare parts inventory”, clearly represents a source of waste for the company. However, this situation is a consequence of other issues, such as the lack of traceability of the failure mode, excessive corrective maintenance, and unreliable performance monitoring. Consequently, addressing Cause 9 without solving the related problems would not generate a positive impact for the organization.

Based on these criteria, the matrix presented in Figure 5.1 identifies the Vital Causes: 1, 2, 3, 6, 10, 11, 12, 15, and 16 from Table 4.2. These causes must be prioritized.

		IMPACT	
		Low	High
EFFORT	Low	4; 7	1; 2; 3; 6; 10; 11; 12; 15; 16
	High	8; 9	5; 13; 14

Figure 5.1: Effort x Impact Matrix of Potential Causes

The action plan and the improvement proposals will be tailored to the causes highlighted in the Matrix above.

5.1.2 Action Plan Development

To develop the Action Plan, the **4W1H** tool will be used, an adaptation designed to meet the specific needs of this project, based on the complete **5W2H** approach.

The 5W2H method consists of answering the following questions [31], [32], [33]:

- **What:** What to do? Related to the action.
- **Why:** Why to do? Related to the cause behind the action.
- **Where:** Where to do? It points out the location or process.
- **When:** When to do? It refers to the schedule of an action.
- **Who:** Who to do? It denotes to an individual or a group who will deal with the action.
- **How:** How will it be done? It describes the way the action will be developed and concluded.
- **How Much:** How much does the action require in terms of investment or periodicity?

Given the specific characteristics of this case study, the question “Where?” will not be considered, as the action plan is exclusively focused on the maintenance department of a company, and no specific places in the maintenance department will be focused, since actions are general for the entire maintenance system. Furthermore, as established in the Project Charter (Figure 4.1) and in alignment with Lean principles, no costly improvements will be proposed. In addition, the actions are not periodic and focus on structuring and improving the maintenance system, rather than routine or operational activities. For these reasons, the question “How Much?” will not be considered as well.

The **4W1H** was developed based on these considerations. It was structured following a logical execution sequence, where actions must be completed in the established order.

It also must be emphasized that the "Why" refers to the Vital Causes, and the following questions refer to the actions proposed.

WHY	WHAT	WHO	WHEN	HOW
(15) Lack of proper equipment categorization, only 4 groups to 140 equipment.	Development of intermediate groups for better classification of equipment based on common characteristics. Removal of the "Others" category.	Author	Immediately	Development of a Logical Sequence for grouping Equipment according to "Group, Family, Equipment, and System."
(12) Lack of equipment subdivision into systems and components.	Division and Standardization of equipment into Systems.	Author / Maintenance Supervisor	Immediately / After defining the pattern	Development of the Logical Sequence. The division into "Systems" will be structured so that each "Family" of equipment follows a standardized model.
(16) Limitations in data collection due to Corrective Work Order Structure.	Addition of new fields in the Work Order system and automation of columns.	Author	Immediately	Development of new columns for data entry in work orders. Automation of spreadsheets for specific entries.
(6) Incomplete/Superficial work order descriptions.	Develop a step-by-step guide for filling out work orders, updating procedures, and communicating with employees.	Author / Maintenance Supervisor	After implementing the new Order model	Update of the work order procedure and employee training.
(10) Lack of procedure for classifying asset criticality.	Development of a procedure for assessing and defining equipment criticality.	Author	Immediately	Proposal for a quantitative analysis for categorizing Equipment based on Criticality.
(11) Maintenance procedures do not describe the influence of criticality on tasks or rescheduling.	Review of maintenance procedures, incorporating the influence of criticality on activities and rescheduling maintenance tasks.	Author	Immediately	Standardization of actions related to Equipment Criticality based on task prioritization and order postponements.
(1) Lack of measurement of indicators: MTBF, MTTR, and Availability.	Monitoring and calculation of KPIs for equipment.	Author	During the MFP development	Development of the MFP, including the calculation and measurement of performance data and equipment condition assessment.
(3) Current metrics are general for all equipment.	Monitoring of performance indicators and metrics linked to equipment groups and their criticality.	Author	During the MFP development	Development of the MFP by segmenting collected data according to the Logical Sequence and Criticality criteria.
(2) Lack of definition of triggers/performance targets.	Creation and standardization of performance triggers, specific targets, and required actions.	Author	During the MFP development	Establishment of triggers and performance targets based on the characteristics of each asset, as well as the actions to be taken in case of non-compliance.

Figure 5.2: 4W1H of Vital Causes

The proposed action plan was tailored to deal with the main failures and correct inefficiencies present in the maintenance system. Based on the defined actions, improvement proposals for all Vital Causes will be developed to address each of them, and the proposals will be shared within the company. The next section outlines the development of these actions.

5.2 Improvement Proposals

In this section, improvements for each Vital Cause, presented in the Figure 5.2, will be proposed, except for Causes 1, 2, and 3, which will be addressed in the ‘Control’ phase, during the MFP development.

5.2.1 Logical Sequence Development

This action focuses on eliminating inefficiencies generated by Causes 15 and 12 from the 4W1H tool (Figure 5.2). Cause 15 results from an overly general and uninformative classification of assets, while Cause 12 relates to the absence of further subdivisions beyond the equipment itself.

The proposed solution involves developing new division categories, similar to those used in software for maintenance management, such as ERP software [34]. For this project, the model presented in Figure 5.3 was developed:

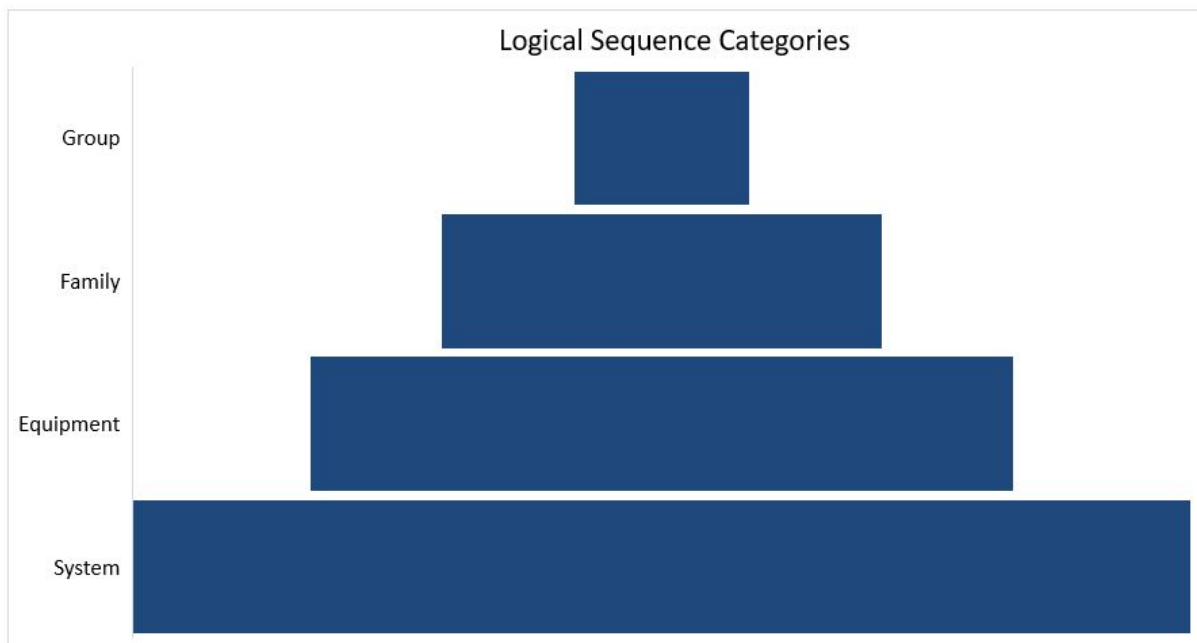


Figure 5.3: Proposal of the new Logical Sequence Categories

As shown in the Figure 5.3, the new Levels are: Group, Family, Equipment, and System. The schematic representation informs us that the first and most general classification is “Group”, within different “Families” will be categorized. Each “Family” will consist of various similar “Equipment”, which contains their own “Systems”. The “System” category represents the most specific and detailed classification level, containing the largest number of elements due to its singularity.

The purpose of this change is to enhance the traceability of failures and improve the accuracy of data collection, allowing solid analysis of the maintenance status for each category. This enables assessments with different levels of detail according to the specific analytical needs.

However, to achieve this, new classes must be created for each equipment type, enabling this traceability within maintenance orders. For this purpose, standardized codes will be developed for each type of equipment, following a Logical Sequence where the subsequent class depends on the previous one, ensuring consistency in the analysis and facilitating the registration of new assets within this methodology.

The upcoming content will describe the update of the “Group” category and the creation of the new “Family” and “System” classes will be presented. This will establish the standardized Logical Sequence for asset classification.

Due to the large number of equipment types, only one categorization at the “System” level will be conducted to develop the classification standard. The remaining classifications should be carried out by the company following the established procedure.

Group Update

The “Group” category will be updated because half of the assets (70) are currently classified as “Others”. After a detailed analysis of the function and type of each of the 140 assets, it was determined that creating two new groups, to be added to the existing ones, would be the best strategy. The original “Groups”, which were not modified, are “Lifting” with 42 equipment, “Machining” with 21, and “Transportation” with 7.

The new groups are “Auxiliary Equipment”, and “Infrastructure and Utilities”.

“Auxiliary Equipment” refers to machinery that supports the production activities by performing specific complementary tasks. This category includes equipment such as welding machines, presses, and plasma cutting systems, which, although not directly involved in the final product assembly, are essential for ensuring process efficiency and continuity.

“Infrastructure and Utilities” refer to assets that provide the necessary conditions for the operation and support of industrial activities. This category includes equipment such as air conditioners, compressors, scales, stoves, and other systems essential for environmental control, energy supply, and basic facility functions.

In the Table 5.1, it is possible to observe the quantity of assets in the two newly created groups.

New Groups	Number of Equipment
Auxiliary Equipment	32
Infrastructure and Utilities	38

Table 5.1: Number of Equipment in the two new Groups

Equipment Families

The new categorization level, called “Family”, will be introduced between “Group” classification and “Equipment”. This new level aims to organize machines of the same type and with similar characteristics in a more specific manner than the previous classification.

The Table 5.2 shows all the “Groups”, the “Families” that composes each group, and the quantity of equipment that belongs to each Family.

Group	Family	Number of Equipments
Lifting	Overhead Crane	10
	Hoist	28
	Gantry Crane	3
	Elevator	1
Machining	Milling Machine	2
	Lathe	12
	Drilling	7
Transportation	Forklift	5
	Platform	1
	Conveyor	1
Auxiliary Equipment	Cutting	5
	Balancer	2
	Surface Treatment	6
	Welding	7
	Press	6
	Washer	3
	Others	3
Infrastructure and Utilities	Storage and Treatments	9
	HVAC and Exhaust Systems	5
	Measurement Devices	1
	Utilities	11
	Infrastructure	4
	Compressor	3
	Scale	5

Table 5.2: Number of Equipments by Family

A total of 24 new “Family” classes have been developed and distributed across the five groups, as shown in Table 5.2. These 24 classes encompass all 140 assets, where each asset must share common characteristics to belong to the same family. By organizing them into smaller classes with similar attributes, it becomes possible to conduct targeted analyses of specific groups, identify recurring failure modes, detect event repetition, and compare the performance of similar assets.

Equipment Systems

The “Equipment” level, including its tags, will be maintained. However, to achieve a more detailed and meticulous division, the “Systems” class will be developed. This class will strive for greater accuracy in conducting analyses, studying the lifespan and durability of components, and identifying the main causes of machine failures in a more in-depth way.

However, this study cannot develop the categorization at this level of detail for all assets. Therefore, an example will be created based on a single equipment and then applied to similar machines. The company must follow this example to continue this activity for the remaining assets.

To develop the categorization of equipment by systems, an in-depth study is required using manuals, the machine catalog, and its diagrams for each asset, in order to identify all systems present in each machine. This enables a systematic and detailed vision of each piece of equipment.

The asset chosen for this study is the “VT2000 - Lathe Romi 2000”, as it is essential production equipment, classified with criticality A. This vertical lathe, a Computer Numerical Control (CNC) machine, has a machining capacity of up to 15 tons, a maximum turning diameter of 2.2 meters, and a maximum speed of 250 RPM. Respecting the machine characteristics, the equipment has been divided into nine systems [35], [36], as shown in the Figure 5.4.

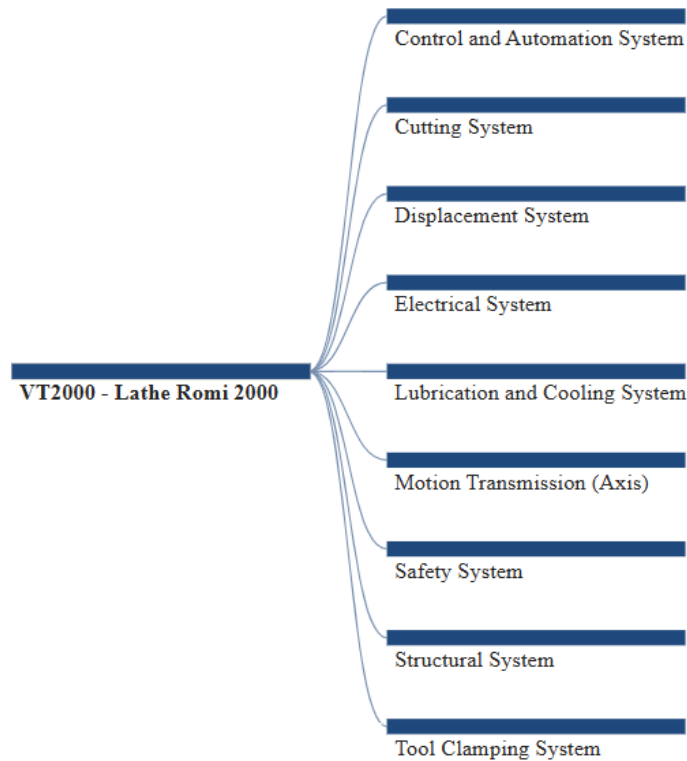


Figure 5.4: VT2000 - Lathe Romi 2000, System division

Machine Traceability Code

Finally, after defining all equipment categorization classes, a standard must be established for all equipment in the factory.

Each of the “Group, Family, Equipment, and System” classes will have a specific coding structure, leading to unique and standardized codes throughout the logical sequence. Thus, it is essential to define the rules that will be the foundation of these code’s creation.

- Abbreviations of three letters have been defined for the “Group and Family” classes. These abbreviations are based on the nomenclature of the respective classes.
- The Equipment level is identified by two letters referencing the name of each asset, followed by its Tag, which must include an additional four digits.

- For the System level, four-letter abbreviations are used to describe the specific system nomenclature.
- Each stage of the coding structure is designated as a level in the logical sequence, with Group as the first level and System as the fourth one.

Below, the structured coding for the VT2000 - Lathe Romi 2000, with Tag 0309, is presented. It demonstrates how the four levels form a logical sequence, with increasing detail as the levels progress. Additionally, the Traceability Code follows the defined standard, guaranteeing a constant number of characters at each level.

The Figure 5.5 presents the example developed for this lathe. However, this prototype must be replicated for all assets, because the company in its current state only has the first and the third Level descriptions defined, and also lacks a Traceability Code for all Levels.

Levels	Complete Description	Traceability Code	N° of characters
1° Level	Machining	USI	3
2° Level	Lathe	USI-TRN	7
3° Level	VT2000 - Lathe Romi 2000 (0309)	USI-TRN-TM0309	14
4° Level	Structural System	USI-TRN-TM0309-SEST	19
	Motion Transmission (Axis)	USI-TRN-TM0309-TRSM	19
	Displacement System	USI-TRN-TM0309-SDES	19
	Tool Clamping System	USI-TRN-TM0309-SFIX	19
	Control and Automation System	USI-TRN-TM0309-SCAT	19
	Cutting System	USI-TRN-TM0309-SCOR	19
	Lubrication and Cooling System	USI-TRN-TM0309-SLUR	19
	Electrical System	USI-TRN-TM0309-SELE	19
	Safety System	USI-TRN-TM0309-SSEG	19

Figure 5.5: Logical Sequence Codes and Description

The creation and standardization of the Traceability Code enable highly detailed maintenance tracking, automation of spreadsheets, and the development of precise dashboards

for maintenance control and measurement. This standardization is essential for the effective implementation of the Maintenance Failure Profile.

In addition to the example shown in Figure 5.5, all the codes since the first to the third level have been created for all assets during this project, and will be shared with the company. The fourth level has not been developed for all assets, only for conventional mechanical lathes similar to the VT2000 model.

5.2.2 Work Order Improvements

This action focuses on solving Causes 16 and 6 (Figure 5.2), and the proposed improvement includes an update to the current format of corrective work orders. As previously identified during the DMAIC analysis phases, it is evident that some critical information is missing from the work order, requiring a restructuring. Additionally, a reduction in manual data entry and partial automation of the spreadsheet is proposed as an enhancement.

Furthermore, a description of the new work order model will be developed. These instructions must be shared by the company's leadership with the maintenance team, ensuring that all employees involved in maintenance tasks have standardized knowledge.

For the new Corrective Maintenance Work Order, the following items will be added:

- The new classification of equipment based on the Logical Sequence, is automatically generated upon entering the TAG and System.
- The equipment criticality, is also automatically generated based on the TAG.
- Calculation of the total work order duration, in days and months.
- Fields for start and end times of the maintenance activity, allowing a precise calculation of the execution period.
- Field for materials used in the activity.
- Automatic priority recommendation for the work order, based on criticality.

- Data validation for specific fields. Some columns, such as TAGs and System, will be restricted to predefined options, preventing reference loss due to incorrect manual entry.
- Creation of a linked database to the Maintenance Work Order spreadsheet, enabling automation.

These changes will serve as the foundation for developing the Maintenance Failure Profile, which will be presented later in this chapter.

The Figure 5.6 shows some of the newly added fields. The columns with blue headers indicate those that must be manually filled in, but data validation ensures that only cataloged information from the database can be entered. This is necessary because the green columns are automatically filled based on this input. As a result, manual input is reduced, and the data becomes more reliable for analysis.

In Figure 5.6, some cells in the columns “System” and “Traceability Code” are left blank. This happens because these cells correspond to assets that are not in the “Lathe Family”. Thus, the four-level Logical Sequence structure has not been developed yet. In this image, only the lathes with TAG 0309 and 0312 have all four levels completed, while other equipment is categorized up to the third level only.

Another note is that some information remains in Portuguese, considering the company’s location is in Brazil, and the documentation and standardization will be used internally.

Criticality	Priority	Group	Family	Tag	System	Traceability Code
A	Alta	Usinagem	Torno	0309	Sistema de Controle e Automação	USI-TRN-TM0309-SCAT
C	Baixa	Elevação	Ponte Rolante	0107		
A	Alta	Infraestrutura e Utilidades	Utilidades	1104		
C	Baixa	Elevação	Talha	0131		
B	Média	Usinagem	Torno	0312	Transmissão de Movimento (Eixo)	USI-TRN-TM0312-TRSM
C	Baixa	Equipamentos Auxiliares	Superficial	0924		
A	Alta	Infraestrutura e Utilidades	Armazenagem e Tratamentos	0926		
A	Alta	Usinagem	Torno	0309	Sistema de Corte	USI-TRN-TM0309-SCOR

Figure 5.6: Logical Sequence in the Order Structure

In the Figure 5.7, the methodology implemented to track the total duration of the work order and precisely measure the execution time is exhibited. This approach excludes secondary activities such as materials and tool mobilization and focuses only on effective task execution.

The color scheme remains the same as in the previous table, with the addition of the orange color, which represents pre-existing data from the previous Work Order format, essential to calculate the total duration.

Conclusion				Execution	Execution End	Start Time -	End Time -	Execution
Start Date	Date	Days	Months	Start Date	Date	Execution	Execution	Total Time
18/07/2024	18/09/2024	62	2,1	19/07/2024	19/07/2024	15:09:00	17:34:00	02:25:00
19/07/2024	03/08/2024	15	0,5	21/07/2024	21/07/2024	16:49:00	18:49:00	02:00:00
19/07/2024	23/08/2024	35	1,2	21/07/2024	21/07/2024	09:32:00	12:27:00	02:55:00
26/07/2024	21/08/2024	26	0,9	28/07/2024	28/07/2024	15:35:00	17:17:00	01:42:00
30/07/2024	09/08/2024	10	0,3	01/08/2024	01/08/2024	11:34:00	14:04:00	02:30:00
30/07/2024	06/08/2024	7	0,2	01/08/2024	01/08/2024	14:54:00	16:58:00	02:04:00
31/07/2024	16/08/2024	16	1	02/08/2024	02/08/2024	14:07:00	17:05:00	02:58:00

Figure 5.7: Duration Control and Execution Time

The leadership must share these instructions with the entire maintenance team to ensure the correct filling of the maintenance orders. Each color present in the columns has a different meaning, to correctly fill the MOs, being essential to follow these guidelines:

- **Orange:** These columns, which were already present in the original spreadsheet, have been maintained.
- **Green:** These columns have newly added. They are automatically filled and should not be edited manually.
- **Blue:** These columns have newly added. Blue columns require manual entry, and it is crucial to input accurate information, so the columns “Tags” and “Systems” include data validation, meaning the description must be selected only from the available options.

Additionally, the database is available for reference and future updates, ensuring it remains aligned with newly introduced equipment.

Lastly, the accurate completion of maintenance orders is a shared responsibility across the entire maintenance process. This means that not only execution and planning technicians but the entire leadership team should prioritize the accuracy of work orders. Leaders must regularly audit and guide their teams, continuously improving the quality of the input into the orders, fostering a positive culture throughout the maintenance department, and reinforcing best practices.

Different methods to improve and automatize even more the work order completion can be applied in the future if the board decides to invest in some technologies, such as badge access control that the employees would use both when starting and concluding a maintenance task - automatizing the Execution Time Control in orders. Another possibility is to develop a specific QR Code for each machine, which would be used to create the maintenance order attached to the specific equipment Tag. These are suggestions for future improvements, seeking continuous improvement, but there are not part of this action plan due to the required investment.

5.2.3 Criticality Assessment Method

To address Cause 10 (4.2), a Failure Modes, Effects, and Criticality Analysis (FMECA), according to the Brazilian Standard 'NBR 5462' [23] will be developed. This is a quantitative study of critical failure modes and their effects on the equipment, often summarized as Criticality Analysis (CA), which seeks to understand the function, effects, and the impact of each equipment in the company. As a result, the degree of criticality is obtained [37].

For this analysis, the severity of failure's effects on applicable factors such as safety, performance, and the environment will be evaluated. The assessment will use values of 1, 3, and 5, where 5 represents the highest impact, and 1 the lowest. [37].

Therefore, the factors under analysis must be defined, selecting those that reflect the

operational reality of the studied company. Below are the factors established [37], [38]:

- **Health and Safety:** Assessment of risks to employees' health and safety in a possible event of loss of equipment function.
- **Environment:** Potential environmental risks in case of equipment failure.
- **Repair Cost:** Estimated costs to replace equipment and facilities in the event of loss of function.
- **Quality / Performance:** Impact on product quality in case of equipment failure during the production process.
- **Process Interference:** Effect on interruptions of production processes, considering equipment redundancy.
- **Failure Frequency:** Refers to the recurrence of failures in facilities and/or equipment.

Another essential point is defining criteria for evaluating assets. Based on the best maintenance practices and in agreement with the company's leadership, a set of evaluation criteria was proposed to address the company's needs. The established criteria can be seen in Table 5.3:

Factors	High (5)	Medium (3)	Low (1)
Health and Safety	Risk of severe or fatal injuries, even with safety procedures.	Risk of minor injuries, even with safety procedures.	No significant risk when following safety procedures.
Environment	Severe contamination with risk to the community with legal compliance requirements.	Contamination restricted to the factory area, with moderate impacts.	Minimal environmental impact, limited to the equipment's location.
Repair Cost	Above 10% of the monthly average of the total maintenance cost of the area.	Between 5% and 10% of the monthly average of the total maintenance cost of the area.	Up to 5% of the monthly average of the total maintenance cost of the area.
Quality/Performance	Product cannot be reused.	Product can be reused.	No impact on quality.
Process Interference	Complete shutdown of the production area.	Shutdown of only the specific equipment.	Reduced production speed without stoppage or no impact on the process.
Frequency	10 or more failures per year.	Between 3 and 9 failures per year.	Up to 2 failures per year.

Table 5.3: Assessment of risks in criticality factors

For the criticality classification, the following criteria were established:

- **Criticality A:** The sum of scores must be greater than or equal to 20.
- **Criticality B:** The sum of scores must be between 19 and 10.
- **Criticality C:** The sum of scores can not exceed 9.

In addition to the criticality assessment methodology development, an automated spreadsheet was created for the company. The image 5.8 shows an example.

Factors	Assessment
Health and Safety	3
Environment	5
Repair Cost	3
Quality/Performance	3
Process Interference	5
Frequency	3
TOTAL	22
CRITICALITY	A

Figure 5.8: Criticality Assessment

Lastly, a criticality assessment must be performed whenever a new machine is acquired, including equipment that performs the same function, since redundancy in the process impacts asset classification. Equipment modifications and changes in production processes also require a new evaluation. Another relevant aspect is the currently absence of a formal procedure for assessing equipment criticality, which may lead to misclassifications. Thus, it is recommended that the board revise all criticality definitions, following this rule.

5.2.4 Maintenance Procedures Update

Currently, maintenance procedures do not have rules based on the equipment's criticality, and this affects both rescheduling preventive work orders and compliance with corrective tasks. This issue is directly related to Cause 11.

As an improvement proposal, criteria based on asset criticality have been established to define these rules and actions for rescheduling preventive maintenance and managing low accuracy in completing emergency work orders. To identify the event that occurred, its cause, and the immediate action required to address it, the fast action method 'Fact, Cause, and Action' (FCA) will be applied.

The proposed control for rescheduling preventive maintenance can be seen in Figure 5.9:

Preventive Maintenance Postponement - Criticality Interference			
Criticality	Priority	Actions	Authorized by
A	High	Develop a "Fact, Cause and Action" (FCA) to understand and treat the cause of rescheduling. Select a new date, as soon as possible.	Maintenance Manager
B	Medium	If there is 2 Postponements in a month, a FCA must be developed. Select a new date, as soon as possible.	Maintenance Coordinator
C	Low	Select a new date within the production team, as soon as possible.	Maintenance Coordinator

Figure 5.9: Preventive Postponements based on the asset criticality

In the figure 5.9, the differences in approach based on asset criticality can be observed. This denotes both the actions that must be taken and the individuals responsible for approving each rescheduling request and lead the team to complete the necessary actions.

Regarding corrective maintenance, two types of control will be proposed. The first is related to the total completion of corrective work orders. In agreement with the

company's maintenance manager, the current completion rate metric (80%) was set as the baseline for assets classified as criticality "C", and increased targets were defined for more critical assets. Based on this, the following rules were established:

- **Criticality A:** The monthly completion rate for corrective orders must achieve **90%**. Otherwise, an FCA must be conducted with the approval of the maintenance manager.
- **Criticality B:** The monthly completion rate for corrective orders must exceed **85%**. Otherwise, an FCA must be conducted with the approval of the maintenance coordinator.
- **Criticality C:** The monthly completion rate for corrective orders must exceed **80%** (current standard). Otherwise, an FCA must be conducted with the approval of the maintenance coordinator.

The second control method relates to work order prioritization. The execution priority of work orders is automatically assigned based on asset criticality, as seen in Figure 5.6, and it might be necessary to reorganize the priority based on the current situation.

To change the execution priority of an order, managerial approval is mandatory for Criticality A assets. For other classes' equipment, approval from the coordinator is sufficient. In both cases, the request must be formalized via email, explaining the reason for the change, and the leader must decide if it is appropriate to change the priority for that specific order.

5.2.5 Future Improvements

Lastly, must be emphasized that the entire development of this action plan, as defined in the initial scope and agreed upon with the company, relies solely on mechanisms and software already used by the organization. This imposes certain limitations on improvements. However, throughout the chapter, some technological suggestions have been

proposed considering potential future investments.

In this regard, the final recommendation for the future, capable of transforming the maintenance department if properly utilized, but requiring a high level of investment, is the adoption of a software for maintenance management, such as an Enterprise Resource Planning (ERP). This system enables centralized control over maintenance activities, historical data tracking, report extraction, cost management, inventory monitoring, and spare parts replenishment.

Another action that can be developed in the future is the implementation of a structured continuous improvement system, by training employees, and encouraging them in a Kaizen approach to promote continuous improvements throughout the work environment. This would enhance efficiency, performance, process control, and the quality of the employees' workplace.

Although the implementation of a structured continuous improvement system, could bring several benefits, this action was not prioritized in this project. Due to the high volume of corrective orders and the lack of process monitoring, this system would not effectively address the company's most urgent maintenance challenges. Consequently, this project prioritized solving the root causes that directly affect maintenance performance and efficiency.

5.3 Control

As previously explained, the implementation of the proposed improvements depends entirely on the company and is beyond the scope of this study. Therefore, the 'Control' phase of the DMAIC methodology will enable the monitoring of the maintenance department's performance, assuming the execution of the proposed actions, addressing Causes 1, 2, and 3 of Table 4.2.

This will be achieved through the creation of the Maintenance Failure Profile (MFP), which will facilitate performance indicator tracking, control of failure levels, execution times, order fulfillment rates, and maintenance goal management. The monitoring process

will be highly flexible, allowing data analysis based on criticality or Logical Equipment Sequence for in-depth and targeted evaluations.

The MFP will be developed using Business Intelligence software (Power BI) and will be available to the company for routine maintenance operations. However, its effective use will only be possible after the improvements and rules established throughout this chapter are adopted by the maintenance department of this company.

A key challenge in creating the MFP is the lack of complete historical data, which prevents retrospective analyses of maintenance conditions. To address this, synthetic data will be generated based on the current state of maintenance, enabling the creation of an MFP model. This approach allows for the visualization of the system in action and an understanding of how it can positively impact maintenance management.

To enable the development of the MFP, it is necessary to have a database that follows the structure established in Figures 5.6 and 5.7. Furthermore, to create the charts accurately, and demonstrate the structure of this tool, the database must be robust. Therefore, the information related to dates, order durations, and recurrence of events in equipment was generated randomly, but always following the criteria defined throughout this thesis. This approach allows the company to use the same file for future analyses in an efficient and structured manner because all the indicators, equipment, logical sequence, and critically agree with the rules established in this work.

After this study, all information will be provided and explained to the company. Whether all proposed improvement actions have been implemented, the synthetic data used to generate the MFP model can be replaced with real data collected under the new standards. This transition will enable accurate and efficient maintenance monitoring, and the MFP will play a significant role in maintenance management decisions and control.

5.3.1 Maintenance Failure Profile

After the development of this work, it is possible to implement the Maintenance Failure Profile (MFP), a tool focused on facilitating management and decision-making by

monitoring and controlling maintenance indicators and status. The tool provides detailed visualization, based on the time, equipment criticality, and the logical sequence of each asset.

This approach allows the company to maintain control over maintenance activities, as well as define and monitor performance targets that must be standardized. These targets should be based on historical data and updated according to the department's progress and achievements. The MFP allows for automated and intuitive monitoring of these targets directly through the Business Intelligence software.

It should be noted that the entire report is adaptable to precisely provide the details to be analyzed. Filters can be applied either in combination or separately, depending on the needs of the analysis, and they affect all charts. For example, it is possible to view the overall maintenance performance for the year 2024. In contrast, it is also possible to select only specific months and focus on assets with Criticality A that pertain to a determined level of the logical sequence. Figure 5.10 shows the implementation of the MFP in the Business Intelligence software.

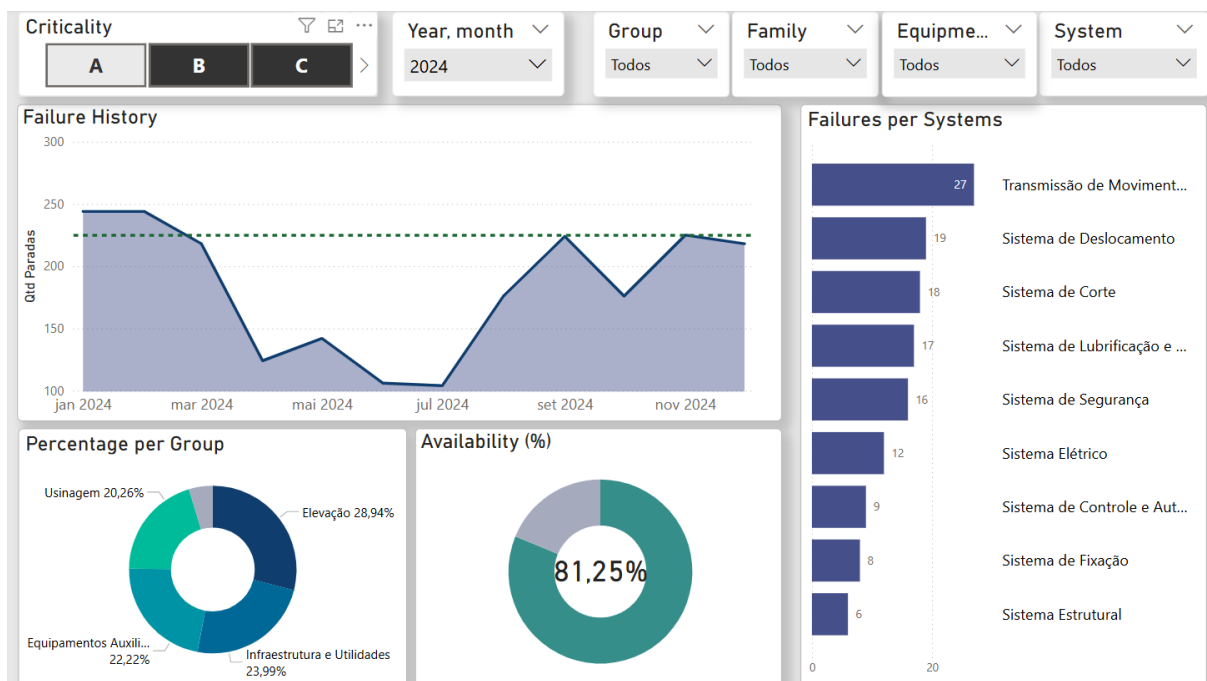


Figure 5.10: General Data of the Maintenance Department

In Figure 5.10, the definition of the graphs was:

- **Failure History:** This chart shows the total number of failures over each period of time. The period can vary from entire years or even days. However, for better visualization, it is recommended to display the history on a monthly or weekly basis. If no filter is selected, it shows the total results of the maintenance department.
- **Availability:** This calculates the percentage of useful time in which the assets were available for normal operation. Similar to the ‘Failure History’, with no filters applied, it shows the global availability of the department.
- **Percentage of Failure per Group:** This indicates the percentage of failures by each equipment group, the first level of the logical sequence, allowing a quick and precise view of which group had a more significant impact on maintenance.
- **Failure per Systems:** This chart shows the number of failures related to each system (4th level of the logical sequence), indicating which systems present the highest defect number.

The Maintenance Failure Profile also includes another data page focused on the main maintenance indicators. Similar to the previous image, the application of cross-filters is essential for the proper use of this tool, allowing leadership to dive into the smallest details of maintenance and its indicators.

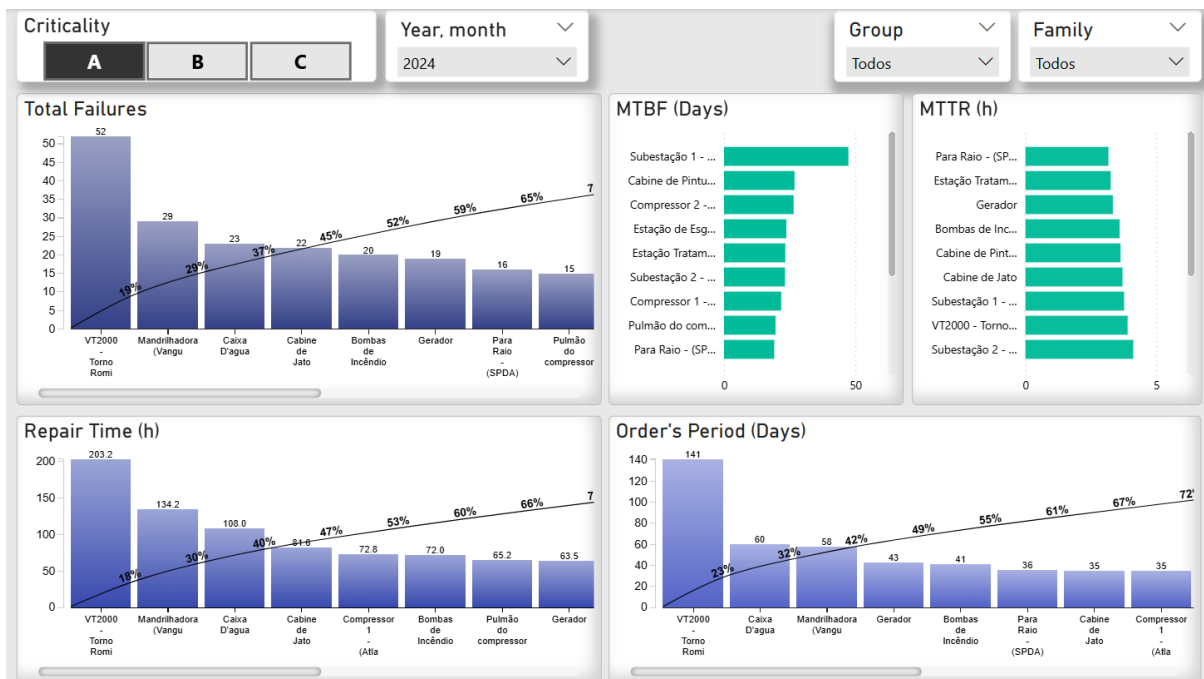


Figure 5.11: Key Performance Indicators of the Maintenance Department

At this stage, the following indicators are calculated:

- **Pareto of Failure Occurrence:** It ranks the equipment with the highest absolute number of failures within a certain period and shows the sum of the percentage of each asset compared to the general.
- **Pareto of Repair Time:** A chart ranking the equipment that required the most repair time to resolve failures, and its percentage compared to the general.
- **Pareto of Order's Period:** A chart ranking the equipment with the longest period from the beginning to the closing of the maintenance order, including diagnostic time, acquisition of materials, lead time of spare parts, and the repair time.
- **MTBF (Mean Time Between Failures):** Calculation of the average time between failures, in days. The higher the time, the better for maintenance. It must be compared with the assets of the same group or family.

- **MTTR (Mean Time To Repair):** Calculation of the average repair time, in hours. The shorter the time, the more efficient the maintenance. It must be compared with the assets of the same group or family.

The figures 5.10 and 5.11 include the main indicators of a maintenance department, concluding successfully the primary objective of this work: analyze the maintenance process, identify the major failures, develop improvement proposals, and enable effective and accurate control.

As a recommendation for the company, it is advised that the proposed improvements be implemented and standardized alongside the Quality Control team, in order to create formal procedures for all improvements. Furthermore, the MFP enables detailed monitoring of the maintenance profile, and based on this control, the company should establish individualized performance targets and triggers for each equipment class and criticality level.

In addition, equipment that has the most significant impact on maintenance results should be prioritized, root cause analyses should be performed, and the most apparent problems should be addressed promptly to enhance the efficiency and effectiveness of maintenance.

Chapter 6

Conclusions

The present report was the result of an in-depth case study conducted in a company that provided historical maintenance data, its hierarchical structure, and maintenance procedures. Based on this case study, a detailed analysis would be carried out following the Lean principles, by implementing DMAIC methodology and other required tools, following the state-of-the-art in maintenance practices to meet the company's needs. The entire analysis performed, along with the development of solutions, represents a significant contribution to the current state of maintenance at this company, enabling a substantial turnaround in terms of maintenance reliability and performance.

The main objective of this work was to study the current state of maintenance using the DMAIC methodology, identifying failures, opportunities for improvement, and issues that negatively impact the company. Throughout the development of this thesis, Lean and quality tools were applied in each stage of the DMAIC process to define root causes and handle process issues. This allowed the creation of an action plan addressing the current needs of the maintenance team and the development of a tool for control and data stratification, the Maintenance Failure Profile (MFP).

The first effective action was a comprehensive study of the current state of maintenance without defining detailed causes, focusing solely on understanding the entire maintenance process. The information provided by the company included historical data from 2024, covering corrective and preventive maintenance, measured indicators, and assets control.

The results obtained in this thesis were explained throughout the DMAIC stages, where each step played a crucial role in the development of an efficient and feasible improvement project for the company. As the study of the company's current state was completed, the project definitions could be established, and then the 'Define' phase began. In this phase, a Project Charter was developed to define the scope of the project and its limitations, also describing the project's objectives and the aspects it would cover. Costly improvements were excluded, and it was defined that the implementation of the proposed solutions would be the company's responsibility. In addition, a SIPOC diagram was created to clarify the inputs and outputs involved in each process that composes the maintenance department, providing a general understanding of the maintenance.

The 'Measure' phase began with the development of a workflow, allowing a sequential understanding of the activities required for maintenance tasks, as well as identifying those responsible for each step. Based on historical data, graphical analyses were also performed on task fulfillment, execution rates, and order prioritization. At this point, it was noted that data collection was insufficient, resulting in low maintenance reliability. Another aspect is the generality of the existing data, despite being divided by criticality and equipment groups, did not effectively influence maintenance planning and control.

The 'Analyze' phase aimed to identify the root causes of the problems mentioned above using various analysis methods. Initially, an Ishikawa diagram was created, and complementary graphical analyses were carried out to list all potential causes related to inefficiencies in the maintenance processes. These potential causes varied from the lack of effective control over performance metrics, insufficient data in work order descriptions, absence of computerized control of maintenance status, non-standardized processes, and difficulties in failure traceability.

Based on the analysis performed, it was possible to start the 'Improve' phase, aimed at developing improvement proposals and solutions addressing the causes identified in the previous stage. However, a method of prioritization of failures was necessary to address the causes that would generate the most significant impact on the process and can be solved more quickly and easily than others. To prioritize the causes, an Effort x Impact

matrix was used, categorizing potential causes according to these metrics and enabling the creation of an action plan to address Vital Causes — those which, when solved, would bring the greatest benefits to the company with moderate implementation effort.

Based on the analyses performed, the ‘Improve’ phase developed proposals aimed at standardization, automation, and controlling maintenance metrics and performance indicators. To create the action plan the 4W1H tool was used. The main actions were divided into three large groups:

- **Logical Sequence Development:** In this action, a logical sequence was developed, establishing new groups, families, and systems for equipment categorization to improve the organization through the creation of “Traceability Codes”.
- **Work Order Improvements:** An update of the maintenance work order format was developed to collect a much broader range of data. It is necessary to establish precise controls, increase reliability, and improve failure traceability. Additionally, the work order creation process was optimized, allowing for automated order filling and data segmentation.
- **Criticality Assessment Method and Procedures update:** It consisted of developing a standard procedure for defining quantitatively the criticality of the maintenance assets. Various criteria that impact the company were evaluated. Additionally, a revision of maintenance procedures was proposed to explain the influence of criticality on non-compliance or postponement of maintenance activities.

In the final stage of DMAIC, ‘Control’, the Maintenance Failure Profile (MFP) was structured using Business Intelligence software, enabling continuous analysis and monitoring of maintenance indicators, whether general or specific, increasing data stratification and decision-making power. This system allows detailed visualization of the maintenance sector, dividing indicators by equipment criticality and their performance over time, providing valuable information for strategic maintenance planning, failure control, and monitoring performance triggers and goals.

The achieved results demonstrate that developing a standardized and less human-dependent system is essential for ensuring proper maintenance process control, improving failure traceability, and providing continuous analysis of performance indicators. The presented proposals enable the implementation of improvements that, when properly applied and monitored, have the potential to significantly enhance the efficiency of the maintenance sector.

All the proposed actions, analyses performed, and tools developed can be implemented in the company by following the action plan and the implementation order. This approach shows that it is possible to achieve a complete turnaround in the current maintenance structure without requiring financial investments or personnel restructuring. This is feasible as long as the best maintenance management practices are followed, combined with cultural changes focused on Lean principles, aiming at continuous process improvement, automation, and task standardization. Furthermore, it is indispensable to share the acquired knowledge with the maintenance team and provide internal training to ensure that the new activities are carried out with excellence, in a standardized manner.

This study addresses a real problem faced by a company which the maintenance department presents clear inefficiencies. Such a situation is not uncommon and compromises the results of various companies worldwide, regardless of their area of business. Adapting Lean principles to maintenance allows focused work towards improvement in this sector. Therefore, the present work can be useful to various companies experiencing similar issues, as well as serving as a starting point for future research in the area of maintenance process improvement.

Additionally, one of the suggestions for future work as a continuation of this study is to monitor the implementation of these actions within the company and the results generated. It is important to measure which actions were most effective and which required adjustments to fit the company's culture. Also, analyzing the employees' receptiveness to the changes and if a culture of continuous improvement is effectively implemented, from leadership to operators.

Another aspect is that automating maintenance processes and transforming the data

structure into a more secure system, less dependent on manual work, is a goal of this study. This could be achieved by different approaches, such as adopting an Enterprise Resource Planning (ERP) system, but it is important to highlight that, although the implementation of ERP brings several advantages to a company, it also involves investment needs. In contrast, the present study, following a Lean approach, demonstrates that it is possible to achieve great operational results without requiring financial investments, considering the current state of this company. In this context, a future study is suggested not only to compare the operational results of ERP implementation with those obtained through the improvements proposed in this work, but primarily to identify the appropriate conditions and define a turning point at which ERP adoption would become strategically advantageous for the company.

Overall, this study provided valuable and significant insights through the DMAIC methodology and the application of Lean tools to optimize processes, and solve the maintenance problems according to the critically and priority criteria towards the continuous improvement in the maintenance area. However, there is room for further investigation, such as analyses related to maintenance costs and the use of the MFP for a detailed analysis of failure modes and breakdowns.

It is important to highlight that, despite the conclusion of this project, according to the Kaizen philosophy, there is always room for implementing new improvements, regardless of the area or process, and this field of study is no exception.

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