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Digitalization of the Lubrication Function

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Resumo

Esta dissertação centra-se na Digitalização da Função de Lubrificação na unidade industrial da Sonae Arauco em Mangualde, com os principais objetivos de melhorar a fiabilidade dos ativos e otimizar os recursos de manutenção através da melhoria da lubrificação. A metodologia adotada baseou-se numa abordagem holística que integrou a formação técnica dos colaboradores, a implementação de boas práticas operacionais, a utilização de sistemas de lubrificação automática, a introdução de tecnologias avançadas de manutenção preditiva (tais como análise de óleo e lubrificação assistida por ultrassons), bem como a centralização e gestão estruturada da informação na plataforma IBM Maximo.

As análises de custo-benefício mostraram retornos significativos, particularmente em iniciativas de formação e na adoção de tecnologias assistidas, comprovando o potencial económico e técnico destas soluções. Embora a lubrificação automática tenha um elevado potencial de criação de valor, ainda requer uma avaliação mais aprofundada em termos das melhores áreas para a sua implementação.

O estudo culmina na definição de um plano de implementação escalável que pode ser adaptado a outras unidades industriais dentro da organização, reforçando a relevância de uma estratégia integrada e orientada por dados, focada na melhoria contínua dos processos de manutenção industrial.

Palavras-Chave: Gestão da Lubrificação, Manutenção Preditiva, Digitalização, Lubrificação Assistida por Ultrassom, Análise de Óleo, Sistemas de Lubrificação Automática, Fiabilidade dos Ativos.

Abstract

This dissertation focuses on the Digitalisation of the Lubrication Function at Sonae Arauco's industrial unit in Mangualde, with the main objectives of improving asset reliability and optimising maintenance resources by improving lubrication. The methodology adopted was based on a holistic approach that integrated the technical training of employees, the implementation of good operational practices, the use of automatic lubrication systems, the introduction of advanced predictive maintenance technologies (such as oil analysis and ultrasound-assisted lubrication), as well as the centralisation and structured management of information on the IBM Maximo platform.

Cost-benefit analyses showed significant returns, particularly in training initiatives and the adoption of assisted technologies, proving the economic and technical potential of these solutions. Although automatic lubrication has high potential for value creation, it still requires further assessment in terms of the best areas for its implementation.

The study culminates in the definition of a scalable implementation plan that can be adapted to other industrial units within the organisation, reinforcing the relevance of an integrated, data-driven strategy focused on the continuous improvement of industrial maintenance processes.

Keywords: Lubrication Management, Predictive Maintenance, Digitalisation, Ultrasound-Assisted Lubrication, Oil Analysis, Automatic Lubrication Systems, Asset Reliability.

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"Time you enjoy wasting, was not wasted."

John Lennon

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List of Acronyms

IoT	Internet of Things
EAM	Enterprise Asset Management
AI	Artificial Intelligence
KPI	Key Performance Indicators
SDGs	Sustainable Development Goals
GPS	Global Positioning System
AM	Asset Management
CM	Corrective Maintenance
PM	Preventive Maintenance
CBM	Condition-Based Maintenance
PdM	Predictive Maintenance
dB	Decibel
HPL	High Pressure Laminate
MDF	Medium-Density Fiberboard
PB	Particleboard
OSB	Oriented Strand Board
ROI	Return on Investment
CMMS	Computerized Maintenance Management
System MAS	Maximo Application Suite
SAKA	Sonae Arauco Knowledge Academy

Chapter 1

Introduction

1.1 Background

Lubrication is a fundamental part in industrial maintenance, it directly influences the efficiency, reliability, and longevity of the assets. When done correctly, adequate lubrication reduces friction, minimises wear, and improves energy efficiency, improving asset performance, and lowering operational costs. However, conventional lubrication practices are often based on scheduled or manual interventions, which can lead to inefficiencies such as over-lubrication, under-lubrication, and suboptimal maintenance planning. These inefficiencies contribute to premature equipment failure, increased downtime, and higher maintenance expenses.

With the growing importance of Industry 4.0, it is evident that digital transformation has revolutionised industrial maintenance, enabling the integration of advanced technologies to optimize lubrication strategies. Techniques such as ultrasonic monitoring, automated lubrication systems and IoT sensors, allow for a more precise, data-driven approach to lubrication management and optimization. Furthermore, the integration of lubrication processes with Enterprise Asset Management (EAM) systems, such as IBM Maximo, enhances decision-making capabilities, streamlines maintenance workflows, and reduces reliance on manual interventions. These advancements align with predictive maintenance strategies, shifting from reactive to condition-based lubrication management.

1.2 Motivation and Relevance

The necessity for optimal lubrication management is underscored by the increased complexity of industrial equipment and the increasing demands for cost reduction, sustainability, and operational efficiency. Due to excessive lubricant use and inappropriate disposal procedures, inefficient lubrication not only increases maintenance expenses and unscheduled downtime but also worsens energy losses and the environmental impact. In addition, there is increased concern about adopting measures that align the company with the Sustainable Development Goals, addressed in Appendix A.

This study advances the creation of more intelligent, effective, and economical lubrication procedures by assessing the possibility of including ultrasonic-assisted lubrication, automatic lubrication, oil analysis, as well as sensors, voice control features, and route optimisation using GPS. It is anticipated that the results would help decision-makers and maintenance engineers alike by offering insights into how these new technologies might be used in practice.

1.3 Objectives

This dissertation aims to achieve:

- Optimisation of Lubrication Management: developing a digitalised system to improve efficiency, reduce waste and optimise the use of lubricants at Sonae Arauco.
- Automation and Intelligent Monitoring: identify and define new tools to implement (ultrasonic sensors, automatic lubrication, GPS, etc.) to increase precision and reduce human effort in lubrication processes.
- Integration with the IBM Maximo system: ensuring system compatibility with IBM Maximo, enabling intelligent lubrication management (potentially through voice commands and automated alerts).
- Improved Reliability and Sustainability: increase the useful life of assets, reduce failures due to inadequate lubrication and align the process with more sustainable industrial practices.

1.4 Methodology

This dissertation follows a case study methodology developed in partnership with Sonae Arauco, one of the world's largest producers of wood-based panels. The work was carried out at the industrial unit in Mangualde, Portugal, which specialises in the production of MDF (Medium-Density Fibreboard).

This unit is characterised by a large number of critical assets, such as bearings, motors, gearboxes and hydraulic systems, whose reliability depends heavily on adequate lubrication. Lubrication, in this context, is of strategic importance to the company, as failures associated with poor lubrication can result in serious breakdowns, unplanned production stoppages and high maintenance costs. Despite its relevance, the lubrication function had previously been managed in a rather unstructured manner, with outdated plans and limited digital integration. Therefore, the optimisation and digitalisation of lubrication was identified as a critical opportunity for improvement at the Mangualde factory.

The methodology adopted was organised into sequential and interdependent phases, ensuring a complete assessment of the current state, identification of inefficiencies and subsequent proposal, implementation and evaluation of technological improvements.

Initially, an extensive literature review was undertaken to establish the theoretical foundation in areas that are relevant to this dissertation.

The empirical phase involved a detailed analysis of the current state of lubrication practices at the factory, including workflows, route management systems, and associated challenges. Data collection included direct observation, technician interviews, training activities, and documentation reviews.

Subsequently, a set of targeted improvements and digitalisation initiatives were developed. These included the centralisation and update of lubrication information, contamination prevention measures, integration of oil analysis, and the adoption of advanced technologies such as ultrasound-based monitoring, and automatic lubrication systems..

It should also be noted that this study is not limited to technical implementation. A critical analysis of the measures applied was also carried out, comparing traditional and digitalised approaches and assessing the technical, operational and economic impacts. This reflection is presented in Chapter 5 and is a central element of the case study. Finally, a standardised lubrication procedure was proposed, including guidelines for applicability across different industrial sites, as well as recommendations for integration with IBM Maximo and future scalability through voice-command systems and sensorisation.

1.5 Dissertation Structure

The structure of this dissertation is designed to reflect a logical progression from theoretical foundation to practical implementation. The chapters are organised as follows:

- Chapter 2 – Literature Review: Establishes the theoretical basis by examining key concepts in asset management, lubrication science, and emerging digital technologies relevant to industrial maintenance.

- Chapter 3 – Current State Analysis: Describes the context of the case study, providing an overview of the company, the production process, and the current lubrication practices. Challenges and opportunities for improvement are also identified.

- Chapter 4 – Methodology: Details the methodological framework, including data collection methods, training activities, and the strategy for selecting and piloting new digital tools for lubrication management.

- Chapter 5 – Analysis and Discussion of Results: Presents and analyses the outcomes of the implemented improvements. This includes an evaluation of tested technologies, their operational impact, and a comparison with conventional lubrication methods.

- Chapter 6 – Conclusions and Future Work: Summarises the main findings, discusses the limitations of the study, and proposes directions for future research and broader application of the developed solutions.

Chapter 2

Literature Review

The theoretical ideas and development processes for this project will be covered in this chapter. To do this, the study was done on books and articles focussing on areas where the central theoretical concepts are based, such as asset management and maintenance strategies, lubrication (monitoring and automation), technological solutions in lubrication management, and integration of lubrication with maintenance systems.

2.1 Asset Management and Maintenance Types

Asset Management (AM) and Maintenance Strategies are an essential part in ensuring the reliability, efficiency, and longevity of industrial assets. In recent years, industrial systems have become increasingly more complex, and this leads to the need for a structured approach that incorporates technical, economic, and risk-based decision making to optimise asset performance throughout its life cycle (Schneider et al., 2006). The ISO 55000 series defines asset management as the "coordinated activity of an organisation to realise value from assets", highlighting the need for a strategic alignment between technical, financial, and operational factors (International Organization for Standardization, 2014).

When done right, asset management not only ensures compliance with regulatory requirements, but also contributes to a better overall business performance. According to research, a structured Asset Management framework leads to reducing downtime, improving asset usage, and enhancing the return on investment (Schneider et al., 2006). In addition, the integration of digital technologies, such as IoT-based monitoring and ultrasonic lubrication analysis, has revolutionised maintenance strategies by enabling real-time decision-making and predictive maintenance.

In this section, the fundamental principles of industrial asset management (Section 2.1.1) will be explored, the different maintenance types will be explored (Section 2.1.2), and also adress the economical and technical factors in asset management (Section 2.1.3).

2.1.1 Industrial Asset Management Principles

Industrial asset management is a systematic and strategic approach used to manage physical assets throughout their entire life cycle, in order to achieve organisational goals. According to ISO 55000, asset management involves the coordinated activities of an organisation to realise value from assets, balancing performance, cost, risk, and sustainability.

2.1.1.1 Core Principles of Industrial Asset Management

The primary tenets of asset management were created to match asset performance to the business objectives of the organisation. These principles, which were delineated in ISO 55000 (International Organization for Standardization, 2014), include:

- The realised value of assets for the organisation and its stakeholders throughout the asset's life.
- Achievement of asset management goals and meeting criteria.
- Constant improvement of asset performance, the asset management system, and asset management.

2.1.1.2 Lifecycle Management and Performance Monitoring

Optimising an asset's performance from purchase to disposal is the main goal of lifecycle asset management. By using this strategy, assets are kept, used, and replaced in a way that maximises their worth over time. A vital part of lifecycle management is performance monitoring, which gives you the information you need to decide whether to replace, repair, or maintain your equipment.

According to Peterhrompo and Parlikad, 2019, the management of the life cycle in multi-asset systems requires a thorough understanding of the relationships between assets and performance measures in order to guarantee optimal system reliability. Performance monitoring tools, including condition-based monitoring systems, are essential to this process since they offer up-to-date information on asset health.

AM follows a lifecycle-based approach that incorporates various phases such as design, acquisition, operation, maintenance, and disposal. Each phase involves data-driven decision making, ensuring that assets are used efficiently while minimising costs. Key considerations in lifecycle asset management include:

- Investment Planning: Aligning capital expenditures with long-term business strategies.
- Condition Monitoring: Employing advanced techniques such as ultrasonic lubrication analysis and thermal imaging to assess asset health.
- Predictive Maintenance: Using historical and real-time data to anticipate failures before they occur.

- Decommissioning and Sustainability: Implement environmentally responsible disposal or repurposing strategies.

2.1.1.3 The Role of Digitalisation in Asset Management

Asset management has been profoundly impacted by Industry 4.0, which has integrated digital twin technologies, AI-powered analytics, and Internet of Things-enabled monitoring into systems. IBM Maximo and other enterprise asset management solutions facilitate automated work orders, real-time asset tracking, and predictive maintenance plans, all of which increase the accuracy of decision-making. By facilitating effective data collecting, analysis, and decision-making, digitalisation is revolutionising asset management. Cutting-edge technologies like IoT, machine learning, and big data analytics are being included to improve predictive capacities and optimise systems.

Digital Asset Management solutions are enhancing operational efficiency, reducing maintenance costs, and improving asset reliability in businesses. Research on lubrication management integration into digital frameworks is growing due to automated lubrication systems and sensor-based monitoring. Digitalisation in multi-asset systems allows for a holistic view of system performance and effective decision-making, especially in industries where asset reliability is crucial for operational success (Peterhrompo and Parlikad, 2019).

2.1.2 Maintenance Types

In order to ensure that industrial systems run effectively, safely, and dependably, maintenance strategies are a crucial part of asset management. According to EN 13306, European Committee for Standardization, 2017, maintenance is the sum of all management, administrative, and technical efforts made to keep an asset in or return it to a functional state. Cost-effectiveness factors, asset criticality, and operational requirements all play a role in choosing the best maintenance plan, and the different maintenance strategies can be seen below in 2.1.

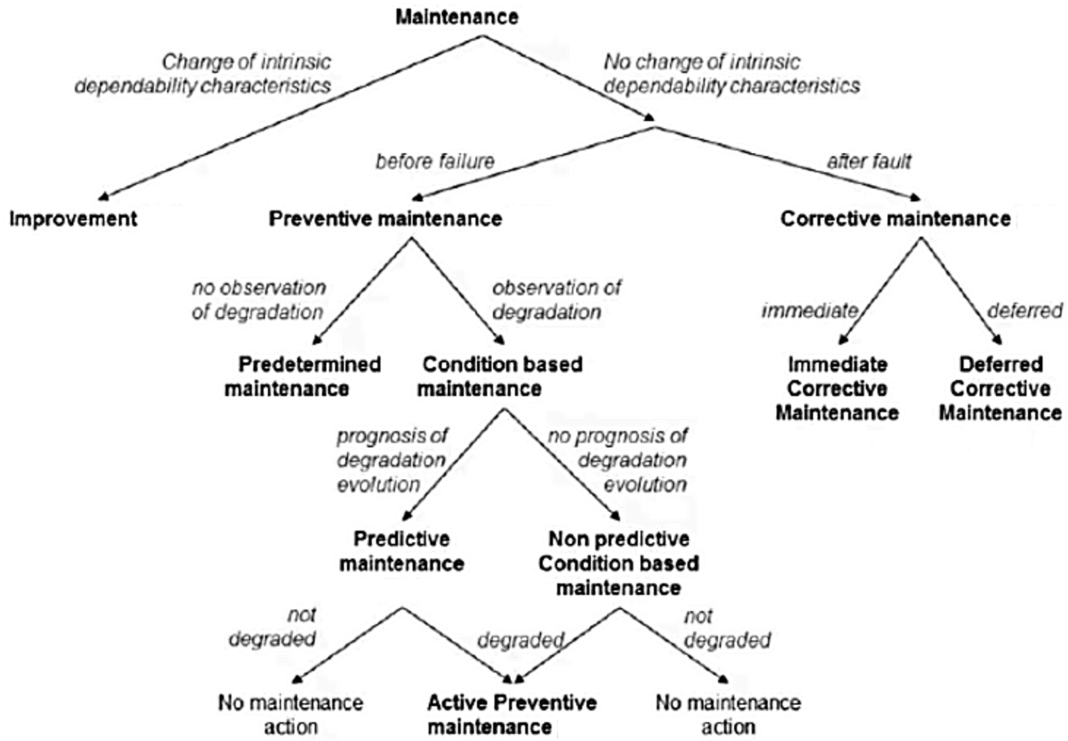


Figure 2.1: Types of Maintenance adapted from EN 13306 (European Committee for Standardization, 2017)

2.1.2.1 Corrective Maintenance

According to EN 13306, Corrective Maintenance is maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function (European Committee for Standardization, 2017).

In Corrective Maintenance (CM), the component is operated until it fails which leads to addressing asset failures as they occur. When that happens the component can either be repaired or replaced. This approach is generally adopted for non-critical equipment where the cost of failure is minimal. However, excessive reliance on corrective maintenance can lead to increased downtime, higher repair costs, and reduced asset lifespan (Trojan and Marçal, 2017).

2.1.2.2 Preventive Maintenance

According to EN 13306, Preventive Maintenance is maintenance carried out intended to assess and/or to mitigate degradation and reduce the probability of failure of an item (European Committee for Standardization, 2017).

Preventive maintenance (PM) involves scheduled inspections, maintenance and replacements based on time or usage intervals, either given by equipment manufacturers or based on the experience of the network operator. It is one of the most widely implemented strategies that aims to reduce unexpected failures and extend the life of the asset. While PM reduces the likelihood of breakdowns, it can lead to unnecessary maintenance actions if scheduling is not optimised through data-driven insights. Depending on the length of the intervals it combines an acceptable availability with comparably high maintenance costs (Trojan and Marçal, 2017).

2.1.2.3 Condition-Based Maintenance

According to EN 13306, Condition-Based Maintenance is a Conservative physical condition monitoring and/or assessment which include analysis and diagnosis to determine whether an item will fail during some future period; may be carried out according to a schedule or request for continuous monitoring (European Committee for Standardization, 2017).

Condition-Based maintenance (CBM) is based on the actual operating condition of equipment, rather than fixed time intervals. This approach enables more efficient maintenance planning, reduces unnecessary interventions, and contributes to improved asset availability and cost control.

Within CBM, it is important to distinguish between two main approaches:

- Non-predictive CBM involves reactive responses to real-time condition indicators. Maintenance is triggered when certain thresholds are reached, such as increased vibration levels, abnormal temperatures, or degraded lubricant quality. While effective in preventing imminent failures, this approach does not necessarily anticipate trends or forecast the remaining useful life of components.

- Predictive CBM, often referred to as predictive maintenance, incorporates trend analysis, historical data, and advanced analytics to estimate when a failure is likely to occur in the future. This allows maintenance teams to intervene proactively, optimising resources and avoiding unplanned downtime. Predictive CBM typically relies on continuous data acquisition and integration with digital systems, making it a key enabler of Industry 4.0 strategies.

Technologies such as ultrasonic lubrication monitoring, vibration analysis, and infrared thermography support both forms of CBM. However, when these tools are integrated into digital platforms with real-time monitoring and automated alerts, they significantly enhance the predictive capabilities of the maintenance function.

In lubrication management, this distinction is particularly relevant. Both over-lubrication and under-lubrication can have serious consequences on equipment performance and lifespan. Predictive CBM provides the means to make data-driven decisions, reduce lubricant-related failures, and ensure a more reliable and sustainable maintenance strategy.

2.1.2.4 Predictive Maintenance

According to EN 13306, Predictive Maintenance is a type of condition-based maintenance carried out following forecast derived from repeated analysis or known characteristics and evaluation of significant parameters degradation (European Committee for Standardization, 2017).

Predictive Maintenance (PdM) builds upon CBM by employing machine learning algorithms and historical data analysis to forecast potential failures. With the rise of Industry 4.0, IoT-enabled sensors and AI-driven analytics have facilitated the widespread adoption of PdM in industrial settings, reducing maintenance costs while maximising equipment availability (Trojan and Marçal, 2017). This is the most advanced Maintenance Type employed in an industrial setting.

Predictive maintenance is based on a combination of advanced technologies that monitor the status of industrial assets in real time. Among the most relevant are IoT sensors, which are responsible for continuously collecting data such as temperature, vibration, pressure, and electrical current. These sensors feed analysis systems based on artificial intelligence and machine learning that identify anomalous patterns and predict failures based on operational histories. Cloud computing and edge computing facilitate decentralised processing and the integration of this data into centralised asset management platforms. In addition, specific techniques such as vibration analysis, thermography and ultrasound analysis are fundamental for the early diagnosis of mechanical and electrical faults. These tools, together with predictive models and digital twins, form the technological basis of a robust predictive maintenance strategy, as described in the technological approaches of IBM Corporation, n.d. and SAP SE, n.d.

2.1.3 Economical and Technical Factors in Asset Management

In order to evaluate the effectiveness of asset management, it is necessary to analyse technical and economic factors. On the one hand, technical factors analyse the reliability, safety and durability of assets. On the other hand, economic factors support decision-making based on cost efficiency, Return on Investment (ROI), and long-term sustainability. This section explores these concepts from both dimensions.

According to EN 13306, European Committee for Standardization, 2017, some of these factors include:

- Life cycle cost: All the costs generated during the life cycle of the item. For a user or an owner of an item, the total life cycle cost may include only those costs pertaining to acquisition, operation, maintenance, and disposal.

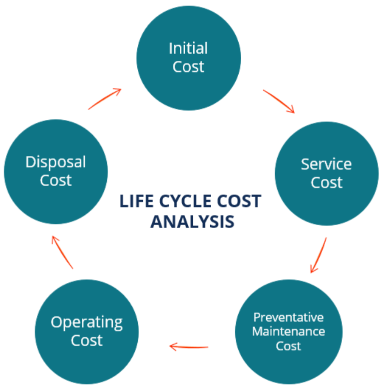


Figure 2.2: Life Cycle Cost Analysis

- Mean Operating Time Between Failures (MOTBF): Average of the operating times between failures. In the field of reliability, mean operating time between failures is defined as the mathematical expectation of the operating time between two failures. This term is applied to reparable items and doesn't include the stop time, seen in Equation 2.1.

$$MOTBF = \frac{TotalWorkingTime - TotalBreakdownTime}{NumberofBreakdowns} \tag{2.1}$$

- Mean Time Between Failures (MTBF): Average of the times between failures. In the field of reliability, mean time between failures is defined as the mathematical expectation of the time between failures. The equation to calculate MTBF is Equation 2.2. The difference between these two concepts is that MOTBF doesn't consider the stop time and MTBF does, and are both applied to repairable items.

$$MTBF = \frac{TotalWorkingTime}{NumberofBreakdowns} \tag{2.2}$$

- Mean Time To Failure (MTTF): Average of the operating time of an item, from the instant it is put in an up state, until failure or, from the instant of restoration until the next failure. It is applied to non-repairable items.

- Mean Repair Time (MRT): Average of the repair times.

- Mean Time To Restoration (MTTR): Average of the times to restoration.

2.2 Fundamentals of Lubrication and Tribology

The maintenance task of lubrication is one of the most important one in an industrial setting. It aims to ensure the reduction of friction, wear, and energy dissipation while enhancing the overall efficiency and life expectancy of the assets. Despite its critical role, traditional lubrication practices often rely on fixed schedules rather than real-time asset condition monitoring, leading to inefficiencies such as overlubrication or underlubrication, lubricant degradation, and accelerated component wear.

The word tribology consists of two terms; classic Greek *"tribo"* meaning rubbing and the suffix *"logy"* for "the knowledge of", so tribology is the study of friction, wear, and lubrication, is a multidisciplinary field that plays a critical role in optimising mechanical efficiency, and Figure 2.3 represents an illustration of the Tribology Triangle. The primary objective of lubrication is to create a protective film between interacting surfaces, minimising direct contact and mitigating wear mechanisms such as adhesive, abrasive, and fatigue wear (Roy, 2021).

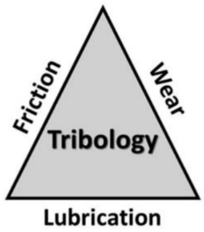


Figure 2.3: Tribology Triangle (Roy, 2021)

It is also important to understand the concepts mentioned in the figure above, to better comprehend what will follow. So, according to Roy, 2021:

- **Friction:** is a natural phenomenon crucial in daily life and tribology studies, often causing wear and energy loss in moving systems. Originating from Latin and French terms meaning "to rub," friction has been described since the 17th century as resistance to motion. There are two types: static friction, which prevents motion between solid surfaces, and kinetic friction, which occurs during motion. Both types are quantified by the force generated between surfaces opposing movement.

- **Wear:** is a key cause of material wastage and surface deterioration, can lead to component failure. Originating in the 13th century to describe clothing degradation, wear in tribology involves material deformation or removal due to mechanical and chemical actions. Defined as the progressive loss of substance from a surface due to relative motion, wear includes various types like adhesive, fatigue, impact, fretting, erosion, and corrosion. Despite its negative aspects, wear has useful applications in surface production and finishing. Tribology, the study of friction, wear, and lubrication, has evolved significantly over centuries to manage these phenomena.

- **Lubrication:** is derived from the Latin word *"lubricatus"*, is used to reduce friction and control wear in tribo-systems. It involves substances that alter surface interactions, including liquids, greases, solids, and gases. Lubrication regimes, discussed in more detail in Appendix B, are categorised into boundary, mixed, and fluid lubrication, with viscosity being a key property. Various types of lubrication, such as solid lubrication and air/gas lubrication, are used in different applications to minimize friction, wear, and surface adhesion, ultimately preventing system failures.

2.2.1 What is a Lubricant?

A lubricant is a substance introduced between moving surfaces to reduce friction, wear, and surface adhesion, and to control temperature. Lubricants can be solids, liquids, solid-liquid mixtures, or gases, each with unique properties. They form a film between surfaces, altering friction and wear characteristics. While commonly known as oils or greases, lubricants can include materials like graphite or air. Their performance, known as lubricity, is influenced by various physical, chemical, and mechanical properties. In some applications, lubricants can also affect processes like metal cutting or wire-drawing by influencing chip formation or surface finish (Roy, 2021).

Lubricants are typically composed of a base oil, which can be mineral, synthetic or biological, and additives. Additives serve to improve the properties of the lubricant and are divided into three main groups: surface protection additives, performance additives and lubricant protection additives. It is also important to note that, over the life cycle of the lubricant, the additives are consumed, causing the lubricant to lose the properties they conferred on it (Roy, 2021).

According to Roy, 2021, it is also important to bear in mind that mixing base oils with different additives confers very important properties on lubricants, which are then essential for determining the most suitable lubricant for each application. Some of the most important properties are described in Appendix B.

2.2.2 Lubricant Life Cycle

Lubricant life cycle management is a strategic process that is essential for ensuring the reliability of industrial assets, optimising operational performance and promoting environmental sustainability. This cycle begins with the careful selection and purchase of lubricants, taking into account factors such as equipment type, load conditions, temperature and material compatibility. Upon receipt, products must be stored properly, protected from contamination, temperature variations and humidity. Application to equipment also requires good practices, ensuring clean tools and correct transfer to avoid cross-contamination. During use, it is essential to monitor the condition of the lubricant through periodic analyses, evaluating parameters such as viscosity, contamination by particles or water, oxidative degradation and loss of additives. This data allows for the early identification of faults and determination of the ideal time for oil replacement or reuse. The cycle ends with the proper removal of used lubricant, following environmentally responsible disposal practices or, preferably, regeneration and recycling.

Factors such as operating temperature, exposure to contaminants, load conditions, type of additives, and storage quality directly influence the durability of the lubricant. A systematic and controlled approach to all these steps contributes to extending the service life of the lubricant and reducing premature equipment failures. This philosophy, known as lubricant life cycle management, is at the heart of good predictive maintenance and industrial reliability practices (Troyer, 2007).

2.2.3 Contamination

According to Bednarz, 2024, lubricant contamination is one of the main causes of premature failure in mechanical systems and accelerated degradation of the lubricants themselves. Effective contamination control is therefore a central element in industrial lubrication management. The presence of contaminants can compromise lubricant performance, interfere with lubricant film formation, significantly increase wear on metal surfaces, accelerate chemical reactions such as oxidation, and contribute to the formation of undesirable deposits such as varnishes and sludge.

Contamination can occur at any stage of the lubricant's life cycle, from production, transport, storage and application to in-service operation. Among the most common mechanisms are seal failures, air or water contamination, incorrect product handling and lack of proper cleaning practices during lubricant replacement.

Contaminants can be grouped into three main categories: solids, liquids and gases. Solid contaminants include abrasive particles such as dust, metal wear debris and fibres from damaged filters or industrial environments. Liquid contaminants mainly include water, which may be present due to condensation or external leaks, as well as fuels and coolants that accidentally mix with the lubricant. The presence of gases such as air or oxygen can also be harmful, as it promotes degradation reactions, especially oxidation, and can cause cavitation under certain pressure and temperature conditions.

To mitigate these risks, the recommended approach is based on three pillars: exclusion, removal and monitoring. Exclusion refers to preventing contaminants from entering, which involves good storage practices, sealing systems and using controlled lubricant transfer procedures. Removal is achieved through effective filtration systems, water separators, drainers and other devices dedicated to cleaning the oil in service. Finally, continuous monitoring through oil analysis is essential to identify early contamination, define corrective strategies and extend the service life of both the lubricant and the assets where it operates.

The systematic adoption of contamination control measures is therefore essential to ensure the reliability and longevity of industrial equipment, as well as being an economically advantageous practice in line with the principles of predictive maintenance and sustainable asset management.

2.2.4 Lubricant Storage

Proper storage of lubricants is essential to preserve their chemical and physical integrity, ensuring effective lubrication and extending the service life of industrial equipment. Improper storage practices can lead to contamination, premature degradation, and operational failures.

Ideally, lubricants should be stored indoors in clean, dry, temperature-controlled environments, seen in Figure 2.4. Temperature fluctuations can cause condensation inside containers, promoting moisture ingress and accelerating oxidation processes. Exposure to direct sunlight should be avoided, as it can degrade the additives present in lubricants. If outdoor storage is unavoidable, it is recommended to protect the containers with waterproof covers and position the drums horizontally, with the closures at the 3 and 9 o'clock positions, to minimise water ingress and drum 'breathing' (Machinery Lubrication, n.d.).

Figure 2.4: Lubricant Storage Room (Machinery Lubrication, n.d.)

Clear and accurate identification of lubricants is essential to prevent cross-contamination. Colour and shape coding systems, applied to both containers, seen in Figure 2.5, and application equipment, facilitate the distinction between different types of lubricants and reduce the risk of errors. In addition, it is crucial to use dedicated transfer equipment for each type of lubricant, such as pumps and filter carts, ensuring that incompatible products are not mixed (Machinery Lubrication, n.d.).

Figure 2.5: Colour coded recipients (Machinery Lubrication, n.d.)

Inventory management should follow the principle of 'first in, first out' (FIFO), ensuring that older lubricants are used before newer ones, avoiding the use of expired products. Regular inspections of containers and storage areas are recommended to identify signs of deterioration, such as corrosion, leaks, or contamination. Implementing these practices significantly contributes to maintaining the quality of lubricants and the reliability of industrial systems (Machinery Lubrication, n.d.).

2.2.4.1 5S Methodology

The implementation of the 5S methodology is a systematic and effective approach to the organisation and management of a lubricant warehouse, aligned with the principles of operational efficiency and preventive industrial maintenance. This Japanese methodology, originally developed in the context of lean production, aims to create clean, safe, and orderly work environments through five sequential steps, shown in Figure 2.6: Seiri (sense of use), Seiton (sense of organisation), Seiso (sense of cleanliness), Seiketsu (sense of standardisation), and Shitsuke (sense of discipline).

Figure 2.6: 5S Methodology (Lean Production, n.d.)

In the context of lubricant storage, Seiri allows you to identify and eliminate unnecessary materials that could compromise safety or cause confusion in the use of products. Seiton ensures the logical and identifiable arrangement of each lubricant, reducing the risk of cross-contamination and facilitating traceability. Seiso focusses on the regular cleaning of facilities and handling equipment, an essential factor in preventing the introduction of contaminants. Standardisation (Seiketsu) ensures the maintenance of good practices through clear procedures, standardised labels, and inspection routines. Finally, Shitsuke promotes organisational discipline by encouraging continuous employee training and a culture of constant improvement. The application of 5S not only contributes to the integrity of the stored lubricants, but also reinforces the reliability of the industrial maintenance system as a whole (Lean Production, n.d.).

2.3 Emerging Technologies in Lubrication Monitoring and Automation

Due to the rise of Industry 4.0, lubrication management is undergoing a paradigm shift, integrating sensor technologies, automation and AI-driven analytics to enable condition-based and predictive lubrication strategies. These developments not only optimise lubricant application and reduce human error, but also align lubrication practices with broader asset management frameworks, contributing to enhanced operational reliability.

However, instead of concentrating on high-tech solutions, the digitalisation of maintenance activities should also emphasize real-world applications. Digitalisation can be further accelerated by also utilising current resources and implementing low-cost digital initiatives. While rules and goals culture might hinder digital culture, people-oriented culture is the most conducive to it.

Understanding the corporate context, identifying issues through workshops and interviews, and talking about how data and digital technology may help with these issues are all steps in the process (Grooss, 2024).

2.3.1 Vibration and Oil Analysis

According to Lima Pereira and Anjos Rito, 2020, a range of methods are used in modern predictive maintenance to keep an eye on the state of industrial machinery. Vibration analysis and oil analysis are two of the best; when combined, they offer a thorough understanding of asset health, and are the first ones that can be detected in order to prevent failure early on, as seen in the Potential Failure Curve in Figure 2.7.

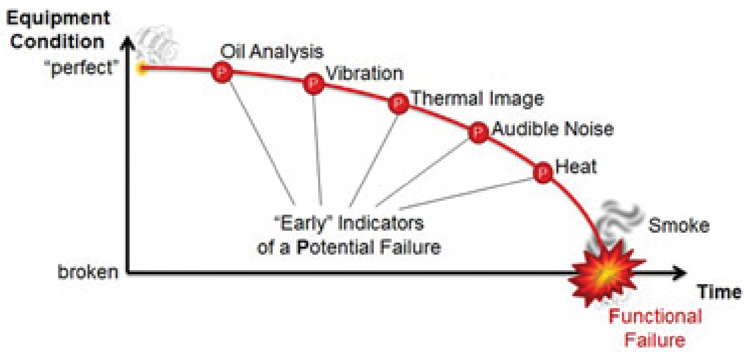


Figure 2.7: Potential Failure Curve (Lima Pereira and Anjos Rito, 2020)

Vibration analysis is widely recognised as one of the best ways to detect faults in rotating machinery such as electric motors, pumps, gearboxes, fans, generators, compressors and turbines. This technique allows you to identify imbalances, misalignments, mechanical clearances, defects in bearings and gears, cavitation and lubrication problems. In addition, in more advanced applications, it is possible to identify resonances in static structures.

Vibration analysis uses tools such as Fast Fourier Transform (FFT), envelope analysis and spectral analysis to diagnose specific faults. A common symptom is an increase in the 'spectral carpet', indicating lubrication faults due to the absence, excess or contamination of the lubricant. In addition, phenomena such as 'oil vortex' or 'dry vortex' can be detected in vibration analysis. These often occur in high-pressure oil slide bearings and can accelerate shaft wear. Oil instability, when it coincides with the critical speed of the machine, can lead to a destructive condition known as 'oil whip', where the vortex remains even at higher speeds.

Oil analysis is an essential technique for assessing the condition of lubricants in service and identifying contamination, component wear and oil degradation. It allows the detection of metal particles, water, viscosity variations and other contaminants that can compromise equipment performance. This technique is particularly effective in the early detection of faults in bearings and gears, often before any significant increase in vibrations. For example, the presence of iron particles in the oil may indicate wear in gears, allowing corrective action to be taken before catastrophic failures occur.

In addition, oil analysis can identify problems such as lubricant degradation, contamination by water or solid particles, and changes in oil acidity, which may indicate oxidation or contamination processes.

2.3.2 Ultrasound Equipment

According to Dempsey, n.d. bearing lubrication is traditionally done on a set schedule; for instance, the technician applies lubricant using a grease gun every "X" months. This strategy's primary goal is to prevent under lubrication, it is a Preventive Maintenance approach, which can be lethal and result in equipment breakdowns, expensive repairs, unplanned downtime, and a subsequent loss of output and revenue. However, there are serious hazards associated with using time-based lubrication alone, or even in conjunction with basic temperature readings, to determine the level of lubrication. One such risk is over-lubrication, which can be just as detrimental as under-lubrication. This time-based approach can be misleading, as it assumes that all bearings behave the same over time, which is rarely true in dynamic industrial environments.

As mentioned previously, when the actual condition of the equipment is not taken into account, the two main risks are: under-lubrication, which can lead to premature wear of components, and over-lubrication, which can cause an increase in temperature and internal bearing pressure, leading to lubricant degradation and, eventually, component failure. Both cases can result in serious problems like the ones mentioned above, and loss of production and revenue. Thus, relying solely on schedule-based lubrication (even if supplemented with basic temperature readings) can ultimately seriously compromise equipment reliability.

With the use of ultrasound technology, professionals may now combine predictive maintenance based on the equipment's actual state with more conventional time-based maintenance procedures. Typically inaudible to the human ear, ultrasonic impulses are detected by ultrasound equipment both in the air and conveyed through the building. Decibels (dB) are shown on a control panel after these signals are electronically transformed into noises that the technician can hear through headphones. The state of the bearing can be more easily interpreted thanks to some sophisticated devices that also enable spectrum analysis of the sound that is received. A skilled technician can therefore determine whether or not intervention is required by precisely evaluating the bearing's condition.

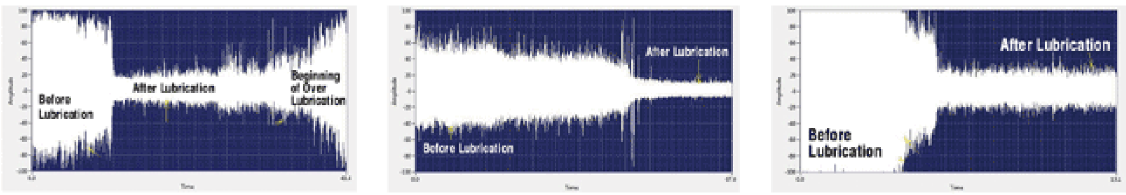
According to Dempsey, n.d. ultrasonic technology has several key advantages for industrial lubrication:

- It can be used in virtually any environment, regardless of adverse environmental conditions.
- Its use is relatively simple to learn and implement.
- The cost of the equipment is affordable, making it a viable option for many facilities.

- Modern equipment allows for the storage of historical data and the monitoring of trends over time, facilitating robust predictive analysis.
- The technology has proven to be highly reliable in predictive maintenance, saving thousands of dollars and hours of lost production.

Just as vibration allows us to "feel" what is not perceptible to the touch and infrared cameras "see" what is hidden from the human eye, ultrasound "hears" what is inaudible in the typical background noise of factories. This is especially important because relevant sounds such as compressed air leaks or electrical discharges can be masked by ambient noise.

One of the most valuable aspects of ultrasonic technology is its ability to provide a localised signal. When the probe is applied to a specific bearing, the signal received is not interfered with by signals from adjacent components, allowing each bearing to be monitored individually. Similar to medical ultrasound, which identifies exactly which artery is blocked, ultrasonic technology can identify the precise condition of each component.



This image shows what happens when too much lubricant is applied. Notice the increase in amplitude or the noise level when lubricant continues to be applied.

This is another time series view of a recorded ultrasound from a bearing in the process of being lubricated.

The image above is a time series view of a recorded ultrasound from a bearing in the process of being lubricated. Notice the before noise or amplitude at the beginning and then once the bearing was properly lubricated at the end.

Figure 2.8: Visual Representation of Using the Ultrasound Equipment during Lubrication (Dempsey, n.d.)

The process begins by establishing a baseline of decibel levels and sound samples during an initial round, comparing similar bearings to easily identify anomalies. The technician can then track the trends of these values over time. A rule of thumb for lubrication is that if the sound amplitude of a bearing exceeds 8 dB without a change in sound quality, it is indicative of the need for lubrication. To avoid over lubrication, the technician should apply the lubricant in small amounts, observing the gradual reduction in the dB level until the reference value is reached again.

In addition to optimising lubrication, the use of ultrasound generates a history of valuable data, which can be used to adjust lubrication plans, identify potential savings in working hours and lubricant quantities, and verify whether the manufacturer's recommendations on lubricant volumes are appropriate. This contributes not only to cost reduction but also to increased operational reliability. Finally, although ultrasonic technology does not solve all reliability problems, it has proven to be a powerful and indispensable diagnostic tool for lubrication technicians.

2.3.3 Automatic Lubrication Systems

For industrial equipment to operate well and last a long time, proper lubrication is crucial. This work is often completed by hand, which increases the risk of operational hazards and discrepancies. An efficient way to provide precise and continuous lubrication without requiring continual human involvement is through automatic lubrication systems.

According to MechLesson, 2023, automatic lubrication systems, also known as centralised lubrication systems, are mechanical devices designed to supply regulated amounts of lubricant to the lubrication points of a machine while it is in operation. They consist of a reservoir with a pump, supply lines, metering valves and injectors, and are often integrated with control systems, seen in Figure 2.9. This configuration ensures efficient and continuous distribution of lubricant, significantly reducing wear and friction on moving parts. These systems are used in a wide range of industrial applications, including the automotive, food, mining, steel, printing and heavy machinery sectors. Depending on the application, the lubricant can be oil or grease, with the choice determined by the operational characteristics of the equipment.

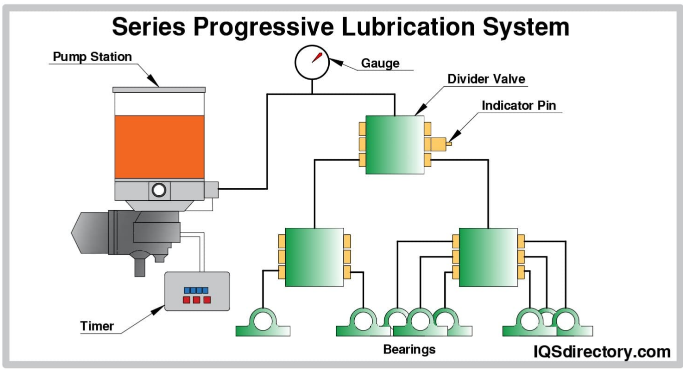


Figure 2.9: Automatic Lubrication System (Mavink, 2025)

The operation is based on an integrated system of components: the controller activates the pump, which in turn transfers the lubricant from the reservoir to the main line. Through metering valves, the lubricant is distributed in a measured manner to the end points via secondary lines. This architecture allows multiple points to be lubricated simultaneously, ensuring consistency and minimising human errors associated with manual lubrication.

In functional terms, the systems can be classified into different types, such as single line systems, progressive systems and parallel systems. Each configuration has particularities in the way the lubricant is directed and quantified, and is chosen according to the specific requirements of the process or machine. There is also the possibility for single point lubricators, for certain applications.

These systems stand out for their effectiveness, extending the service life of components, reducing downtime for maintenance and contributing to the operational reliability of equipment. However, their implementation requires specific care, particularly in calibration and maintenance, to avoid over-lubrication situations that can compromise system performance and cause unwanted environmental impacts.

2.3.4 Enterprise Asset Management (EAM) Solutions - IBM Maximo

Enterprise Asset Management (EAM) refers to the systematic management and maintenance of an organisation's physical assets throughout their entire lifecycle. This process covers everything from capital planning, acquisition, installation, operation, maintenance, compliance and risk management to the decommissioning or replacement of assets (SAP, 2025).

The main objective of EAM is to optimise the quality and utilisation of assets, increasing productive uptime and reducing operating costs. To achieve this, EAM integrates software, systems, and services that enable the planning, optimisation, execution, and monitoring of necessary asset-related activities, including priorities, competencies, materials, tools, and associated information (IBM, 2025).

With the advancement of technology, EAM systems have evolved from locally installed solutions to cloud-based platforms. This provides benefits such as increased data storage capacity, enhanced security, and easier integration with complementary applications such as supply chain management systems, mobile workforce management, Internet of Things (IoT) sensors, geographic information systems (GIS), and GPS (SAP, 2025).

In addition, the incorporation of advanced analytics and artificial intelligence (AI) allows data collected from instrumented assets to be analysed to provide insights that help maintenance teams make more informed decisions, improve efficiency, perform preventive maintenance, and maximise investments in physical assets (IBM, 2025).

IBM Maximo Asset Management is a robust Enterprise Asset Management (EAM) platform designed to help organisations monitor, manage and maintain a wide range of physical assets. According to Webuild IT Services, Maximo offers an integrated solution that enables companies to efficiently manage assets in sectors such as energy, transport, industrial production and facilities. The platform provides advanced features for maintenance planning, work order management, inventory and purchasing, promoting more reliable, secure and sustainable operations. In addition, Maximo is highly scalable and can be customised to meet the specific needs of each organisation, making it a proven choice for companies seeking to optimise the use and lifecycle of their physical assets (Webuild IT Services, 2025).

2.3.5 Route Optimisation and GPS Applications in Lubrication

Route optimisation and the use of GPS technology are essential components of the digitalisation of industrial maintenance, with direct application in the lubrication function in manufacturing environments. In a context where technicians need to cover large areas to perform tasks on different assets (such as engines, bearings, gearboxes or hydraulic systems), it is essential to plan these trips efficiently, minimising time, costs and physical effort.

Tools such as OptimoRoute, for example, allow you to create optimised sequences of interventions based on criteria such as asset location, priority, production availability and estimated operating time. The application of optimisation algorithms reduces travel time, avoids redundant routes and ensures complete coverage of lubrication points. For example, the use of planned routes avoids omissions and improves the performance of the maintenance team (OptimoRoute, n.d.).

In addition, IBM Maximo Maps takes this concept further by integrating geospatial functionality directly into the asset management system. This functionality, allows all factory assets to be viewed on an interactive map, with their exact location and real-time operational data. In the case of lubrication, the technician could view the points that need intervention directly on the map, the most efficient route between them, and receive detailed instructions on their mobile device, based on their GPS location (Webuild IT Services, 2025).

Integration with Maximo Mobile also allows the system to automatically update the technician's position and reorder the sequence of tasks in real time if a priority, failure or lack of access arises. This type of adaptability is critical in dynamic industrial environments, where production conditions can change rapidly (Esri, n.d.).

These systems not only enable better operational efficiency, but also contribute to safety (by avoiding risk areas) and full traceability of interventions, since all movements and actions are recorded by georeferencing.

2.3.6 Voice Control

The introduction of voice control in industrial maintenance operations has been gaining prominence as a technology supporting the digitalisation of the lubrication function. This innovation allows technicians to perform manual tasks, such as inspecting and lubricating equipment, while interacting with computer systems via voice commands, without having to interrupt their work to operate mobile devices or fixed terminals. This represents a significant improvement in terms of ergonomics, safety and operational efficiency.

In the context of industrial asset maintenance, voice control can be integrated with Enterprise Asset Management (EAM) platforms, such as IBM Maximo, allowing technicians to consult work orders, record interventions, consult maintenance histories or check lubrication routes in real time through simple verbal commands.

According to IBM, n.d. the application of voice technologies speeds up workflows and reduces human error associated with manual data entry, contributing to more consistent and reliable operations. Furthermore, in scenarios where safety is critical voice control allows the operator to remain fully focused on physical tasks, minimising distractions. AI-powered virtual assistants and voice interfaces can enhance platforms like IBM Maximo by enabling real-time, hands-free interaction, increasing technician autonomy and reducing reliance on physical devices.

Industrial maintenance activities, particularly the lubrication function, have been revolutionised by the use of aided reality devices like the RealWear Navigator 520, seen in Figure 2.10. With it, technicians can carry out manual activities and communicate with asset management systems using voice commands, freeing up their hands for useful work. It provides a clear view of technical texts, schematics, and real-time sensor data—even in noisy industrial settings. This technology helps to boost worker safety, decrease errors, and improve operational efficiency (RealWear, n.d.).

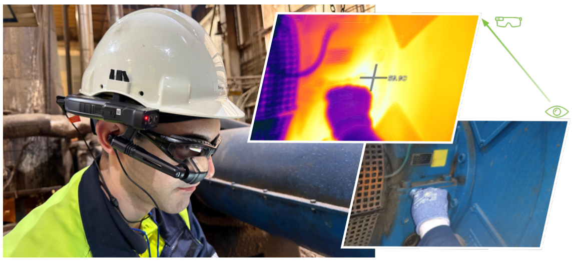


Figure 2.10: RealWear Navigator 520

2.3.7 Sensors

According to Redlist, 2023, the integration of sensors in the context of lubrication digitalisation represents a significant advance in predictive maintenance and efficient industrial asset management. The application of the Internet of Things (IoT) allows sensors to be incorporated into lubrication systems and equipment, enabling continuous monitoring of critical parameters such as vibration, temperature, pressure and velocity. These sensors transmit real-time data to central systems, where it is analysed to provide actionable insights that optimise lubrication practices and anticipate maintenance needs.

The real-time monitoring provided by IoT sensors offers substantial benefits, including the prevention of over-lubrication or under-lubrication, reduced equipment downtime and improved operational safety. By providing accurate and up-to-date data on machine operating conditions, immediate adjustments can be made to lubrication processes, ensuring optimal equipment performance and extending its service life.

In addition, advanced analysis of the data collected by sensors enables the implementation of predictive maintenance strategies. It is possible to predict potential failures and schedule maintenance interventions only when necessary, avoiding unexpected downtime and optimising available resources.

Chapter 3

Current State Analysis

3.1 Company and Factory Overview

Sonae Arauco is one of the largest wood-based solutions companies in the world. This company was born out of the merger of two brands of wood-based products: Sonae Indústria and Arauco. It is a company that currently has several industrial units, including the Mangualde factory, which specialises in the production of Medium-Density Fiberboard (MDF). A more detailed presentation on Sonae Arauco can be found in Appendix C.

3.1.1 Overview of the Production Process

The Sonae Arauco industrial unit, Figure 3.1, located in Água Levada, in the municipality of Mangualde, district of Viseu, is where the current dissertation was carried out. Built in 1988, this complex occupies 27 hectares, of which 9 hectares are set aside as an industrial zone and 3.6 hectares are used for covered production areas. The Mangualde facility is specialised in producing electricity, paraffin emulsion, and medium-density fiberboard (MDF). Currently, this unit has about 183 employees.

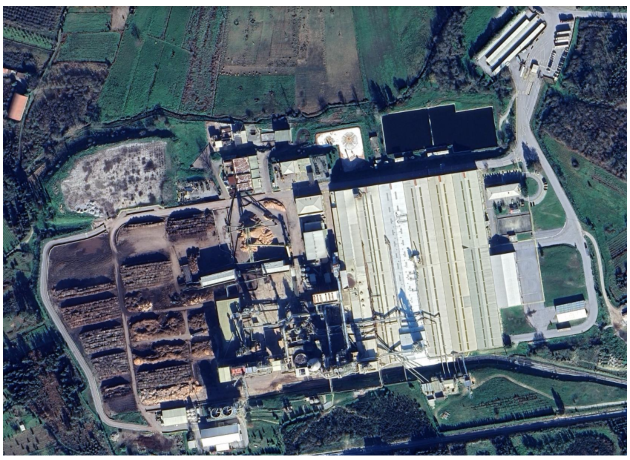


Figure 3.1: Sonae Arauco Mangualde Unit Top View

3.1.1.1 MDF Production Process at the Mangualde Facility

At the Mangualde unit, MDF is produced using a methodical process that transforms different kinds of wood (such slabs, logs, and wood chips) into sturdy, rigid boards that may be sliced, painted, milled, sanded, and covered with paper, PVC, wood veneer, or other surface treatments. There are eleven essential steps in this production process, that can be observed in figure 3.2:

1. **Screening:** The raw wood material is sorted to remove unwanted particles.
2. **Chip Washing:** Foreign particles such as sand and stones are eliminated.
3. **Chip Cooking:** The wood chips are softened under controlled pressure and temperature.
4. **Defibration:** The softened chips are mechanically refined into high-quality wood fibers.
5. **Resin Application:** The fibers are mixed with resin and wax to enhance bonding properties.
6. **Drying:** The fiber mixture is dried to achieve optimal moisture content.
7. **Mat Formation:** The dried fibers are evenly distributed to create a uniform mat.
8. **Pressing:** The mat undergoes high pressure and temperature to form rigid MDF panels.
9. **Sanding:** The panels are sanded to ensure a smooth, even surface.
10. **Cutting:** The MDF panels are trimmed into the required dimensions.
11. **Packaging:** The final products are packaged for distribution.

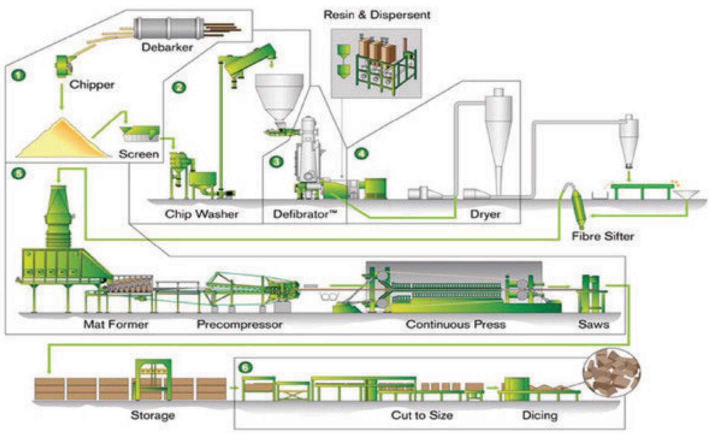


Figure 3.2: Production Process of MDF

The Mangualde facility also includes a semi-finished storage area where panels await quality validation before proceeding to the finishing lines. In addition, a second choice storage warehouse holds finished panels that require further inspection due to potential quality deviations.

3.2 Lubrication Practices and Maintenance Context

At the Mangualde plant, as already mentioned, production is centred on MDF wood panels, of the various types available in Sonae Arauco's range of options. As is to be expected, in order to be able to produce these boards, it is necessary to have a factory that is properly equipped to do so, a factory that has thousands of assets on its lines. These assets include gearboxes, motors, bearings, hydraulic units and many others, most of which require correct and effective lubrication.

Lubrication is one of the pillars of maintenance and asset management and is often neglected. Although there is not always potential for savings in lubricant consumption, there is great potential for savings in lubricant-related maintenance costs (ranging from reduced downtime due to breakdowns to a much longer asset life).

Throughout this dissertation, the importance of lubrication will always be recognised as vital when it comes to effective asset management. Therefore, and based on the objectives set for this dissertation, we will analyse the current state of the Mangualde plant in this respect.

3.2.1 Current Lubrication Strategies and Workflows

As far as Sonae Arauco's current lubrication strategies are concerned, it is essential to mention BP, one of the company's largest lubricant suppliers. As well as supplying the products, the company offers an additional lubrication route management service called LubGest, as well as other services such as oil analysis and the possibility of providing training, which will be mentioned in more detail later.

This programme, LubGest, allows work plans to be issued and given to lubricators to carry out their tasks. The work plans were drawn up several years ago. In the meantime: assets have ceased to exist, others have been replaced, and new assets have come into existence. In addition to these changes in assets, there have also been some changes on the lubricants used. In other words, the work plans were created at the beginning and have not been altered according to the changes made to the plant.

In 2018, Sonae Arauco began implementing IBM Maximo software in all its plants, with the aim of centralising maintenance-related information. With this change came the need to migrate all maintenance-related information to IBM Maximo, namely the lubrication routes that were in LubGest. This data migration process has not yet been fully completed. Currently, the number of lubrication routes entered into Maximo is still small in relation to the total number of assets requiring lubrication in the plant. As a result, the routes are still scattered between LubGest and Maximo, and some are not even registered in either system. This leads to a lack of organisation and monitoring of asset lubrication.

As mentioned earlier, another problem identified is that the LubGest routes are not updated according to the changes made in the plant. As a result, there are cases in which lubricants that are no longer used keep appearing in the work plans, generating inconsistencies and confusion for the technicians. This can lead to using the wrong lubricant and forgetting to lubricate the equipment, both of which are very damaging to the life of the asset.

In addition to the limitations identified in the management and planning of lubrication, there are also challenges in the practical execution of the tasks. One of these difficulties is the result of an internal restructuring of the company, during which a mechanical technician was transferred to the role of lubricator without receiving adequate training. In addition to the lack of training, the period of supervision he had was very short given the complexity of the subject in question. This situation jeopardises the quality of lubrication and reinforces the need for a more efficient and up-to-date system for managing these activities.

In addition, it can be seen that the current lubrication policy is corrective and preventive (time-based). Lubrication always takes place in the same way, at predetermined intervals, always with the same amount of lubricant, regardless of the condition of the asset, apart from the exceptions where lubrication is corrective.

The standard maintenance policy at all Sonae Arauco plants is based on predictive maintenance, replacing the existing corrective and preventive approaches. In this context, the standards in force mainly emphasise the use of thermography, vibration analysis, ultrasound and lubricant analysis as key aspects to consider in this transition.

With regard to the use of the technologies mentioned above, there is currently a mechanical technician in charge of taking temperature measurements and analysing vibrations and the results of these analyses could indicate the need for lubrication, which was communicated to the lubricator. These analyses are carried out from a more general maintenance perspective and are not geared towards lubrication. There is no use of equipment that measures or analyses ultrasound. As far as oil analysis is concerned, during the annual shutdown, which usually takes place in August, oil samples are taken by the lubricators and sent to BP for them to analyse and send the report, as contracted.

In addition, something that would also be beneficial in terms of moving towards predictive maintenance would be the implementation of automatic lubrication in assets that warrant it, in order to ensure that they are well lubricated. Currently, there are very few places where this exists. Automatic lubrication, in addition to guaranteeing the proper and effective lubrication of assets, can also be essential in increasing the ability to carry out the lubrication plan and in improving safety for the lubricator (there are places with difficult and dangerous access that also require lubrication).

Allied to automatic lubrication, but not only, is sensorisation. The use of sensors is fundamental to predictive maintenance. Obtaining continuous data for analysis is what allows decisions to be made when it comes to this maintenance. Currently, Sonae Arauco has a contract with Preditec in which they are installing sensors in critical assets predetermined as relevant for this monitoring and analysing the data collected. This analysis is provided to Sonae Arauco as problems are identified. The implementation of this technology is being gradual throughout the group, with the Mangualde plant not yet equipped with this technology and, in principle, it will be the last plant in the group where sensors will be implemented, as there is already monitoring and analysis of temperatures and vibrations.

The aim of this dissertation is to implement the technologies needed to digitalise the lubrication function and, at the same time, to assess the plant's current level of maturity in terms of predictive maintenance. Only after carrying out this maturity assessment will it be possible to identify the areas that need to be improved in order to achieve the final objective.

Considering the company's current state, the main focal points of this dissertation will be:

- Ensuring good lubrication practices performed by the lubricator;
- Ultrasonically assisted lubrication;
- Automatic lubrication;
- Lubricant sampling;
- Mapping and optimisation of lubrication routes;
- The use of voice commands to support lubrication tasks.

3.3 Challenges and Opportunities for Improvement

By analysing the current state of maintenance strategies relating to lubrication at the Mangualde plant, it is possible to identify where the current challenges are in this area and the potential for improvement. This identification is based on current best practices recommended by experts in the field and the maintenance standards currently in force at the company itself.

3.3.1 Identified Inefficiencies and Limitations

As mentioned above in section 3.2.1, it is possible, through the current state of the company, to identify the limitations and shortcomings of the Sonae Arauco plant in Mangualde when it comes to lubrication. In the aforementioned section, good lubrication practices were explained in detail in conjunction with the current state of the plant, along with a brief explanation of the importance of each of the good practices.

In this section, the aim is to focus more objectively on the limitations and challenges of the act of lubrication and associated activities, in order to clearly identify the problem. These limitations will then be listed:

- Decentralisation of information on the lubrication plan: Lubrication work plans are scattered across the LubGest and IBM Maximo platforms; and fieldwork knowledge obtained by the lubricator.
- Lack of information and/or outdated information on lubrication: There are assets for which there are no lubrication work plans, just as there are assets whose plans are not up to date, and there are also plans for assets that no longer exist.

- Lack of training for the technician responsible for lubrication: Due to a restructuring in the company, responsibility for lubrication was passed on to a mechanical technician with no previous training in the subject.
- Adopting a preventive and/or corrective approach rather than a predictive approach to lubrication: Lubrication is carried out at predetermined time intervals and in predetermined quantities and is not based on the current condition of the equipment, nor on data that allows these two parameters to be adapted.
- Not using tools that enable a predictive approach to lubrication (such as ultrasound): Technicians do not have the knowledge to use these tools, nor are they actively encouraged to do so.
- Oil analyses concentrated in a short space of time, which makes it difficult to guarantee non-contamination: Oil analyses are normally carried out during the annual shutdown in August, unless there is a need at other times; the samples are taken by the lubricators, but the best conditions for collection and non-contamination of the samples are not guaranteed.
- Lack of conditions to prevent contamination of the greases used: The storage of greases and the refuelling of grease guns are not carried out in such a way as to guarantee non-contamination, due to a lack of conditions and equipment to do so.
- Lack of automatic lubrication systems: Some systems are already being used, but there are not enough of them to meet the needs of the factory.
- Lack of sensorisation throughout the plant: There are already plans to implement sensors in critical equipment, but they have not yet been realised.

3.3.2 Potential Areas for Technological Enhancement

For all the problems found and named above, it is possible to apply an improvement and solve them. The solutions can be simple changes in behaviour that can generate significant gains, or the adoption of technological improvements to the same end. The first step in implementing any improvement must be to assess the maturity for its adoption. Meaning, before implementing technological improvements, the foundations of good lubrication practices must first be secured.

Potential improvements were found and should be considered in the following sequence: the provision of training in the field of lubrication for technicians; the centralisation and updating of all information pertaining to lubrication; the establishment of conditions that prevent lubricant contamination; the conducting of regular oil analyses; the utilisation of tools that facilitate the transition to Predictive Maintenance, including ultrasound readings, thermography, and vibration analysis; the implementation of automatic lubrication systems; and the installation of Internet of Things (IoT) based sensors.

Chapter 4

Methodology

After analysing the current state in Chapter 3, where the context of the company, the production process, the current state, the challenges encountered and possible areas for improvement were explained, it is necessary to explore the methodology used to achieve the objectives of the work and implement the improvements identified.

This chapter will first analyse in more detail the improvements identified and the parameters used to evaluate them. Once these parameters have been defined, it is necessary to identify the data needed to obtain them and how they were obtained.

Next, the methodology used to explore new technologies and different solutions in response to the aforementioned improvements will be explained. And finally, how everything was integrated with what had already been implemented in the company.

4.1 Data Collection Methods

In order to know what data needs to be collected, we will now delve into the improvements identified.

4.1.1 Lubrication Training

The basic aspect for carrying out any task is the knowledge to do it. As such, this is undoubtedly the starting point when it comes to implementing improvements. The need for training was ascertained through a series of questions put to the lubrication technician in an interview at the beginning of this work, which aimed to determine the current state of lubrication at the Mangualde plant. He then revealed that he had never had any training in lubrication, lubricants or tribology. All he was learning was from the technician who had carried out this work before him for just over a month.

This information was presented to the lubricator's supervisor, the Mechanical Maintenance Coordinator, and to the team responsible for providing training to Sonae Arauco employees, SAKA - Sonae Arauco Knowledge Academy. It was agreed that it was important to go ahead with the training.

To this end, one of the lubricant suppliers, Castrol, was contacted to see if they could provide the training. They agreed, providing a partnership between them and Travocar, and an iterative process began to align the training content. This process included inputs from SAKA, the lubrication technician, the Mechanical Maintenance Coordinator, the Travocar specialist, and myself. The contents of this training will be discussed later in Chapter 5, because it will be the guide for future standardised trainings.

The results obtained for this specific improvement were quantified and evaluated by the training organisation in the training itself and should also be evaluated in a post-training visit to assess the knowledge acquired.

4.1.2 Avoid Lubricant Contamination

One of the most important maxims of lubrication is to avoid contamination at all costs. As mentioned in Chapter 2, the existence of contaminants in lubricants seriously affects the lifespan of the respective asset, leading to breakdowns and failures that could have been avoided.

Information on this problem was gathered through an interview with the lubricator, the Gemba Walk carried out at the start of the job to accompany the lubrication task and a visit to the lubricants warehouse. Around 4 years ago, a 5S Lean Methodology work was carried out at the lubricants warehouse in Mangualde to ensure that they were stored correctly. The lubricants warehouse, in general, meets most of the conditions necessary to avoid contaminating lubricants, as long as it is kept clean and organised. In the warehouse, for oils, there are accessories applied to the drums that allow the lubrication containers to be refilled and stored without contamination. However, when it comes to greases, there are no such fittings, which means that the grease guns are refilled manually, which leads to contamination, and the drums are not sealed properly to prevent contaminants from entering.

The way to improve on this would be to purchase accessories, later specified in Chapter 5, that would be placed on the grease drums to allow them to be sealed correctly and for the grease guns to be filled directly from this accessory. It was also identified that obtainig more recipients for oil handling would be benefitial. The method of evaluating the benefits of this implementation would be to analyse the reliability of the assets where the greases are used over time through vibration analyses and compare them with the values before this implementation.

4.1.3 Centralisation and Update of the Lubrication Information

In the interview, one of the biggest obstacles identified in carrying out the task of lubrication was the lack of organisation in terms of work plans.

When LubGest was implemented, a plant-wide survey was carried out of the lubrication routes and the lubricants used in each one. In the meantime, Sonae Arauco invested in the implementation of IBM Maximo software in 2018 in order to centralise all maintenance information. So, for the IBM Maximo software to be effective, all the information needs to be in there. As far as lubrication is concerned, since LubGest existed, this was somewhat neglected until the beginning of this work, with only around 21% of the lubrication routes currently in IBM Maximo. As previously mentioned in Chapter 3, the information that has yet to be transferred to IBM Maximo is outdated, it is split between two different platforms (LubGest and IBM Maximo), and some of it is not even registered.

This information was initially obtained, as mentioned above, in an interview with the lubricator and confirmed by observing the lubrication work plans in both LubGest and IBM Maximo. The improvement to be implemented is to finalise the transition from LubGest to IBM Maximo. A meeting was therefore held with the Mangualde maintenance team to create a time slot for them to complete this task. The method for evaluating the implementation of this improvement will be to compare the percentage of integration into IBM Maximo with the percentage expected in that time frame. The time frame obtained for this improvement will be presented and explored in more detail in Chapter 5.

4.1.4 Oil Analysis

As mentioned in the previous section, avoiding contamination in lubricants is very important. Therefore, it is important to have a recurring analysis of this parameter in order to adjust current practices in the best way. In particular, analysing oils on a recurring basis is important for assessing the need to replace oil or adopt improvements in terms of contamination control, or even for assessing the condition of the asset in question.

The oil samples to be analysed are taken by the lubricator and sent to Castrol for analysis. According to the lubricator we interviewed, most of this collection takes place during the annual shutdown in August. This causes a gap in analyses throughout the rest of the year and difficulty in maintaining optimum sample collection conditions, due to the high volume of work in this regard. To address this need, one of the implementations in Sonae Arauco's 2023 Lubrication Standard is the acquisition and use of an oil analysis machine to be present in all of the group's plants. However, this equipment is not currently used due to a lack of expertise in its handling. There are therefore two proposals for improvement to be implemented in this regard. The first involves acquiring the necessary knowledge to use the oil analysis machine. The second is to create work plans throughout the year to collect oil samples, either for external analysis by Castrol or for internal analysis using the aforementioned equipment.

In order to implement this improvement, it would first be necessary to disseminate knowledge of how to use the oil analysis machine and evaluate it by comparing the results obtained by it and by Castrol. Next, it would be necessary to set a deadline for having all the sample collection routes in IBM Maximo, so that the percentage result of their execution could be obtained.

4.1.5 Tools to Aid Predictive Maintenance

Sonae Arauco's Lubrication Standard mentioned above aims to set a clear path for the adoption of Predictive Maintenance in its plants. As explained in Chapter 2, Predictive Maintenance is a set of techniques that uses monitoring tools and data analysis to identify potential faults in equipment at an early stage.

A survey was carried out of the techniques currently used at the Mangualde plant. From a general maintenance point of view, various vibration and thermography analyses are carried out on the plant's various assets by maintenance technicians. These analyses can detect problems related to lubrication, which are reported to the lubricator in order to resolve them. However, at the time of the lubrication task itself, no technology was being used in this regard, despite the Mangualde plant having equipment for this purpose. One of these is ultrasound equipment which, when applied to lubrication, can be used to determine the optimum amount of lubricant for each asset.

Once this possibility for improvement was identified, efforts began to teach the lubricator how to use the equipment. It was also important to determine the most effective way to use it and which assets would benefit the most from this usage. The logic behind using this device is: the assets have a base dB level at the start of their operation (optimal conditions are assumed); with use, the equipment needs lubrication and even then it deteriorates; when lubricating with ultrasound, the aim is to add lubricant until the dB level stabilises as low as possible (as close to the base level as possible) and when it starts to increase again, stop lubricating. This guarantees the optimum amount of lubricant in the asset.

The results obtained from implementing this improvement will be measured in terms of the amount of lubricant used (and the associated cost), the time spent lubricating and the reliability of the equipment.

4.1.6 Automatic Lubrication Systems

Automatic lubrication is a way of carrying out the task of lubrication more rigorously, reliably and safely. Often, when lubrication is done manually, there is a lack of precision in the quantities of lubricant to be used, sometimes forgetfulness occurs and equipment is left unlubricated, and there are lubrication points that are difficult and unsafe to access. In addition, it is becoming increasingly difficult to find qualified technicians to do this, so there is a growing need to automate this task. The visit to the factory included a survey of the automatic lubrication currently in place at the plant.

At the time of the visit, some automatic lubrication systems had already been implemented, but most of the plant's lubrication is still done manually, including critical equipment and lubrication points with difficult and dangerous access. In order to increase the efficiency and safety of the lubrication task, it was suggested that they meet with a supplier of automatic lubrication solutions, Harker Solutions, in order to carry out a project to implement automatic lubrication systems in places where lubrication needs to be done at great heights. After this meeting, they will present this project for approval for implementation. The way to evaluate the results of this improvement will be through asset reliability and safety improvements.

4.1.7 Sensorization

As mentioned earlier in Chapter 2, something very important when it comes to Predictive Maintenance is the analysis of continuous data to obtain the right strategies from a maintenance point of view to minimise failures. A very common method of collecting this data is to use sensors on the assets to be monitored. The more data collected, the better the information obtained regarding the maintenance to be carried out. In the specific case of lubrication, this would make it possible to adjust both the amount of lubricant used and the frequency with which lubrication is carried out.

The initial visit revealed that few assets have built-in sensors. Sonae Arauco currently has a contract with Preditec to implement sensors in all the super-critical equipment in the group's plants. Mangualde will be the last plant in which these sensors will be implemented, as it has maintenance technicians who regularly analyse vibrations and thermography. There is already an implementation plan made by Preditec for this. The results obtained from this improvement will mainly translate into an improvement in asset reliability, reducing the number of failures that occur and increasing the effectiveness of maintenance, both in terms of time and money.

4.1.8 Summary of the Data Collection Methods

All the information mentioned above can be summarised into the following table 4.1. The parameters listed in the second column of the Table 4.1 were selected with the aim of enabling practical, reliable data collection that is directly aligned with the expected results for each type of improvement. For lubrication training, attendance records, content covered, and knowledge assessments before and after training are essential for measuring the effectiveness of the educational process. In the case of centralising lubrication information, the percentage of routes documented in IBM Maximo and the list of updated or missing routes allow monitoring the progress of digitalisation and standardisation of activities. To avoid lubricant contamination, it is necessary to understand storage conditions and the use of appropriate accessories, data that directly impact the quality of the product applied. Oil analysis requires data on equipment proficiency, sampling frequency and method, as well as comparative results, as this information ensures the reliability of the analyses and their usefulness in predictive maintenance. Predictive maintenance tools, on the other hand, rely on operational data such as dB levels, lubricant consumption and task execution time to identify opportunities for optimisation. Automatic lubrication systems require a detailed inventory of hard-to-reach points and the current status of facilities to assess their impact on reliability and safety. Finally, sensorisation requires a list of critical equipment and a detailed implementation plan, as this data guides actions to reduce failures and optimise maintenance costs and performance.

Table 4.1: Summary Table – Improvements, Data Collection and Evaluation

Improvement	Required Data	Evaluation Criteria
Lubrication Training	• Attendance records • Training content • Knowledge assessments (before and after training)	• Feedback from training sessions • Knowledge retention assessed during follow-up visit
Centralisation of Lubrication Information	• % of lubrication routes in IBM Maximo • List of updated or missing routes	• Progress vs. target completion percentage within allocated timeframe
Avoidance of Lubricant Contamination	• Storage conditions in lubricant warehouse • Availability and use of appropriate handling accessories	• Asset reliability trends via vibration analysis before and after improvement
Oil Analysis	• Proficiency in oil analysis equipment • Frequency and method of oil sampling • Comparison results (Castrol vs. in-house)	• Alignment of internal vs. external results • Completion rate of sampling plans in IBM Maximo
Predictive Maintenance Tools	• Ultrasound dB readings per asset • Lubricant quantities used per cycle • Task duration	• Reduction in lubricant waste • Reduced time spent on lubrication • Equipment reliability improvement
Automatic Lubrication Systems	• Inventory of hard-to-reach lubrication points • Systems currently installed vs. required	• Reliability of affected assets • Safety improvements (reduced risk to operators)
Sensorisation	• List of critical equipment • Implementation plan from Preditec	• Decrease in unscheduled failures • Improved response and preventive actions • Maintenance cost and time optimisation

4.2 Strategy for Exploring New Technologies

As can be seen in the Table 4.1, the improvements have already been identified, as well as the results that will be analysed in each of them. It was also analysed how these improvements could be implemented. To do this, it was necessary to carry out research into available technologies.

4.2.1 Selection of Lubrication Automation Tools

Starting with automatic lubrication systems, several locations in the factory were identified that could benefit from the implementation of these systems. In order to identify these locations, it was first necessary to define the criteria that would be used. Of the various possible criteria such as: criticality of the equipment, lubrication periodicity, difficulty of access, safety, recurrent under- or over-lubrication, those chosen as a priority were difficulty of access and safety in carrying out the task. The sites identified as priorities were twelve rotary valves where the lubrication points are located at very high heights. Subsequently, a market survey was carried out to identify companies that provide this type of solution.

In addition to analysing the different types of systems available and the elements that could be purchased, the plant's current suppliers were also considered in this context. The two main suppliers identified were SKF and Harker Solutions.

For reasons unrelated to this project, Harker Solutions was chosen to develop a project in this area. To move forward with the project, a search was made of the company's catalogue to identify the different solutions they had to offer.

Subsequently, a meeting was arranged with the local sales manager and a company technician to visit the factory and the locations where the automatic lubrication systems were to be implemented. During this visit, photographic and video data was collected, as well as technical information on the different components, namely chains, bearings and gearboxes. This data was collated with the help of the plant's technicians and sent to Harker Solutions so that they could draw up a quote and a suitable project. Harker Solutions was also asked to send data on previous projects they had developed, so that we could have a basis for comparison in terms of success rates and relevant indicators for assessing the project's effectiveness.

Once the project has been finalised, the aim will be to present it to the plant managers in the maintenance area in order to move forward with its implementation and obtain the necessary funding.

Another area was identified where an automatic lubrication project had already been started, but had yet to be finalised. In this case, it was only necessary to finalise the installation of the automatic lubrication pump, along with some accessories and pipework. This point was noted as a priority project to be completed, as it involves very important chains in the Wood Park.

In addition to the project to implement automatic lubrication, it is necessary to ensure the maintenance of this system to guarantee the correct lubrication of the assets it covers. Therefore, there are two measures that need to be adopted: creating refuelling or replacement routes for automatic lubrication systems and creating inspection routes for these systems. Both of these routes must be created in IBM Maximo.

4.2.2 Evaluation of Ultrasonic Lubrication Monitoring

With regard to lubrication using ultrasound technology, the first step was to carry out research into how this technology works. In order to assess its effectiveness and the results obtained, it is essential to understand the logic behind how it works - which was explained in Chapter 2.

In this case, it wasn't necessary to carry out market research, since the ultrasound analysis equipment had already been purchased by the factory. The challenge therefore consisted of implementing the use of the equipment, rather than acquiring it.

To begin this implementation, it was necessary to find out whether anyone in the factory had been trained to use the equipment. It turned out that there was a maintenance technician who had already received this training. Together with him and the person responsible for the lubrication task, tests were carried out with the equipment on various assets in the factory.

Subsequently, the maintenance technician's knowledge was passed on to the lubricator, enabling him to use the ultrasound equipment during lubrication routines.

With the use of the equipment now viable, the next step was to define how to evaluate the effectiveness of the results obtained with this technology. It was decided to carry out a pilot test on a specific set of equipment.

The test was carried out on five different ventilators, each with two bearings. Initially, data was collected on ultrasound levels in decibels during the lubrication process with the amount of grease recommended by the manufacturer, in order to establish a starting point.

Once this starting point had been established, a periodicity of one month was maintained for three consecutive months. The idea was to check how long and how much grease would be needed to reach the decibel levels considered ideal again. The results were always compared with the initial results.

This method made it possible to determine the amount of grease used more precisely and the amount of time saved during lubrication routines, thanks to the application of ultrasound technology.

However, cost and time savings are not the only relevant indicators. It was also necessary to prove the real benefits of improving the condition of the assets by checking their reliability. To do this, vibration analyses were carried out, which were then compared with previous analyses, serving as validation of the results obtained with the new ultrasound-assisted lubrication approach.

There is another important aspect to consider, which is that this new data collected with ultrasound needs to be stored in IBM Maximo. Recording this data is important for comparing the baseline obtained in terms of dB and the mass used in each lubrication. To do this, it is necessary to update the IBM Maximo dashboard and add fields that allow this data input. To introduce this improvement in a way that does not incur errors that compromise the reliability of the asset, two scenarios will be created:

- 1st scenario: the reduction in dB in the ultrasound equipment is observed, the lowest possible dB level is recorded, and the amount of lubricant introduced to achieve this is also recorded.

- 2nd scenario: almost no change in dB is observed in the ultrasound equipment, the maximum amount of lubricant to be added is that indicated in the asset description, to avoid over-lubrication

4.2.3 Integration of GPS for Route Optimisation

For the plant's current level of maturity, the existing challenges and possible improvements to be implemented were identified, so that the plant complies with the Lubrication Standards in force at Sonae Arauco. However, part of the objectives of this work was also to study the feasibility of implementing route optimisation and voice control in conjunction with the lubrication task. These two objectives can only be implemented once the plant is mature enough to apply them. Despite this, both have been studied so that an implementation plan can be drawn up for each of them, for when it is possible to do so.

Starting with route optimisation and GPS integration, as the title of this section indicates. In order to explain how it would be possible to optimise routes, we first need to explain how they are currently organised.

Firstly, we need to understand how the equipment is identified in IBM Maximo and what this code means. Specific equipment is identified on the basis of its position, function, system, area, stage and factory, as shown in the following figure.

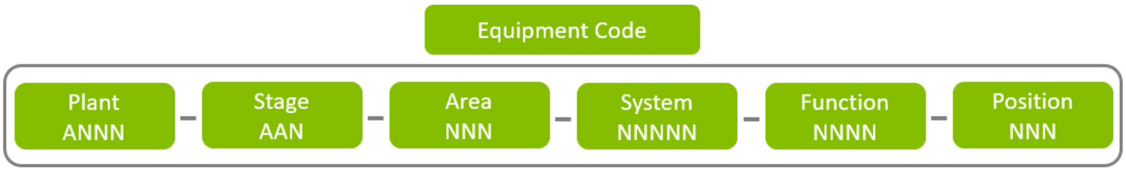


Figure 4.1: Equipment Code in IBM Maximo

Current lubrication routes are achieved by grouping together equipment that shares one of the attributes (from stage to function) that makes up its code and that shares the same periodicity. The aim of this organisation is to group together lubrication with the same periodicity, with lubrication points in close proximity, in order to minimise wasted time due to travel and forgetfulness. However, as mentioned above, there are still many routes to be put into IBM Maximo (and updated) and some yet to be created. What's more, lubrication isn't just done on the basis of routes. As the need for lubrication arises, work requests are made to the lubricator and assigned to him at the start of each day.

Route optimisation and integration with GPS is aimed at resolving the following issues: optimising the route between pre-existing routes assigned for the same day, optimising routes to be entered into IBM Maximo, optimising the route to be taken when carrying out lubrication tasks that arise out of necessity. In addition, the question of tracking the lubricator's position in real time when carrying out tasks also arose, due to the associated risks. He works alone in this role and there are many lubrication points that are difficult and dangerous to access, so this location tracking would allow him to know where he was in the event of an accident.

Initially, various options on the market were studied to track the position of the lubricator within the factory, but this is complex because it is an environment where lubrication points are very close together, there are lubrication points at height (one on top of the other), which makes it very difficult for the available software to pinpoint the exact locations to be lubricated in order to optimise the routes. In order to try and solve this problem, a meeting was held with IBM to see if they had similar functionality in the already implemented IBM Maximo programme.

It emerged from this meeting that there is indeed a Maps feature that would allow us to do what we wanted, however, due to the difficulties expressed above in pinpointing the precise coordinates of the lubrication points, additional development would be required on top of this feature. This development was based on creating a model of the factory using georeferencing, with different levels representing the different heights at which the lubrication points were located. This involved a total survey of all the plant's assets and their lubrication points, with their precise coordinates and the subsequent creation of the model.

In 2026, the current version of IBM Maximo will be upgraded to IBM Maximo Application Suite, so as far as development is concerned, it only makes sense to make this effort for the new version. To find out whether this development is profitable, the aim was to carry out a pilot test to check whether GPS tracking works by activating the Maps feature and choosing an area that could be checked, with lubrication points whose coordinates are not too close together.

Due to time constraints and other priorities currently present in the company, this pilot test could not be carried out, however, an action plan has been drawn up for this specific issue for when it is possible to move forward, which will be presented in Appendix F.

4.2.4 Voice-command Functionalities and Technician Interface

Another aspect that was identified as an improvement in terms of lubrication, as mentioned above, was voice control. This refers to the technician operating a device integrated with IBM Maximo, which enables real-time access to asset information, the ability to receive audio instructions or alerts, and to issue commands or record data directly within the system. In other words, the technician would use the equipment, receive directions to go to the next lubrication location, and upon arriving at the location, hear information about the task to be performed. There, they could start the task, provide information about the asset and the task, finish the task, and even create another one, just by using voice commands. The advantages of this improvement would be the immediate and accurate recording of information and the performance of the task without the risk of contamination by checking things on the mobile phone.

For this improvement to happen in its entirety, it is necessary to have the previously mentioned development of Maps, because of the part of providing directions and detailed information about the task, based on its location; as well as the acquisition of the equipment that allows it to occur and the development of IBM Maximo to enable all these features.

As with the previous improvement, due to time constraints and also because of the IBM Maximo update in 2026, this work was not completed, and an action plan was drawn up for when it can be implemented, which will be presented in Appendix F.

Chapter 5

Analysis and Discussion of Results

This chapter provides a thorough and organised study of the outcomes of the lubrication digitalisation project that was implemented at the Sonae Arauco industrial unit in Mangualde. The knowledge gained, the tools introduced, and the processes assessed served as the basis for the development of a standardised and scalable approach that can be applied and replicated across other manufacturing sites within the organisation, each with its own level of technological maturity, even though the practical work was concentrated on this particular site.

5.1 Lubrication Training

Prior to implementing any digital or predictive maintenance technology at the Mangualde factory, it was deemed necessary to lay a solid foundation of operational maturity. This preliminary phase included standardising lubrication operations across all mechanical assets, increasing technical expertise among maintenance professionals, and strictly adhering to industry-recognised lubrication best practices. Without such preparations, the usefulness of modern diagnostic tools would be greatly hampered, resulting in inefficient utilisation and potential misinterpretation of crucial machine health data.

On May 29-30, Travocar and Castrol collaborated with SAKA to provide a two-day training session for field technicians and personnel from the internal Competence Centre. The main goal was for attendees to get a comprehensive and scientifically rigorous grasp of lubrication and tribology, ensuring the smooth integration of future digital projects.

5.1.1 Training Content

The training content was developed jointly and covers more theoretical topics on lubrication, tribology and lubricants, as well as more practical topics on the correct storage of lubricants, avoiding contamination, good lubrication practices and the use of equipment that enables predictive maintenance. The detailed content can be found in Appendix D.

5.1.2 Evaluation and Outcomes

To rigorously assess the efficiency of the training programme, all participants gave their feedback after completing the session. The goal was to assess various factors, including presentation clarity, technical depth of material, module relevance to participants' operational contexts, and perceived utility of practical sessions. Their feedback was evaluated and combined and indicated the following key findings:

- The training event was well-attended by personnel from both field-based maintenance teams and the office-based Competence Centre. This broad participation created a heterogeneous learning environment and reflected the organisation's strong commitment to skill development across functional domains. Attendance was continuously high over both days, and participants were highly engaged in both the academic and practical components.
- Over 90% of participants evaluated the programme, especially the hands-on practical sessions, as "excellent" for its instructional value and relevance to their normal maintenance tasks. Respondents emphasised the real-world relevance of the gained abilities, particularly in terms of contamination prevention and the execution of lubricating activities in accordance with best practices.
- Most of attendees indicated increased confidence in employing diagnostic tools like ultrasonic monitoring. Many participants stated that they were more prepared to understand condition-monitoring data and incorporate these findings into their maintenance decision-making processes.
- Many participants showed a desire to pursue advanced, topic-specific training modules. There was a high demand for follow-up sessions on the use of data analytics in lubrication management, as well as the deployment of in-line lubricant monitoring systems and IoT-enabled condition-based maintenance methods.

These results clearly show that the training course achieved its goals of increasing knowledge, improving technical competency, and preparing maintenance personnel for the use of digital lubrication instruments. The good reviews and high levels of participation demonstrate not just the relevancy of the course material, but also the success of the training delivery techniques.

To preserve the longevity of this information and to encourage continued progress, occasional refresher courses should be included in the annual training calendar. Furthermore, the creation of an internal lubrication competence network, consisting of qualified champions from all departments, could serve as a platform for exchanging best practices, diagnosing lubrication issues, and mentoring new employees. Such activities will be crucial in maintaining high lubricant management standards and maximising the dependability and performance of critical assets throughout the Mangualde facility and, perhaps, other production units within the business.

5.2 Implementation of Best Practices

As previously mentioned, a complete set of field assessments and procedural audits were carried out to assess the maturity and compliance of the Mangualde site's existing lubrication processes. These audits were vital for validating the alignment of theoretical training and day-to-day operational procedures, as well as identifying any lingering critical deviations that could jeopardise asset reliability or limit the effectiveness of future digitisation efforts.

While the central lubricant storage facility had recently received structural enhancements, such as sealed floors, vented enclosures, defined containment zones, and standardised labelling, two substantial procedural holes were identified:

- **Improper Use of Oil-Handling Containers:** It was discovered that certain oil transfer activities continued to use non-dedicated containers. This constituted a significant contamination risk, due to unintentional oil mixing, infiltration of airborne particles, and inadequate traceability. These techniques were not only incompatible with international lubrication standards, but they also contributed to lubricant deterioration, which jeopardised machine dependability.
- **Inefficient and contamination-prone grease gun Refilling:** Grease was manually transported from Original Equipment Manufacturer (OEM) drums to grease guns using crude methods, sometimes utilising open scooping tools or even by hand. This technique was prone to external contamination, uneven dosage, and operator fatigue, as well as being time-consuming and ergonomically unsatisfactory. The lack of a regulated environment while refilling raised the likelihood of dirt and moisture entering the lubricating system.

5.2.1 Remedial Measures and Implementation Strategy

To address these issues, a systematic action plan was created and implemented, with an emphasis on the implementation of standardised, contamination-free lubricant handling techniques. The primary interventions were acquiring:

- **SKF LAGF Series Pumps (LAGF 18 and LAGF 50):** Pneumatically driven grease-filling systems are used to assure the clean and efficient transfer of grease from OEM drums to grease guns. These closed-loop systems minimise manual touch, reducing contamination risk and providing constant volume management. The incorporation of these pumps considerably increased operating efficiency while reducing lubricant waste and technician burden.
- **SKF LAOS Colour-coded Oil Transfer Containers:** The SKF LAOS (Lubricant Application and Organisation System) architecture included a comprehensive set of colour-coded, clearly branded oil transfer containers. To avoid cross-contamination, each container was permanently given a distinct lubricant type. For oils used only, rarely, a cleaning routine was developed to ensure safe reuse, which included flushing procedures and inspection reports. This system also enhanced visual management and traceability, which aided audits and internal compliance checks.

5.2.2 Cost–Benefit Analysis and Reliability Gains

From a strategic maintenance standpoint, the financial investment necessary for the procurement and installation of these lubricating instruments might be relatively low, especially when considering the operational benefits that could be obtained. The switch to sealed, standardised systems would be expected to result in quantifiable gains across numerous key performance indicators:

- **Lubricant Waste Reduction:** Using specialised transfer systems could result in considerable reductions in spillage, over-application, and contamination-related discards.
- **Improved Task Efficiency:** Lubrication duties would be accomplished in less time and with more consistency, freeing up technician time for more valuable maintenance tasks.
- **Improved Equipment Reliability:** Initial monitoring findings might show more stable operating temperatures and lower bearing noise levels, indicating better lubrication regimes and early signs of decreased wear.
- **Increased Accountability:** The explicit assignment of containers, paired with verifiable SOPs, would strengthen operational discipline and make troubleshooting easier.

In the Section 5.8, the equipment expenses will be compared to the possible operational gains after deployment. These findings support the idea that targeted investments in lubrication infrastructure are essential facilitators of overall dependability and digital transformation plans.

5.3 Centralisation of Information on IBM Maximo

The centralisation and methodical consolidation of all pertinent data under a single digital platform is a key facilitator of the digitisation of lubrication management. The organisation has set a strategic goal to completely transfer all maintenance-related data and procedures (this includes all lubrication data and procedures) into the IBM Maximo Enterprise Asset Management (EAM) system by July 2025, in line with its larger digital transformation goals. It is anticipated that this change would make it easier to integrate with complementary features like real-time performance dashboards, asset condition monitoring, and predictive maintenance.

Significant holes in the digitisation process were discovered, nevertheless, by a first evaluation of the current situation. In particular, it was found that only about 21% of IBM Maximo's lubrication pathways were explicitly documented and structured. Furthermore, regular lubrication operations were not reliably monitored using digital tools. These flaws endanger data integrity, traceability, and maintenance effectiveness in addition to impeding the full use of Maximo's capabilities.

The following action plan has been created in order to solve these shortcomings and guarantee a thorough and long-lasting adoption of lubrication digitalisation:

- All present lubrication routes, including those that are currently managed outside of digital systems, should be fully mapped and documented.

- Lubrication tasks are incorporated into preventive maintenance plans, guaranteeing that they are in line with operational risk and asset criticality.

- Creation and implementation of interactive dashboards and Key Performance Indicators (KPIs) to track the efficiency, compliance, and execution of lubrication operations.

A thorough implementation schedule that includes a suggested timeline, in Figure D.1 in Appendix D, and the important tasks to the maintenance and digital transformation teams who will support this plan. In order to achieve it, it is necessary to hire one person dedicated only to do this through the course of 5 months. This schedule and collection of necessary resources was done through meetings with maintenance technicians to assess the feasibility of deadlines.

5.4 Oil Analysis and Equipment Use

The need for quick, on-site diagnostics has grown, even though Castrol offers an external oil analysis service.This is especially true when it comes to operational continuity and asset reliability decision-making procedures that have a tight deadline. Particularly in situations that are high-risk or production-critical, outsourcing-related delays, such as sample transportation and report turnaround times, might impair the responsiveness of maintenance interventions.

In 2015, the organisation purchased a Hydac FCU1310 portable fluid contamination unit to fill this gap. Key characteristics like temperature, water saturation, particle counts, and ISO cleanliness codes can all be included in the in-field examination of oil quality and contamination levels that this device can provide. The lack of properly trained staff and procedural integration into current maintenance procedures prevented the unit from ever being operational, despite its technical promise.

5.4.1 Remedial Measures and Developing Capabilities

The initial lubrication training consultant would be brought back to provide a specialised, practical technical session that was only focused on using the Hydac FCU1310 as part of the lubrication function's digitisation and capabilities enhancement agenda. The training was intended to instil analytical thinking in ordinary lubrication activities in addition to to familiarise maintenance personnel with the operation of the equipment.

The following essential learning modules will be included in the training programme:

- Appropriate methods for gathering samples, such as best practices for reducing contamination and guaranteeing representative samples from different kinds of reservoir.

- The Hydac FCU1310's user interface, including data logging features, parameter selection, and startup processes.

- Interpretation of analytical results with an emphasis on particulate count analysis in compliance with manufacturer and industry thresholds, and ISO 4406 cleanliness codes.

- Making decisions based on in-field diagnostics gives staff members the ability to recognise patterns in oil condition and start remedial measures like fluid replacement, filtration, or root-cause analysis.

5.4.2 Integration with IBM Maximo

Within the IBM Maximo Enterprise Asset Management (EAM) system, a series of new digital workflows should be developed in order to institutionalise the process and guarantee data traceability, repeatability, and visibility across departments. The oil sample procedure and its connection to asset health monitoring are formalised by these workflows. Important IBM Maximo setups include:

- Creation of oil sample routes that are categorised by asset criticality and operating environment and are in line with current lubrication programmes.
- For assets determined to be lubrication-sensitive or operationally critical, recurring work orders for oil sampling are created at weekly and monthly intervals.
- The Hydac unit's diagnostic data can now be digitally recorded thanks to the use of an organised results entry template. When anomalous values are identified, the system can initiate alarms or follow-up work orders because the template allows for the assignment of alert thresholds.

5.4.3 Next Steps and Value Realisation

In addition to improving the organisation's diagnostic capabilities, the successful implementation of the Hydac FCU1310 unit is a crucial step towards a condition-based lubrication strategy. A systematic implementation plan that includes scheduling, training reinforcement, and economic rationale will be established in order to guarantee long-term sustainability, cross-functional alignment, and quantifiable benefits.

1. **Sampling Schedules Are Formally Established:** The framework for planning preventive maintenance will incorporate a methodical oil sample programme. Based on past failure data, lubricant change intervals, and operational duty cycles, this plan will rank essential assets in high-load or high-temperature situations. High-risk systems will be sampled more frequently than lower-risk assets. To encourage operational awareness and adherence, the schedule will be graphically displayed on asset boards and published digitally using IBM Maximo.
2. **Records of Training and Knowledge Retention:** Standardised Operating Procedures (SOPs), quick-reference manuals, and instructional films housed on the company's internal learning platform will be used to supplement the training session on the Hydac unit in order to minimise skill atrophy and guarantee continuity despite people turnover. In addition, biannual refresher courses could be scheduled to ensure operational proficiency.

3. **Including Analytical Perspectives in Decision-Making:** In addition to the technical aspects of oil sample and analysis, the outcomes will provide useful information for maintenance decision-making. The reliability engineering team's reports will benefit from these insights, which will allow for data-driven improvement of lubricant selection and maintenance plans.

4. **Initial Forecast for Return on Investment (ROI):** To assess the operational and financial effects of the internal oil analysis program, a preliminary ROI model has been created. The model's key variables include: Preventing emergency maintenance interventions, minimising secondary component damage, and avoiding unexpected downtime due to early failure identification; instead of using fixed-time replacement schemes, real-time condition monitoring allows for the extension of oil drain intervals; reduced mean time between failures (MTBF) and increased asset availability and dependability indirectly boost production efficiency.

A thorough cost-benefit analysis backed by quantitative data gathered will be provided in Section 5.8. In addition, together with the maintenance team, a schedule was created for the introduction of sample collection routes in IBM Maximo, in Figure D.1 in Appendix D, which includes all the tasks necessary for its implementation, as well as the allocation of responsibilities and resources.

A template was also created to be implemented in IBM Maximo, seen in Figure D.2, which enables the introduction of oil analysis results associated with Work Orders for sample collection routes. The fields to be entered are directly relevant to assessing the condition of the oil.

5.5 Ultrasound-Assisted Lubrication

Since its purchase in 2023, the Ultraprobe 401 Digital Grease Caddy (ultrasonic monitoring tool intended to maximise grease application during hand lubrication) has been mainly underutilised. Limited training and procedural integration has previously prevented its successful usage in normal maintenance tasks, despite its promise to improve the lubrication process' accuracy and efficiency.

An internal training programme was started in order to take advantage of this asset's complete diagnostic and operating capabilities. A maintenance professional who had previously used the equipment first-hand helped with this. The goal of the training was to give the chosen lubrication technician the know-how to integrate ultrasound-guided lubrication techniques into routine operations.

5.5.1 Training Content and Practical Outcomes

The following critical competencies were covered in the training programme, which combined supervised field application with theoretical instruction:

- Decibel (dB) measurements are used to quantitatively evaluate the lubricating condition: Real-time detection of frictional anomalies in rotating elements and bearings is made possible by the Ultraprobe 401. These anomalies may be a sign of over-lubrication (hydraulic resistance and potential seal failure) or under-lubrication (increased friction noise).

- Controlled grease application: The lubricator was trained to apply lubricant only when necessary, in response to auditory feedback, as opposed to applying predetermined volumes based on time-based schedules. This strategy seeks to minimise lubricant waste and the dangers of excessive lubrication, including elevated bearing temperature and early seal failure.

- Decibel levels are evaluated both before and after lubrication: This allows for the early diagnosis of bearing degradation and the identification of abnormal patterns by providing a dataset for each lubrication point. They are also a useful resource for confirming the efficacy of lubricants over time.

5.5.2 Pilot Project Implementation and Findings

A four-month pilot project was created and carried out to methodically assess the technical viability and practical advantages of incorporating ultrasound-guided lubrication into the current maintenance framework. The project's goal was to evaluate the Ultraprobe 401 Digital Grease Caddy's performance on a chosen lubrication route in actual operating circumstances.

Accessibility, lubrication frequency, and asset criticality were taken into consideration when selecting the pilot route. The chosen path included 10 lubrication points, which were located in 5 ventilators and 10 bearings. These parts function at different loads and speeds, offering a microcosm of the facility's overall lubricating environment. In the past, the assets in question were lubricated at time-based intervals without any accompanying condition-monitoring data. They were therefore perfect for assessing the effects of switching from a preventive strategy to a condition-based strategy that was informed by ultrasonic measurements.

In order to confirm the efficacy of ultrasound-guided lubrication while staying in line with current manufacturer guidelines, the pilot project used a two-stage methodology.

1. **Initial Calibration Phase - Baseline dB Measurement with Suggested Grease Volume:** In the initial intervention, the recommended amount of grease was used to service each lubrication site along the chosen path. The Ultraprobe 401 Digital Grease Caddy was used to test decibel (dB) levels both before and after lubrication. By collecting the acoustic response linked to a "theoretically optimal" lubrication state, these observations created a reference profile for every asset. Every measurement was carefully noted and linked to the appropriate equipment identification.

2. **Phase of Monitoring and Adjustment - Monthly Reevaluation and Greasing Using Ultrasound Feedback:** Using the same ultrasonic device, each lubrication point was examined once a month for the next three months. Before lubricating, the technician measured

the dB level at each visit and compared it to the previously noted values. Only when the decibel level rose, suggesting possible underlubrication or increased friction, was grease progressively added. Until the dB level steadied or dropped to the lowest possible point, lubrication was maintained. No extra lubricant was used in situations where the dB level stayed constant and within allowable bounds, meaning it didn't significantly differ from the prior month. This method reduced the possibility of over-lubrication and conserved material resources by ensuring that lubrication was condition-driven rather than calendar-based.

The amount of grease used per point, the dB levels prior to and following each intervention, and the amount of time needed to complete the task were among the data collected during the trial. In order to evaluate machine condition and operational impact, these results were subsequently cross-checked with vibration measurements and maintenance logs.

5.5.3 Key Findings

Strong proof of the advantages of using ultrasound-guided lubrication procedures was provided by the pilot study's quantitatively significant and operationally significant findings. The Ultraprobe 401's integration made it possible to go from time-based to condition-based lubrication, which improved the precision of determining when and where grease was actually required. Without endangering the health of the machine, this resulted in quantifiable decreases in the amount of grease used and the amount of time spent on lubrication duties. In parallel, the programme increased technician knowledge and involvement by encouraging a more critical, evidence-based approach to lubrication through the use of real-time dB data.

- **Reduction of about 57% in the amount of grease used:** Throughout the route, a notable decrease in the overall amount of grease applied was seen. Although not consistent, this drop showed a high correlation with sites that had previously been routinely over-lubricated. In addition to saving material, removing needless grease applications also decreased the possibility of lubricant migration, seal deterioration, and contamination of nearby machine parts. This can be seen in Tables D.1 and D.2 in Appendix D.

- **Task Execution Time Reduction (about 41%):** Because there was less need for manual greasing and inspection, the technician reported significant time savings each route. Operational efficiency increased significantly by removing lubrication operations where ultrasonic feedback showed proper lubrication. Increased availability of the maintenance crew for higher-value jobs is also suggested by this decrease in technician hours. This can be seen in Tables D.1 and D.2 in Appendix D.

- **Asset Condition Stability:** There was no discernible decline in the machine's condition during the four-month timeframe. All monitored stations displayed similar vibration analysis findings; no anomalous peaks or new fault frequencies were detected. This demonstrated the effectiveness of employing dB thresholds as indicators for lubrication needs and proved that the reduction in grease volume had no detrimental effects on bearing health. This can be observed in Figures D.4, D.5, D.6, D.7 and D.8 in Appendix D.

- **Enhanced Awareness and Engagement of Technicians:** Additionally, the pilot produced significant but intangible advantages. The lubrication technician expressed increased confidence in lubricating decisions and a heightened understanding of machine behaviour. Lubrication was transformed from a mundane duty to a diagnostic one by the interactive nature of the ultrasound tool, which encouraged a more analytical approach.

5.5.4 Limitations and Considerations

When analysing the results and thinking about wider implementation, it is important to recognise a number of limitations, even if the four-month pilot's results were encouraging and showed obvious operational improvements.

- **Manual Data Logging:** During the pilot, all decibel (dB) values were recorded on paper forms, introducing potential human error in data transcription and organisation. These issues could affect the reliability of retroactive assessments and trend analysis. To address this, future workflows will use direct data entry into IBM Maximo, allowing digital collection of ultrasonic measurements within work orders. This will improve data accuracy, traceability, and integration with existing condition-monitoring tools. A template for entering ultrasound data into IBM Maximo has been developed (Figure D.3, Appendix D) for potential future use.

- **Observation Period:** Even though the pilot lasted four months, which is longer than most short-term trials, it might not have been long enough to fully capture the effects of ultrasound-guided lubrication on long-term asset health, lubrication intervals, and bearing degradation. The advantages of improved lubrication techniques, such as extended mean time between failures (MTBF), may not be noticeable for six to twelve months, and bearing failure mechanisms frequently emerge over long operating cycles. Therefore, to confirm the durability and scalability of the noted improvements, ongoing monitoring is advised.

- **Limited Operational Scope:** Although representative, the trial involved only one technician on a fixed route, limiting its generalisability. A broader rollout across multiple routes and staff with varying experience is needed to assess consistency, scalability, and training needs, as well as to identify potential implementation challenges across different asset types.

With regards to the costs of lubricants used, in Table 5.1, given that this equipment can only be used on bearings, which are lubricated with grease, the consumption of lubricating grease for the year 2024 at the Mangualde factory was calculated and used as a reference. The value obtained after implementation was calculated by multiplying the previous cost by the percentage reduction obtained in the pilot test with a safety factor of 1.5 applied. This safety factor was applied because of the limitation mentioned previously, in order to obtain more realistic values of cost reduction.

Table 5.1: Total Lubricant Cost of Improvements regarding Ultrasound Equipment

Lubricant Cost	
Pre Lubricant Consumption [€]	Post Lubricant Consumption [€]
24 425,51€	15 061,52€

5.6 Automatic Lubrication Systems

A strategic initiative was initiated in partnership with Harker Solutions to implement automatic lubrication systems in production zones that have limited physical accessibility in an effort to improve operational safety and equipment reliability. The realisation that hand lubrication in these areas poses inherent dangers to maintenance workers and frequently leads to less than ideal adherence to recommended lubrication schedules served as the impetus for this endeavour.

5.6.1 Prioritisation Criteria for System Deployment

A set of objective prioritisation criteria was created to guarantee that implementation efforts were focused on areas having the greatest potential benefit. The following important risk and accessibility criteria were used to evaluate and rank the lubrication points:

- Ladders are needed to reach elevated or overhead lubrication locations, which raises the risk of accidents and falls.
- Access to lubrication locations behind interlocked or fixed safety barriers requires process pauses and safety override protocols, increasing downtime and procedural complexity, and jeopardises operator safety and production continuity.

After this evaluation, a shortlist of potential pieces of equipment was created for the project's pilot phase, with a primary focus on high-frequency lubrication locations with crucial functional functions, particularly those that call for ladders.

5.6.2 Expected Operational and Safety Benefits

A number of concrete and quantifiable advantages are anticipated when autonomous lubrication systems are implemented in certain specific sectors, including:

- **Improved Operator Safety:** The initiative greatly lowers exposure to working at heights, hot surfaces, moving machinery, and other occupational hazards by doing away with the need for manual intervention in dangerous or difficult-to-reach areas.
- **Increased Adherence to Lubrication Intervals:** Regardless of accessibility or human availability issues, automated solutions guarantee that lubrication is administered accurately and reliably in accordance with preset schedules. This uniformity lessens the possibility of

excessive or insufficient lubrication, which are both recognised causes of early component deterioration.

- **Decrease in Unplanned Downtime:** It is expected that increased lubrication delivery dependability would lead to fewer lubrication-related failures, which will lower the need for emergency repair procedures and increase equipment availability.
- **Maintenance Resource Optimisation:** By automating repetitive lubricating chores, maintenance teams may focus their energies on more valuable predictive and corrective duties, which will increase worker productivity.

The cost-benefit analysis of this improvement will be done in Section 5.8.

5.7 General Implementation Plan for All Units

An implementation strategy has been meticulously developed to provide a thorough, step-by-step framework for the digitalisation of lubrication practices across all Sonae Arauco industrial sites, regardless of each unit's existing level of maturity in maintenance processes. This plan draws extensively on the successful application of digital tools and methodologies at the Mangualde unit, encapsulating lessons learned, best practices, and scalable strategies. It integrates training, process optimisation, digital tools, and predictive maintenance technologies to ensure a sustainable and effective transition. The plan showed in Appendix E represents the steps of the implementation plan designed to implement the digitisation of the lubrication function.

5.8 Cost-Benefit Analysis and Projections

In this section, we will analyse the cost-benefit ratio of the improvements mentioned in the previous sections. To do so, we will take into account the implementation cost of the improvement and the savings associated with maintenance.

The implementation cost is divided into two categories: the cost of the equipment itself and the cost of its installation or associated training. In the case of Automatic Lubrication, the cost is related to the installation of the systems in the respective locations; in the case of Ultrasound Equipment, the cost is associated with training in the use of the equipment provided by the supplier. The implementation costs are all based on actual budgets or former costs associated with each improvement.

With regard to Maintenance Savings, it was assumed that the benefit to be considered is the reduction in downtime associated with failures caused by lubrication. The cost associated with repairing and replacing equipment was also considered for inclusion in these calculations. However, due to a lack of representative data associated with this, and because it normally represents a reduced cost impact compared to the cost associated with a line stoppage, it was not taken into account. Therefore, to calculate the cost savings associated with maintenance, the following factory data was taken into account:

- The factory loses €1 500/hour when a production line is down.
- In the last 6 months, the downtime associated with mechanical failures was 125 hours. Extrapolating to 1 year, it can be inferred that, on average, the annual downtime due to mechanical failures is 250 hours.
- Of these mechanical failures, it is possible to estimate, thanks to input from the factory's reliability engineers, that 25% correspond to failures that can be associated with lubrication.
- When a failure occurs, technicians are needed to fix it. The number of technicians needed to fix it depends on the severity of the failure, so 1.2 per failure was considered. The employee cost associated with a technician is €15.15/hour.

In addition, it was also necessary to obtain the reliability improvement associated with the implementation of each improvement. To this end, research was carried out, which led to the theoretical improvements possible when implementing the improvements. These percentages were then presented and discussed with the company's reliability engineers, as well as the rest of the maintenance team, in order to adapt them to the case study in question. The percentage improvements used to calculate the benefits, decided with the help of reliability engineers, are lower than those found in the literature, as the measures are implemented gradually in terms of asset coverage.

To obtain maintenance savings, multiply the cost of the production line being down for 1 hour (including the downtime cost plus the cost associated with the technician's work to repair the breakdown) by the number of hours that there was a breakdown associated with lubrication (obtained by multiplying the downtime of mechanical breakdowns by the probability that the breakdown was due to lubrication) and by the reliability improvement associated with each improvement, seen in Equation 5.1.

$$\text{Maintenance Savings} = (1500 + 15.15 \cdot 1.2) \cdot (250 \cdot 25\%) \cdot \text{Reliability Improvement} \tag{5.1}$$

Next, Table 5.2 shows the implementation costs, as well as the savings due to reliability and the total yearly savings from the different improvements. The total yearly savings are equal to the reliability savings in all improvements, except for ultrasounds. In this case, in addition to the savings associated with reliability, savings related to the amount of lubricant used were also included, obtained from Table 5.1 in Section 5.5.

Table 5.2: Cost-benefit analysis on the first year of implementation

Improvements	Cost of Implementation			Maintenance Savings		
	Equipment	Instalation/ Training	Total Cost	Reliability Improvement	Savings due to Reliability	Total Yearly Savings
Best Practices	1 108.54€	-	1 108.54€	1%	948.87€	948.87€
Oil Analysis	10 239.75€	-	10 239.75€	2%	1 897.73€	1 897.73€
Ultrasound Equipment	6 758.85€	1 230€	7 988.85€	10%	9 488.65 €	18 853.39 €
Automatic Lubrication	3 086.32 €	363.68 €	3 450.00 €	3%	2 846.60 €	2 846.60 €

The yearly breakdown of the implementations was then calculated. In the first year, this is calculated by subtracting the cost of implementation from the total savings, Equation 5.2:

$$\text{Total Savings on Year}_1 = \text{Yearly Savings} - \text{Cost of Implementation} \tag{5.2}$$

To bring this study closer to reality, an annual inflation rate of 2% was applied. This rate was obtained by averaging the annual inflation rate over the last 10 years in Portugal. Therefore, the calculation to obtain the total yearly savings, after the first year, is the sum of the previous year's total savings and the yearly savings, adjusted for inflation, of the year to be calculated, Equation 5.3. The results of these calculations can be seen in Table D.3 in Appendix D.

$$\text{Total Savings on Year}_x = \text{Total Savings on Year}_{x-1} + (\text{Yearly Savings} \cdot 1.02^{x-1}), x > 1 \tag{5.3}$$

In order to obtain the Return on Investment (ROI), it is necessary to subtract the investment cost (IC) from the investment gain (IG), divide this subtraction by the implementation cost and multiply by 100%, resulting in the following expression: [(IG-IC)/IC]*100 (the equipment acquired is considered as a one-time cost instead of an asset that retains value after acquisition). In order to calculate the ROI over a time horizon of 1, 5 and 10 years, taking into account inflation of 2%, the values in Table D.3 in Appendix D were used. The values in this table represent the numerator of the previous expression (IG-IC), taking into account annual inflation. The Weighted ROI was calculated using the average ROI of its implementation and the respective Investment Cost. The results of this calculation are in Table 5.3.

Table 5.3: Return on Investment

Return on Investment (ROI)					
Years	**Best Practices**	**Oil Analysis**	**Ultrasound Equipment**	**Automatic Lubrication**	**Weighted ROI**
1-Year	-14.40%	-81.47%	136%	-17.49%	7.72%
5-Year	345.44%	-3.55%	1 128.13%	329.39%	460.59%
10-Year	837.25%	102.93%	2 484.09%	803.46%	1 079.52%

5.9 Discussion of the Results Obtained

This section will analyse and discuss all the results obtained throughout this study.

Following a thorough examination of the findings, it is evident that the primary investment in training and the dissemination of optimal lubrication practices constitutes the most cost-effective strategy. A minimal investment resulted in a return of 345.44% over a five-year period and 837.25% over a ten-year period. These findings demonstrate a significant impact on equipment reliability and reduced downtime.

The implementation of technologies such as automatic lubrication and ultrasound equipment also proved to be extremely beneficial. Despite having an higher initial costs, the medium and long-term results prove their effectiveness, with a return of up to 1,128.13% over five years in the case of ultrasound and 2,484.09% over ten years. The findings of this study corroborate the hypothesis that these tools have the potential to serve as essential components within a predictive maintenance strategy.

Furthermore, oil analysis has been shown to be a promising method, with a reasonable implementation cost. It is recommended that this method be evaluated for its applicability to the factory's needs, in terms of performing its own analyses. Prior to its adoption, it is imperative that personnel be trained in the utilisation of the equipment and the collection of crucial information regarding the samples to be analysed.

The integration of technologies with IBM Maximo has been identified as a pivotal element in the centralisation and digitisation of data, thereby fostering traceability and data-driven decision-making processes. Nevertheless, challenges associated with technological maturity and full integration with the existing system currently limit the full exploitation of the expected benefits.

Chapter 6

Conclusions and Future Work

6.1 Summary of Key Findings

In recent years, there has been an increasing trend in the field of industrial maintenance towards the adoption of digital transformation processes. Lubrication, a component that has historically been underappreciated in terms of its critical role, has emerged as a significant area of focus for enhancement. In this context, the work developed at Sonae Arauco's Mangualde unit clearly illustrates how a structured, phased approach to the digitalisation of the lubrication function can deliver tangible results across operational, technical and strategic dimensions.

This work demonstrated that the digitalisation of the lubrication function, when properly structured and implemented in phases, can generate significant gains in terms of asset reliability, operational safety and maintenance efficiency.

The introduction of specialised training, aligned with best practices, was identified as the essential basis for the success of any subsequent technological initiative. Beyond technical knowledge, it fostered cultural alignment and awareness among maintenance teams, ensuring the correct adoption of new methodologies.

The integration of oil analysis, ultrasound-assisted lubrication and automatic lubrication proved to be a natural and effective extension of this process, with a measurable impact in reducing equipment failures, lubricant waste, and unnecessary interventions.

Moreover, the centralisation of information in IBM Maximo will signify a pivotal step towards standardising and controlling technical data. This centralised approach has been demonstrated to enhance traceability and decision-making processes, thereby establishing a foundation for future automation. This includes the implementation of dynamic work orders based on sensor input, thus aligning lubrication management with the principles of predictive maintenance and Industry 4.0.

6.2 Study Limitations

The following limitations of the study should be noted:

- The implementation of automatic lubrication systems and oil analysis has been undertaken without the requisite pilot tests.
- The estimation of financial benefits is based on historical data and projections, without full empirical validation in the long term.
- The non-implementation of improvements related to voice navigation with RealWear devices and route optimisation using GPS, which remain in the planning stage due to time constraints, is a matter of concern.
- The integration of the sensors with IBM Maximo was unsuccessful due to time constraints.

6.3 Suggestions for Future Work

It is recommended that this project be continued through a structured and progressive approach that allows for further development of the results already achieved. In particular, priority should be given to the implementation and operational evaluation of automatic lubrication systems, especially in areas that are difficult to access or have high operational risk, allowing for the validation of the expected gains in terms of safety and efficiency.

Another key factor is the completion of the installation of condition monitoring sensors and their subsequent integration with the IBM Maximo system, ensuring the automation of alerts and the dynamic generation of work orders based on real-time operational parameters.

Concurrently, it is recommended to develop and validate voice command and georeferencing features applied to mobile-assisted maintenance, with a particular focus on assisted reality devices such as the RealWear Navigator 520, which have previously been studied in this work. The objective of these features is to enhance ergonomics, traceability, and the autonomy of technicians in the field.

Finally, it is important to emphasise the necessity of extending the digitalisation plan to the organisation's other industrial units, with due consideration for the technological maturity levels of each unit and their respective operational contexts. The basis for this adaptation should be the principles defined in this dissertation, with the objective of promoting the harmonisation of practices and overall strategic alignment.

The elements supporting these recommendations, including the future work plan, are detailed in Appendix E and F.

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Appendix A

17 Sustainable Development Goals (SDGs)

The 2030 Agenda for Sustainable Development, established by the United Nations in 2015, outlines global priorities and goals for sustainable development until 2030, aiming to unite nations in achieving these targets. The agenda comprises 17 Sustainable Development Goals (SDGs), Figure A.1, calling for collaboration between all countries to address pressing issues and create a shared global partnership. The current trajectory of development is resulting in environmental degradation, climate crises, rising inequalities, and social unrest. The SDGs present a crucial opportunity for promoting sustainable, inclusive growth essential for combating the climate emergency, biodiversity loss, and social disparities. It highlights the need for a paradigm shift towards regenerative practices to tackle these challenges effectively. (United Nations, n.d.)

Figure A.1: 17 Sustainable Development Goals (SDGs)

Among the 17 sustainable development goals, I would like to highlight three that fit within the scope of this dissertation and discuss them in more detail:

- Goal 9 - Industry, Innovation and Infrastructure: Build resilient infrastructure, promote inclusive and sustainable industrialisation, and foster innovation.
- Goal 12 - Responsible Consumption and Production: Ensure sustainable consumption and production patterns.
- Goal 13 - Climate Action: Take urgent actions to combat climate change and its impacts.

The Digitalisation of the Lubrication Function is closely linked to Sustainable Development Goals 9, 12 and 13, which focus on innovation, industrial sustainability and environmental impact reduction. Embracing technologies like IoT sensors and predictive maintenance fosters efficiency, safety and resilience in industrial processes (Goal 9). This shift also aligns with Goal 12 by facilitating better lubricant usage, minimising waste, extending equipment lifespan and optimising resources. Furthermore, by reducing friction, energy usage and part replacements, the environmental impact is lessened, resulting in decreased greenhouse gas emissions and lubricant consumption, supporting Goal 13. In essence, digitalising lubrication serves as a strategic approach in enhancing industry intelligence and promoting environmental responsibility.

Appendix B

Appendix of Literature Review

B.1 Lubricant Properties

Some of the most important lubricant properties, according to Roy, 2021, are:

- Viscosity: Physical-chemical property that measures the internal resistance of a liquid to flow at a given temperature.
- Flash point: Temperature at which the vapours generated by the lubricant ignite due to proximity to a flame. This allows lubricants to be classified in terms of flammability and gives an idea of the presence of aromatic compounds.
- Oxidation resistance: Oxidation occurs when oxygen reacts with any petroleum product. The process is accelerated in the presence of heat, light, metal catalysts, water, acids or solid contaminants. Lubricant oxidation causes: Increased viscosity, Formation of deposits/lacquers and Corrosion of metal surfaces.
- Thermal Stability: This is the resistance of a lubricant to decompose under high temperature conditions. Specific characteristic of the base oil used in the lubricant. It is not improved by additives.
- Detergency: This is the characteristic that a lubricant has to prevent or reduce the formation of compounds that give rise to deposits, as well as their accumulation in mechanical parts when operating at high temperatures.
- Dispersibility: This is the characteristic that a lubricant has to keep deposits formed at low operating temperatures in suspension and disperse them, essentially through interaction with condensation water.
- Demulsibility: The property of a lubricant to separate from water. Poor demulsibility of the lubricant can cause: Lack of Lubricating Film, Rust and Corrosion, Reaction and Decomposition of Additives, and Filtration Problems.

- Deaeration: The property that the lubricant has to separate from air. Poor deaeration can cause: Cavitation Problems in Pumps and Foam Formation.
- Anti-wear: The ability of a lubricant to prevent or reduce wear in areas where the formation of an adequate lubricating film cannot be guaranteed.
- Anti-rust and anti-corrosion: Additives that prevent rust (formed due to moisture and water condensation) and corrosion (formed due to organic acids produced during combustion and lubricant contaminants) from forming.

B.2 Lubrication Regimes

Lubrication regimes describe the conditions under which a lubricating film separates surfaces in relative motion. Understanding these regimes is essential for selecting the appropriate lubricant and ensuring the efficiency and longevity of mechanical components.

Firstly it is important to discuss **Boundary Lubrication**, seen in Figure B.1. In this regime, metal surfaces come into close touch because the lubricating coating is insufficient to entirely separate them. Starts, stops, low speeds, and large loads are examples of typical scenarios, where friction is high, and the wear is significant. This regime is one that is usually avoided. To counteract these effects, anti-wear or extreme pressure chemicals are utilised to create protective coatings on metal surfaces, and also it is very important to select a lubricant with the right viscosity (Machinery Lubrication, 2025).

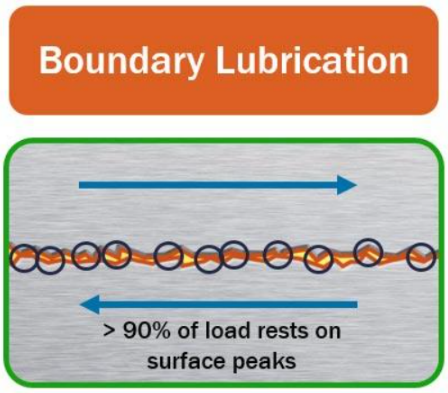


Figure B.1: Boundary Lubrication (Machinery Lubrication, 2025)

Now regarding the **Mixed Lubrication Regime**, seen in Figure B.2, as the speed rises, a partial lubricating coating builds between the surfaces, which reduces direct contact. In this intermediate regime, the lubricating coating supports part of the load while the roughness of the surfaces supports the rest. Friction is reduced compared to boundary lubrication, however there is still a risk of wear (Machinery Lubrication, 2025).

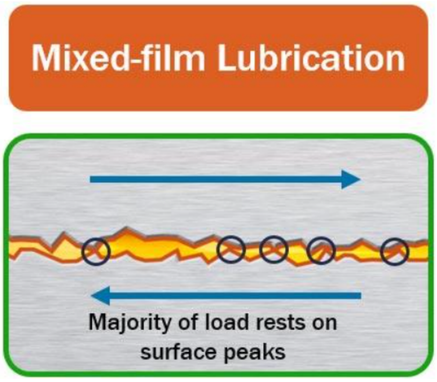


Figure B.2: Mixed-film Lubrication (Machinery Lubrication, 2025)

Hydrodynamic Lubrication, seen in Figure B.3, occurs when a continuous coating of lubricant entirely separates the moving surfaces, preventing direct contact between them. This regime is accomplished at greater speeds and with appropriate component geometry, such as simple bearings. This is a desirable condition to avoid friction and wear, friction is greatly minimised, and wear is low (Machinery Lubrication, 2025).

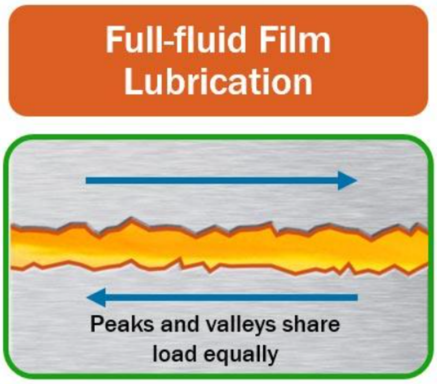


Figure B.3: Full-fluid film Lubrication (Machinery Lubrication, 2025)

Regarding **Elastohydrodynamic Lubrication**, seen in Figure B.4, it is a regime that exists in high-pressure, low-compliance contacts, such as bearings and gears. Under these conditions, the surfaces flex elastically, and the viscosity of the lubricant rises due to pressure, resulting in a film that separates the surfaces. Despite the high loads, direct contact is avoided, resulting in less wear (Machinery Lubrication, 2025).

Figure B.4: Elastohydrodynamic Lubrication (Machinery Lubrication, 2025)

Understanding and using these regimes correctly is critical for selecting lubricants and designing efficient and long-lasting mechanical systems.

Appendix C

Company Overview

C.1 Description of the Company and Industrial Sector

Sonae Indústria, founded in 1959, was a multinational wood-based panels company. It began its activity in Maia, in the north of Portugal, with an HPL factory, but continued to develop products for the furniture, construction and decoration industries in all over the world. Its focus was on using natural resources in a sustainable way and keeping environmental impact to a minimum.

Arauco was created in 1970 in Chile with the aim of producing and managing renewable forest resources and is an international benchmark in terms of forest surface management, industrial plant efficiency, production standards, innovation, environmental responsibility, and social commitment.

In 2016, the two companies, Sonae Indústria and Arauco, established a partnership from which Sonae Arauco emerged, as mentioned above. The company currently has around 2,600 employees, 20 industrial and commercial units in 9 different countries: Portugal, Germany, Spain, France, South Africa, the Netherlands, Switzerland, the United Kingdom, and Morocco, as you can see in C.1. Sonae Arauco's products are distributed to 76 countries, establishing it as one of the world's largest producers of wood-based panels.

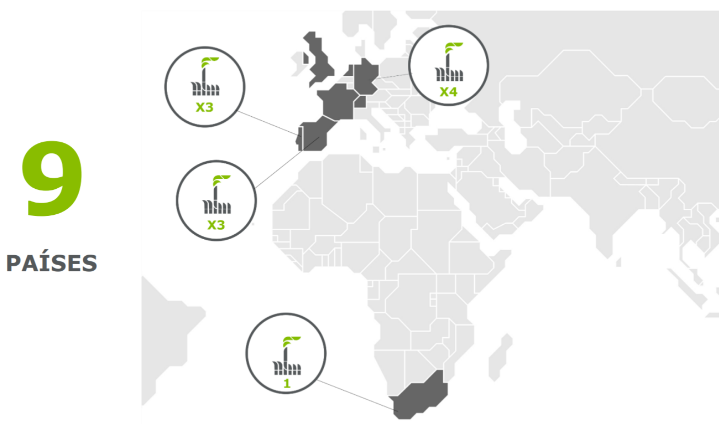


Figure C.1: Industrial and Commercial Units of Sonae Arauco

C.2 Vision, Mission and Values

Sonae Arauco's vision is to develop wood-based solutions for a better life and a better planet. The company is committed to the importance of wood in people's lives and strives to offer sustainable solutions that raise contemporary living standards. It wants to be the go-to wood-based brand for consumers, workers, suppliers, and communities, helping to improve quality of life, the future, and the planet's health.

Sonae Arauco's mission is to improve people's lives by providing wood-based products. It works with its business partners to achieve excellence and long-term profitability. By providing an ideal blend of industrial knowledge, functionality, sustainable quality, design, and affordable price, the company is dedicated to helping its clients achieve their goals.

Sonae Arauco's key values include a long-term company strategy, a strong growth ambition, a great manufacturing tradition, and expertise in wood-based solutions. The business has solid foundations and is designed to last for many generations.

C.3 Main Products and Brands

The foundation of Sonae Arauco's business is made up of wood-based panels, which are the most adaptable, environmentally friendly, and practical substitute for solid wood. From common applications to extremely complex and specialist needs, the company's portfolio comprises a wide range of goods made to satisfy various demands in the furniture, interior design, and construction industries. The main products made from wood panels are:

- **Medium-Density Fibreboard (MDF):** An excellent alternative to solid wood, ideal for furniture, flooring, and construction applications.
- **Particleboard (PB):** A versatile product recommended for furniture and construction industries.
- **Oriented Strand Board (OSB):** A highly durable product, suitable for both structural and non-structural applications in the construction sector.

The following brands are used to market Sonae Arauco's product line. Sonae Arauco continues to meet the changing demands of contemporary furniture manufacturing and construction through these brands and product lines, guaranteeing premium, eco-friendly, and cutting-edge wood-based solutions.

- **Innovus® Decorative Products:** This brand provides versatile and contemporary solutions for interior applications. It includes decorative panels and laminates designed to inspire creative and sustainable interior designs.
- **AGEPAN® SYSTEM:** Offering environmentally friendly wood fibre insulation, diffusion-open wood-based panels, and OSB Ecoboard® solutions, it supports sustainable construction practices.

- **Core & Technical Range:** Encompassing various wood-based panels such as PB, MDF, and OSB, this range provides flexibility and high performance for a wide range of applications.
- **3DF – Three Dimensional Fibreboard®:** A wood-based composite designed for compression moulding, allowing for the creation of complex and customised three-dimensional designs.

Appendix D

Results

D.1 Training Content

D.1.1 Theoretical Component

The theoretical component was delivered through a series of lectures and facilitated discussions, covering:

1. **Fundamentals of Lubrication:** Definition of lubrication, the role of lubricants in reducing friction and wear, and the five principal functions of lubricants (lubrication, cooling, cleaning, sealing and corrosion protection).

2. **Tribological Principles:** Detailed exploration of frictional regimes (static, boundary, mixed and hydrodynamic lubrication), surface asperity interactions, and wear mechanisms including abrasive, adhesive, corrosive, pitting and cavitation wear.

3. **Physicochemical Properties of Lubricants:** Viscosity and viscosity index; oxidation stability; demulsibility; detergency and dispersancy; the composition and consumption of additives (anti-wear, extreme-pressure, antioxidants, anti-foam).

4. **Contamination Control:** Origins and pathways of particulate, moisture and air ingress; effects of solid and water contamination on film integrity and fatigue life; methods for contamination quantification (particle counting, moisture measurement, air release tests).

5. **Storage and Handling Best Practices:** Design criteria for bulk storage and satellite reservoirs; environmental influences on lubricant ageing; colour-coding and labelling protocols; safe transfer techniques to prevent cross-contamination.

6. **Predictive Maintenance Technologies:** Principles and practicalities of oil-analysis (spectroscopy, ferrography, in-line sensors); ultrasound for early detection of bearing faults; trend analysis through vibration monitoring, alligned with the Sonae Arauco's Standards for Lubrication.

7. **Health and Safety Considerations:** Appropriate selection and use of personal protective equipment (gloves, goggles, overalls); risk assessment for spill containment; safe disposal of used lubricants in accordance with environmental regulations.

D.1.2 Practical Workshop

Complementing the theory, hands-on sessions were structured to reinforce best practices in a controlled laboratory environment. The key activities included:

1. **Assessment of Storage Infrastructure:** Participants were guided through a systematic assessment of the on-site lubricant storage area. This included the inspection of structural conditions—such as sealed and colour-coded floors and walls designed to minimise contamination risks — as well as the proper spatial arrangement of lubricant barrels to ensure safe handling and accessibility. The presence and correct installation of critical accessories were verified. Attention was also given to the cleanliness and organisation of the storage area, the existence of spill response stations, and the application of clear and standardised labelling in accordance with company policy. These elements collectively exemplified a model storage setup aligned with international best practices for contamination control and safety.

2. **Handling Technique Demonstrations:** The practical component included the complete execution of a lubrication task under real operational conditions. Participants first engaged in refilling a grease gun using the available methods, followed by the application of lubricant to machinery in the field. The task incorporated preparatory steps such as surface cleaning of the lubrication points and surrounding areas to prevent ingress of foreign matter. Best practice techniques were demonstrated and followed, highlighting the importance of cleanliness, accuracy, and discipline in manual lubrication activities.

3. **Instrument Familiarisation:** Technicians were trained in the use of the Ultraprobe 401 Digital Grease Caddy to support condition-based lubrication through ultrasound analysis. This included proper placement of the probe on bearing housings, live observation of ultrasonic signal fluctuations during lubrication, and interpretation of dB level changes. During the hands-on session, participants observed the progressive reduction in sound amplitude (dB) as grease was applied, confirming optimal lubrication while simultaneously preventing over-greasing. The instrument's ability to display real-time decibel readings when paired with the ability of the grease gun to display the amount of grease dispensed facilitated a data-driven approach to precision lubrication.

D.2 Centralisation of the Information in IBM Maximo

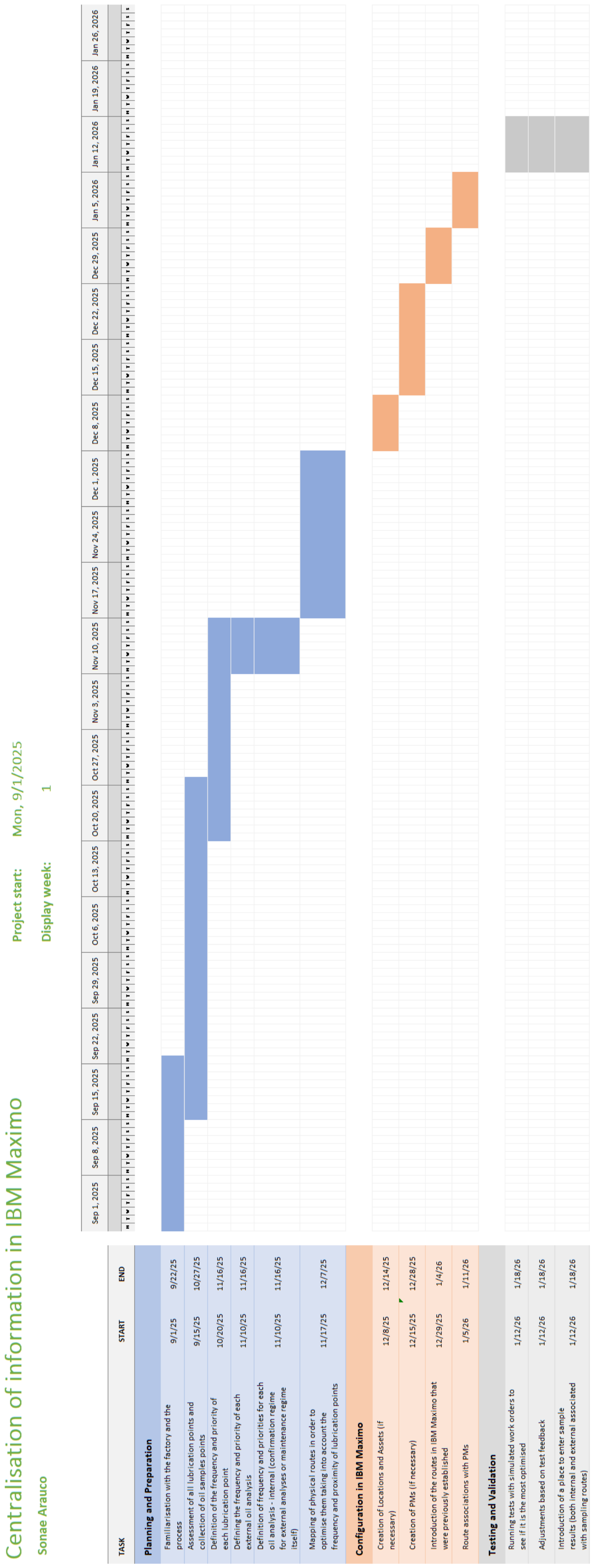


Figure D.1: Gantt Diagram of the Centralisation of information in IBM Maximo including the tasks about Oil Analysis

D.3 Templates of IBM Maximo

Figure D.2: Template of IBM Maximo to introduce the information retrieved from oil analysis

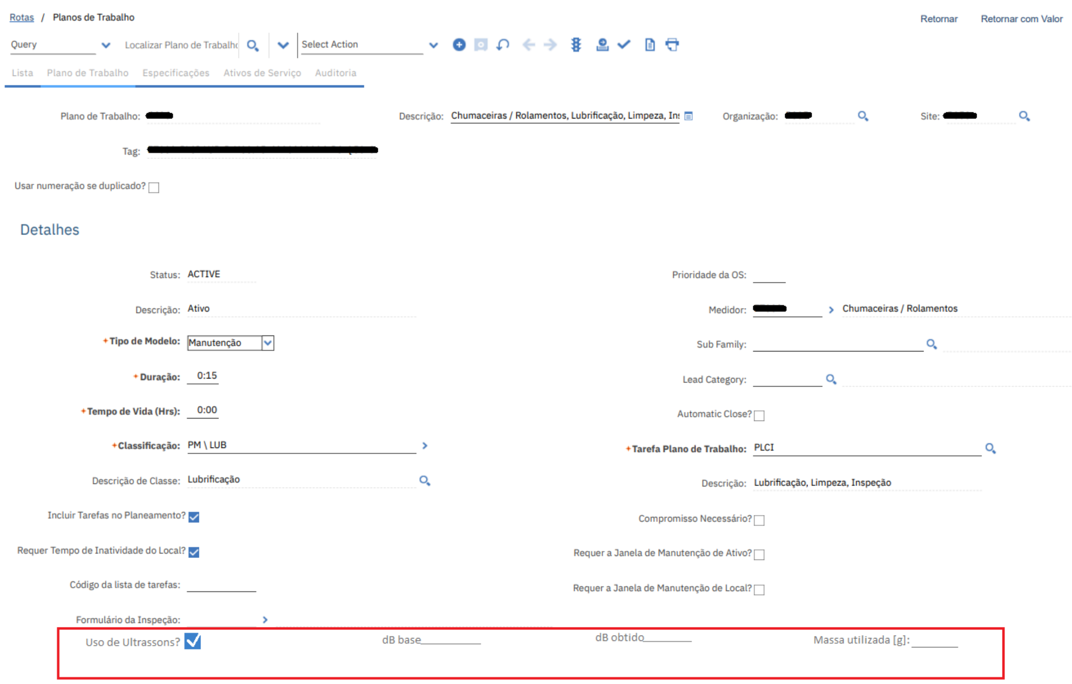


Figure D.3: Template of IBM Maximo to introduce the information retrieved using the ultrasound equipment

D.4 Data Collected

D.4.1 Ultrasound Pilot Test

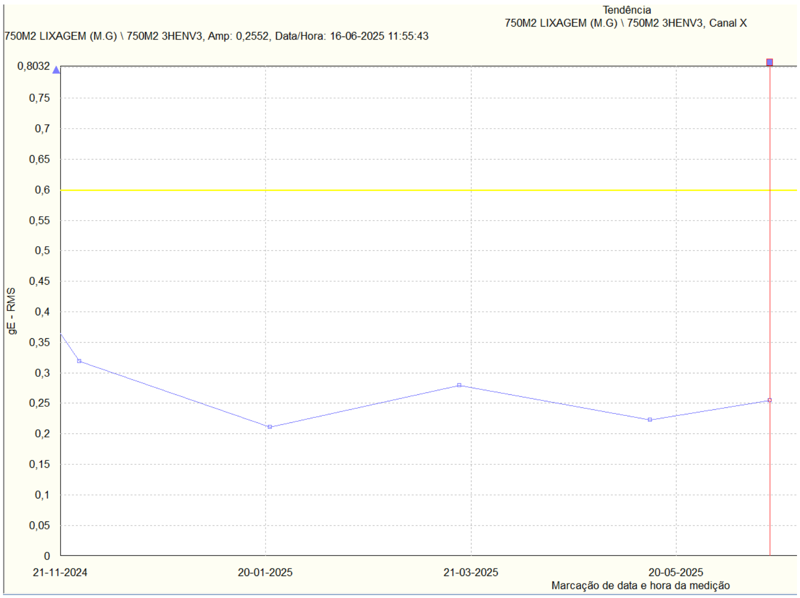
Table D.1: Results of the Pilot Test using the Ultrasound Equipment, level of noise (dB) before and after lubrication, amount of grease used (g) and time spent lubricating

Lubrication Date	**Variables Analysed**	**Assets**									
		1008838		**1002482**		**1002503**		**1000667**		**1000682**	
24-03-2025	Initial dB	60	63	51	55	56	57	46	49	40	43
	Final dB	48	45	51	38	37	37	31	35	29	23
	Grease Amount [g]	25	25	35	35	25	25	35	35	35	35
	Time	15:00									
16-04-2025	Initial dB	57	53	50	53	38	42	41	45	46	38
	Final dB	42	40	37	50	40	42	32	30	23	27
	Grease Amount [g]	11.6	7.2	25	40.4	12.5	18.8	14.4	10.1	13	21.6
	Time	09:50									
20-05-2025	Initial dB	65	59	52	53	30	50	40	48	38	41
	Final dB	47	46	51	53	29	33	28	32	23	23
	Grease Amount [g]	12	12.5	21.2	20	20	11	20.2	19	10	10
	Time	08:32									
20-06-2025	Initial dB	66	61	48	40	49	37	53	50	48	49
	Final dB	51	51	42	40	37	37	50	37	37	26
	Grease Amount [g]	15.4	8	5	0	5	0	5.3	10	7	9
	Time	08:15									

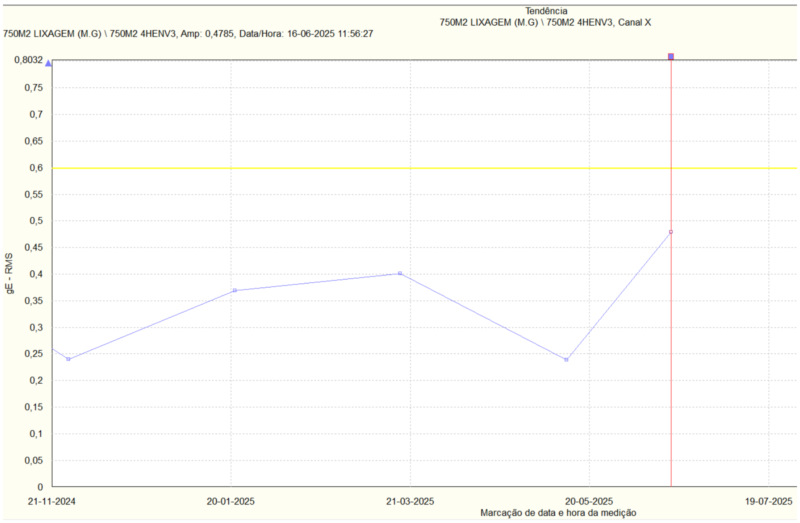
Table D.2: Results of the Pilot Test using the Ultrasound Equipment, total mass and time expenditure on each date, as well as percentage reductions compared to the initial sample

Collection Date	**Grease Amount [g]**	**Time [s]**	**Comparison with initial sample [g]**	**Comparison with initial sample [s]**
24/03/2025	310	900	**-**	**-**
16/04/2025	174.6	590	-43.68%	-34.44%
20/05/2025	155.9	512	-49.71%	-43.11%
20/06/2025	64.7	495	-79.13%	-45%
Average Reduction			**-57.51%**	**-40.85%**

D.4.2 Vibration Analysis

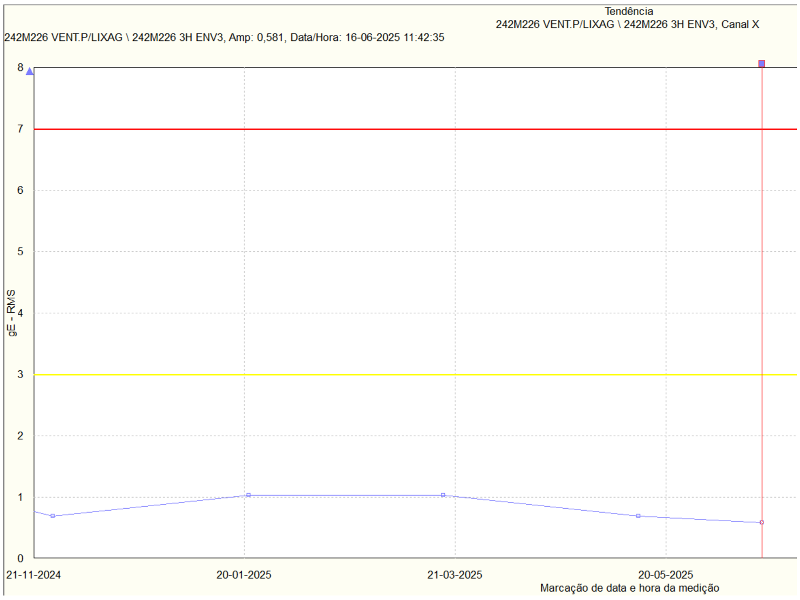


(a) Pulley side bearing

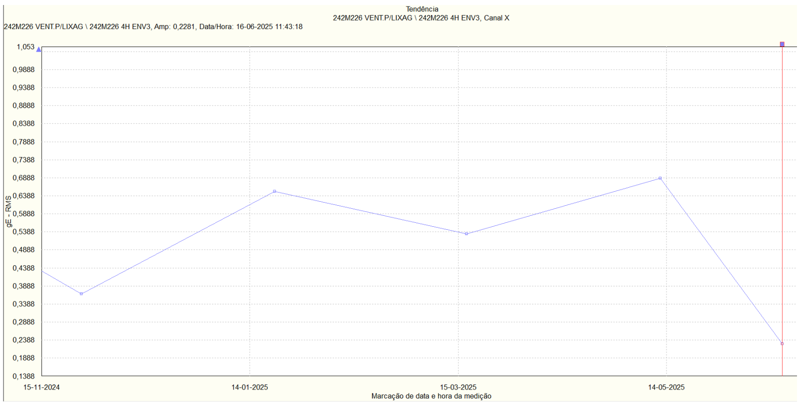


(b) Rotor side bearing

Figure D.4: Vibration analysis throughout the case study on fan 1008838

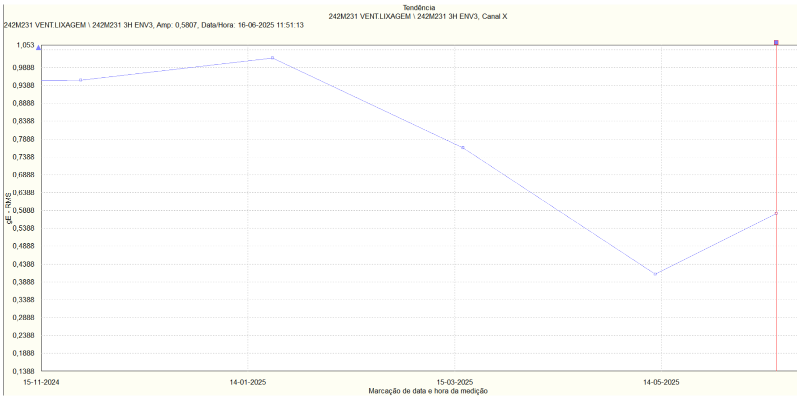


(a) Pulley side bearing

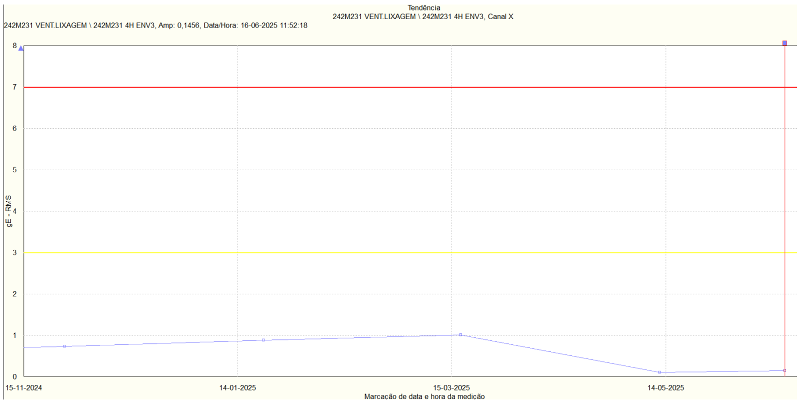


(b) Rotor side bearing

Figure D.5: Vibration analysis throughout the case study on fan 1002482

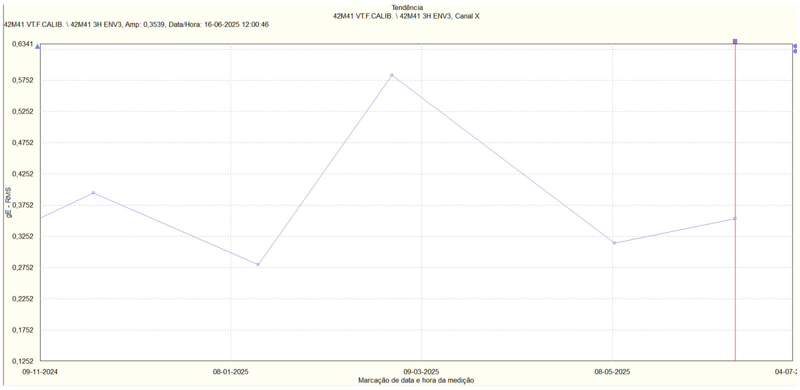


(a) Pulley side bearing

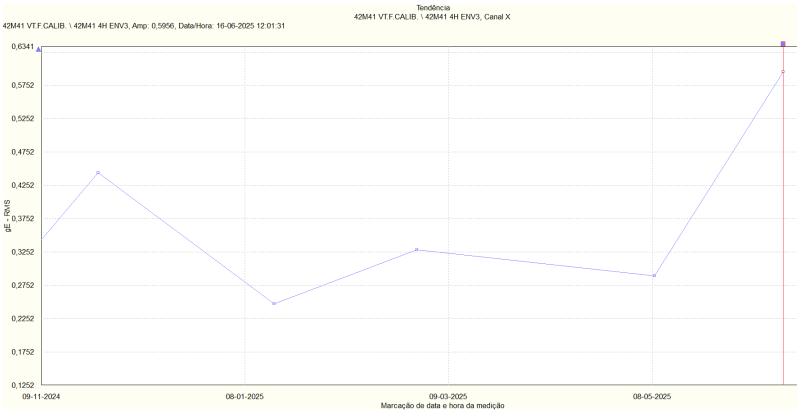


(b) Rotor side bearing

Figure D.6: Vibration analysis throughout the case study on fan 1002503

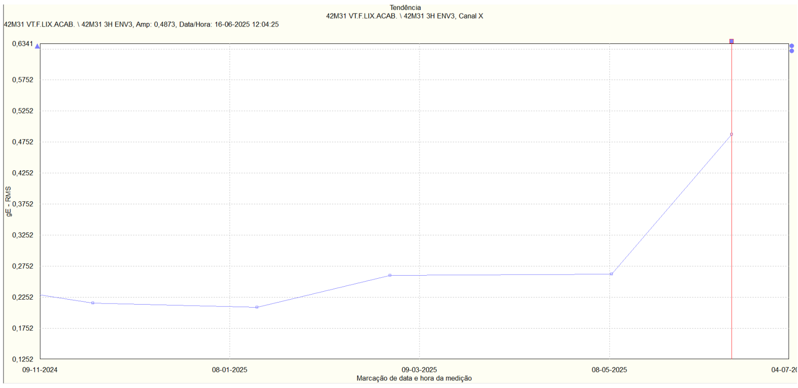


(a) Pulley side bearing

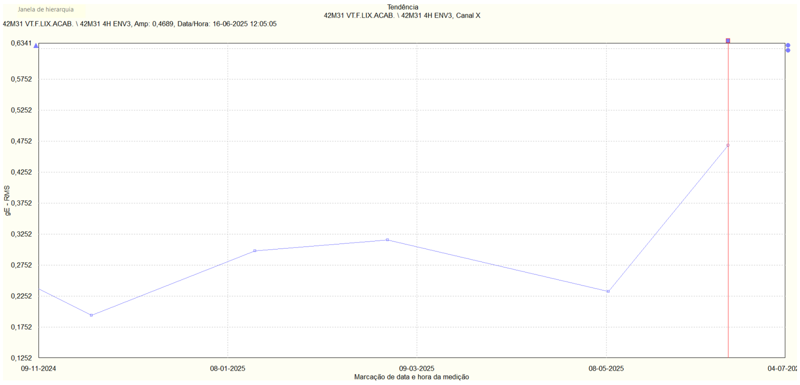


(b) Rotor side bearing

Figure D.7: Vibration analysis throughout the case study on fan 1000667



(a) Pulley side bearing



(b) Rotor side bearing

Figure D.8: Vibration analysis throughout the case study on fan 1000682

D.5 Total Yearly Savings Breakdown

Table D.3: Yearly Balance Breakdown of the Improvements

Yearly Breakdown					
Years	**Best Practices**	**Oil Analysis**	**Ultrasound Equipment**	**Automatic Lubrication**	**Total**
Year 1	-159,67 €	-8 342,02 €	10 864,54 €	-603,40 €	1 759,44 €
Year 2	808,17 €	-6 406,34 €	30 095,00 €	2 300,12 €	26 796,96 €
Year 3	1 795,37 €	-4 431,94 €	49 710,07 €	5 261,72 €	52 335,22 €
Year 4	2 802,31 €	-2 418,05 €	69 717,44 €	8 282,55 €	78 384,25 €
Year 5	3 829,39 €	-363,89 €	90 124,95 €	11 363,80 €	104 954,26 €
Year 6	4 877,02 €	1 731,36 €	110 940,62 €	14 506,67 €	132 055,67 €
Year 7	5 945,59 €	3 868,51 €	132 172,60 €	17 712,40 €	159 699,10 €
Year 8	7 035,54 €	6 048,41 €	153 829,22 €	20 982,24 €	187 895,41 €
Year 9	8 147,29 €	8 271,90 €	175 918,97 €	24 317,48 €	216 655,64 €
Year 10	9 281,27 €	10 539,87 €	198 450,52 €	27 719,43 €	245 991,08 €

Appendix E

Implementation Plan

E.1 Establishing a Strong Foundation Through Training

The first and arguably most crucial phase of the implementation involves equipping personnel with the knowledge and skills necessary to carry out lubrication activities effectively and safely in a digitalised environment. Structured training programmes should be designed and delivered to the following target groups: lubrication technicians, maintenance planners, mechanical and reliability engineers.

It is important to note that the training provided must also be tailored to the level of pre-existing knowledge. However, there is some basic knowledge that is fundamental, and there is no harm in reviewing it in order to continue building a strong knowledge base. The training curriculum should cover both theoretical and hands-on practical components and culminate in formal certification of competencies. Key areas of focus should include:

- Fundamentals of lubrication and tribology, to build a solid understanding of how lubricants function and the role they play in machinery health.
- Common sources of contamination, alongside methods for prevention and control, to improve lubricant reliability and asset longevity.
- Best practices in lubricant storage and handling, ensuring compliance with industry standards and reducing the risk of degradation or cross-contamination.
- Introduction to predictive maintenance (PdM) tools and technologies, enabling personnel to anticipate failures and optimise maintenance interventions.
- Health and safety procedures associated with lubrication tasks, emphasising hazard awareness and proper personal protective equipment (PPE) use.

E.2 Standardisation of Storage and Handling Procedures

To support a high standard of lubrication practice, physical infrastructure and handling methods must be upgraded where necessary. This step begins with a comprehensive audit of existing lubricant storage conditions to identify areas for improvement. Based on audit results, the following upgrades should be implemented:

- Floors should be sealed and painted for easy cleaning and spill detection.
- Storage rooms must be enclosed, ventilated, and secure, with access control if necessary.
- Racking systems should be installed to ensure neat and safe storage of lubricant barrels.
- Spill containment systems, such as bunds or floor drains, must be in place to manage accidental releases.

Furthermore, equipment and tools to improve consistency, safety, and efficiency in handling lubricants should be adopted, including:

- Battery-operated grease guns for uniform application and reduced operator fatigue.
- Colour-coded top-up containers to prevent cross-contamination between lubricant types.
- Clear labelling systems for all lubricant types and storage areas.
- Grease pumps, both manual and electric, to support precise application.
- Filter carts to facilitate oil transfer while minimising the risk of introducing contaminants.

It is important to assess the needs of each factory and act accordingly, in order to standardise lubricant storage and ensure that all factories are at the same level.

E.3 Centralising Lubrication Data in IBM Maximo

A cornerstone of digitalisation is the effective use of Computerised Maintenance Management Systems (CMMS). All lubrication-related data should be consolidated within IBM Maximo to ensure transparency, traceability, and ease of access. A survey should be conducted in all factories to assess their progress in this area. Factories that have not yet completed this process should follow the steps below that are appropriate to their situation in order to complete it as quickly as possible. This includes:

- Comprehensive registration of all assets and equipment, including identification numbers.
- Documentation of lubrication points, types of lubricant used, and recommended lubrication intervals.
- Historical data on work orders, interventions, and failures, if possible.

Standardised route templates should be created within Maximo to streamline: manual lubrication tasks, ensuring no point is overlooked; inspection and resupply routines for assets equipped with automatic lubrication systems; oil sampling and condition monitoring activities.

Additionally, customised fields should be introduced to capture critical condition monitoring metrics such as: oil analysis data; ultrasound readings in decibels (dB) for monitoring bearing and gearbox conditions; visual inspection notes, allowing qualitative observations to be logged.

E.4 Leveraging Existing Predictive Maintenance Tools

Before investing in new technologies, it is essential to make full use of equipment that has already been procured. Tools such as the Hydac FCU1310 (for fluid condition monitoring) and the Ultraprobe 401 (for ultrasonic inspection) are already catalogued and should be re-integrated into regular maintenance workflows.

Where knowledge gaps exist among staff, targeted training must be delivered to ensure correct usage. Data outputs from these devices should be integrated into Maximo or other central monitoring platforms to support data-driven decision-making.

E.5 Introducing Advanced Predictive Maintenance Technologies

Depending on the maturity level of each factory, new predictive technologies may be introduced to complement existing tools. This process should begin with a feasibility assessment, ensuring that conditions justify further investment.

Pilot projects should be launched with clearly defined objectives and key performance indicators (KPIs), allowing for measurable outcomes. Successful pilot implementations can then be scaled across the site. Key prerequisites include:

- Comprehensive training for relevant staff on equipment usage and data interpretation.
- Integration of monitoring outputs into Maximo.
- Clearly defined response workflows in the event of abnormal readings or alarms.

E.6 Automation Through Automatic Lubrication Systems

Where feasible, automatic lubrication systems should be introduced to enhance consistency and reduce human error. This requires a detailed audit of lubrication points to identify areas where automation offers the most value—particularly:

- Inaccessible or hazardous locations, where manual application poses safety risks.

- Safety-critical assets, where lubrication failure could result in significant downtime or hazards.
- Components prone to under-lubrication, as evidenced by historical data or maintenance records.

Selected systems (e.g., single-point or multi-point lubricators) must be suited to the specific application. Maximo should then be configured to include inspection and refill tasks for these automated systems, ensuring accountability and performance tracking.

E.7 Scaling Sensorisation for Condition Monitoring

As digital maturity increases, sensor deployment should be expanded to cover a broader range of critical assets. The aim is to move towards continuous condition monitoring for key machinery components.

Integration with existing platforms is essential, allowing sensor data to be analysed in context with other operational parameters. As part of this process: Alert protocols must be established, including escalation procedures for abnormal conditions; and collaboration with system suppliers and IBM is advised to enable the automatic generation of work orders based on sensor alerts.

E.8 Optimising Routes and Enabling Voice-Controlled Maintenance

To further enhance technician efficiency, route optimisation technologies and voice-assisted tools such as RealWear headsets should be introduced. The initial step involves creating a georeferenced digital map of the facility, with each asset and lubrication point linked to a unique Maximo location ID and its corresponding physical coordinates.

Voice-controlled devices offer several operational advantages:

- Hands-free access to Maximo during maintenance tasks.
- Enhanced task documentation through real-time voice input.
- Improved safety and productivity, as technicians can navigate routes and access data without pausing their work.

Appendix F

Future Works

F.1 Sensorisation

A key facilitator of the shift from reactive or time-based maintenance tactics to a predictive, data-driven strategy is the use of condition monitoring sensors. Because of an existing service agreement with Preditec that includes the purchase, installation, and calibration of sensors on vital equipment, sensorization has already started in the framework of this project. However, it was determined that a strong and smooth integration of sensor data with IBM Maximo — the site's Computerised Maintenance Management System (CMMS) — is beneficial to fully achieve the advantages of this technology. This integration limits the usefulness of valuable condition data in automated decision-making by keeping it separate from the maintenance planning process.

Although the technical implementation of the sensor network and its possible integration with IBM Maximo was outside the direct scope of this project, it is anticipated that such integration will yield substantial operational benefits. These include the automation of condition-based work order generation, faster response to emerging faults, improved accuracy in maintenance prioritisation, and enhanced traceability of asset health. As such, the sensor infrastructure represents a foundational element for the factory's broader transition toward a predictive and digitally enabled maintenance strategy.

F.2 Route Optimisation and Voice Control

Two state-of-the-art technological solutions were assessed for their potential to greatly improve maintenance efficiency and operator safety as part of Sonae Arauco's ongoing digital transformation strategy: voice-activated maintenance execution using RealWear head-mounted devices and GPS-based route optimisation. The planned switch to the IBM Maximo Application Suite (MAS), which offers the fundamental digital infrastructure needed for their deployment and smooth integration, is inextricably tied to these advancements.

The creation of a thorough georeferenced digital map of the complete plant is required for the initial stage of this integration. In order to do this, each lubrication point and other important maintenance locations must be carefully linked to a specific, individually defined Maximo asset location. To accurately track and optimise maintenance procedures within the physical layout of the plant, this spatial correlation must be established. Once integrated into Maximo, the digital map will make it easier to visualise asset locations and technician positions in real time.

Parallel to the mapping efforts, workflows must be devised to integrate the RealWear voice-controlled interface with IBM Maximo. This integration aims to allow maintenance personnel to interact hands-free with the CMMS during task execution—enabling voice commands to navigate work orders, record data, and access remote assistance without the need for manual device operation.

Preliminary evaluations indicate significant advantages, even though concrete outcomes and empirical data from operational deployment were not yet available because of the MAS update. It is expected that GPS route optimisation will significantly cut down on needless transit time inside the building, leading to more effective scheduling and maintenance work completion. Additionally, the implementation of voice-controlled maintenance is anticipated to improve operator safety by enabling continuous attention to the work environment and limit the handling of mobile devices, which could lower contamination risks and task completion times.

Other expected benefits include real-time operator position tracking with GPS-enabled mobile devices connected to Maximo Mobile, which offers vital safety advantages in emergency situations by instantly knowing the presence of personnel. By bringing specialised advice right into the technician's line of sight, the ability to provide remote expert support with RealWear devices also promises to increase first-time fix rates and decrease downtime.

The purchase of RealWear headsets accounts for the majority of the actual hardware investment, but the required software development, system integration, and implementation work within the Maximo environment account for a sizable amount of the project's cost. Because of increased operating efficiency, better safety procedures, and more precise maintenance reporting and verification, the anticipated return on investment is significant even with the initial capital expenditure.