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Intelligent Management of Physical Assets to Maximise Operational Efficiency and Reduce Environmental Impact

Project Report to fulfil the Master's degree in Engineering and Management of Physical Assets

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ACRONYMS

AG	Autogenous
AI	Artificial Intelligence
AM	Asset Management
AR	Augmented Reality
CBM	Condition-Based Maintenance
CIAM	Centre of Intelligent Asset Management
COVID-19	Corona Virus Disease 2019
D	Detection
DT	Digital Twins
EN	European Norm
FM	Failure Mode
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects, and Criticality Analysis
FRO	Frequency Converter
IAM	Intelligent Asset Management
IEC	International Electrotechnical Commission
IIoT	Industrial Internet of Things
IoT	Internet of Things
ISEC	Instituto Superior de Engenharia de Coimbra
ISO	International Organization for Standardization
IT	Information Technology
KPIs	Key Performance Indicators
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LCI	Life Cycle Investment
LKAB	Luossavaara- Kiirunavaara Aktiebolag
LTU	Luleå Tekniska Universitet
ML	Machine Learning
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
P1 and P2	Primary mill 1 and 2
PAM	Physical Asset Management
PdM	Predictive Maintenance
PPT	People, Process and Technology
O	Occurrence
OEM	Original Equipment Manufacturer
ROI	Return On Investment
RPN	Risk Priority Number
RQ	Research Question
S	Severity
SAMP	Strategic Asset Management Plan
SMART	Specific, Measurable, Achievable, Realistic, and Time-bound

VFD	Variable Frequency Drive

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ABSTRACT

This thesis explores the field of Intelligent Asset Management (IAM), emphasizing the integration of advanced strategies and technologies to enhance the management of physical assets in industrial contexts. In response to the demand for operational efficiency and environmental responsibility, this thesis critically examines existing asset management practices to identify opportunities for performance improvement and enhance long-term resilience.

As a key contribution, new framework for Intelligent Asset Management was developed. Designed to integrate technology, people, process and external regulations and policies, align with the Industry 5.0 principles, providing valuable insights to improve industrial asset management and promote sustainable operational practices.

To validate and apply the framework, a case study was conducted in collaboration with LKAB company, focusing on the analysis of two grinding mills. The study assessed maintenance effectiveness and operational performance through a detailed examination of shutdown frequency, downtime duration, and failure modes. Analytical tools employed include maintenance Key Performance Indicators (KPIs), Failure Modes, Effects, and Criticality Analysis (FMECA), and Cause-and-Effect diagrams. Additionally, the potential benefits from downtime reduction were modelled, projecting corresponding gains in production efficiency and energy savings.

For future research, the application of additional analytical tools such as Weibull and Pareto distributions, as well as energy and cost-related KPIs, is recommended. Furthermore, future studies should analyse the interface between humans and IAM systems and evaluate how the proposed framework can be adapted across various industries facing operational challenges.

Keywords:

Physical Asset; Intelligent Asset Management; Operational Efficiency Strategies; Sustainability; Industry 5.0

RESUMO

Esta tese explora o campo da Gestão Inteligente de Ativos (IAM) com ênfase na integração de estratégias avançadas e tecnologias inovadoras para otimizar a gestão de ativos físicos em contextos industriais. Em resposta às crescentes exigências de eficiência operacional e responsabilidade ambiental, procede-se a uma análise crítica das práticas atuais de gestão de ativos, com o objetivo de identificar oportunidades de melhoria de desempenho e reforço da resiliência a longo prazo.

Como contribuição principal, foi desenvolvida uma nova estrutura para Gestão Inteligente de Ativos. Concebida para integrar tecnologia, pessoas, processos e, regulamentos e políticas externos, alinhada com os princípios da Indústria 5.0, fornecendo informações valiosas para melhorar a gestão de ativos industriais e promover práticas operacionais sustentáveis.

Para validar e aplicar a estrutura, foi realizado um caso de estudo em colaboração com a empresa LKAB, com foco na análise de dois moinhos industriais. A avaliação incidiu sobre a eficácia das práticas de manutenção e o desempenho operacional, através da análise detalhada da frequência de paragens, da duração dos tempos de inatividade e dos modos de falha. As ferramentas analíticas utilizadas incluem indicadores-chave de desempenho (Key Performance Indicators - KPIs) de manutenção, Análise de Modos de Falha, Efeitos e Criticidade (Failure Modes Effects, and Criticality Analysis – FMECA) e diagramas de Causa e Efeito. Além disso, foram simulados os potenciais benefícios decorrentes da redução dos tempos de inatividade, com projeções de ganhos na produção e poupança energética.

Para pesquisas futuras, recomenda-se a aplicação de ferramentas analíticas adicionais, como distribuições de Weibull ou Pareto, bem como KPIs relacionados à energia e custos. Além disso, estudos futuros devem analisar a interface entre humanos e sistemas IAM, e avaliar como a estrutura proposta pode ser adaptada em vários setores que enfrentam desafios operacionais.

Palavras-Chave:

Ativos Físicos; Gestão Inteligente de Ativos; Eficiência Operacional; Sustentabilidade; Indústria 5.0

1 INTRODUCTION

The management of physical assets has evolved from a routine operational activity into a strategic function critical to the success of contemporary organisations. Beyond their tangible value, physical assets such as structures, machinery, or equipment play a central role in ensuring operational efficiency, enabling innovation, and supporting sustainability objectives. As industrial environments become increasingly complex and competitive, the ability to manage assets effectively is crucial for long-term performance and environmental responsibility [1].

In recent years, the field of Physical Asset Management (PAM) has expanded significantly, reflecting the rising pressures of technological advancements, environmental concerns, and economic volatility. Traditional asset management approaches – often limited to maintenance operations, logistics, or engineering functions – are no longer sufficient to meet organisational objectives or stakeholders' expectations. In response, a more integrated and value-driven paradigm has emerged, supported by standards like ISO 5500X series, which emphasizes the alignment of asset management practices with organizational goals [2].

In diverse industrial sectors physical assets represent significant investments and serve as the backbone of operations. Their effective management is essential not only for business continuity and return on investment, but also to respond to rising demands for sustainable practices and better use of resources.

The emergence of Industry 5.0 marks a new evolution in industrial strategy. While Industry 4.0 emphasised digitalisation, automation, and connectivity, Industry 5.0 extends this trajectory by placing emphasis on human-centricity, resilience and sustainability. This paradigm shift demands for asset management systems that are not only technologically advanced but also socially responsible and environmentally aligned [3], [4].

Although the concept of Intelligent Asset Management (IAM) is not entirely new, its interpretation and application are evolving. In the context of Industry 5.0, IAM is no longer limited to technological optimisation but is increasingly viewed as a strategic framework that embraces sustainability, resilience and human-centric values [5].

In this context, intelligent and sustainable asset management has the potential to transform industrial performance. Standards and complementary framework support this transformation by providing structured methodologies for asset life cycle management. These approaches enable organisations to improve performance, optimise resources utilisation, and reduce their environmental footprint in a coherent and measurable manner.

1.1 Problem statement

Industries that rely heavily on physical assets are under increasing pressure to enhance operational efficiency while meeting sustainability expectations. However, current asset management practices often lack the adaptability, integration, and long-term perspective needed to address these complex and evolving demands. There is a need for more intelligent, structured, and forward-looking approaches that align with the principles of Industry 5.0.

1.2 Purpose and objectives

The purpose of this research is to analyse and propose innovative strategies for the intelligent management of physical assets in the industrial sector, with a focus on maximising operational efficiency and promoting environmental sustainability.

The main objective is to develop and propose a comprehensive framework for Intelligent Asset Management (IAM) that aligns with the principles of Industry 5.0.

The sub-objectives are the complement of the main objective and will guide the research steps:

Sub-objective 1: Identify the limitations of traditional Physical Asset Management (PAM) approach and explore Industry 5.0 principles;

Sub-objective 2: Analyse a real-world case study and propose strategic recommendations for intelligent asset management;

Sub-objective 3: Design a framework that illustrates how IAM can be implemented to optimise performance, reduce downtime, and support strategic industry goals, leading industries to achieve Industry 5.0 development.

1.3 Research questions

The three research questions below are a fundamental part of this thesis, to provide a clear focus and direction for the research:

- **RQ1:** What are the main challenges associated with managing physical assets in industry?
- **RQ2:** What are the key elements that influence the implementation of asset management in industry?
- **RQ3:** How should intelligent asset management of physical assets be implemented to support Industry 5.0?

1.4 Scope and limitations

The scope of this thesis focuses on the development of a new framework from traditional asset management (AM) to Intelligent Asset Management (IAM), in the context of Industry 5.0.

The study also conducts a case study whose objective is to analyse the management of two grinding mills. The research investigates asset performance, maintenance effectiveness, and propose strategic recommendations for long-term value creation of the physical assets.

The main areas covered included:

- Evaluate existing PAM practices to identify strengths, weaknesses, and areas for improvement;
- Analyse operational data, including downtime, failure modes, stoppage frequency, to uncover inefficiencies and systemic issues;
- Model potential improvements using IAM methodologies to support data-driven decision-making;
- Discuss maintenance strategies focused on operational efficiency and sustainability;
- Explore Industry 5.0 principles: human-centricity, resilience, and sustainability.

While the thesis provides valuable insights, several limitations are acknowledged:

- The research is limited to a single case study with two specific grinding units;
- The analysis relies on operational data provided by the company, any limitations in data may affect the accuracy of the results;
- While the thesis conceptually incorporates Industry 5.0 principles, the practical implementation was not tested;
- The research was conducted over a limited period of time, which restricted the possibility of long-term validation of the proposed improvements.

1.5 Structure of the thesis

This thesis consists in six chapters:

1. Introduction: This chapter sets the stage for the thesis by introducing the importance of physical asset management in modern industries and highlighting its evolution from a technical function to a strategic priority. Additionally, it outlines the research purpose, objectives and the research questions. The chapter also defines the scope, limitations, and overall structure of the thesis.

2. Research Methodology: This chapter explains the research approach, detailing the background, purpose, and strategy of the study. It outlines the research process and describes the methodologies used for data collection and analysis.
3. Theoretical Framework: This chapter introduces the foundational theories and concepts that have been applied or are essential to understanding the frameworks, tools, and methodologies developed in this research.
4. Case Study: This chapter includes a detailed case study that analyses two industrial autogenous mills, and the methodology applied.
5. Results and Discussion: This chapter presents the outcomes derived from the research in response to the formulated research questions, and the case study results.
6. Conclusions: This chapter offers a comprehensive conclusion, analysing the results and discussions from Chapters 5. Also, highlights the contributions of the research, summarizing the key findings, methods, and practical implications. This chapter suggests potential avenues for future research based on the results and conclusions of this thesis.

2 RESEARCH METHODOLOGY

This chapter outlines the case study methodology employed to investigate intelligent management of physical assets focusing on maximising operational efficiency while reducing environmental impact. The methodology integrates both qualitative and quantitative approaches, leveraging advanced tools and frameworks to ensure robust and replicable findings [6].

2.1 Research participants

The Instituto Superior de Engenharia de Coimbra (ISEC) is the home university for the master's degree.

This internship was conducted through the Erasmus+ Programme, in collaboration with Luleå University of Technology (LTU - Luleå Tekniska Universitet) in Sweden (Figure 2.1). The work took place within the Division of Operation and Maintenance Engineering, with the eMaintenance and AI Factory research group, and in partnership with the Centre of Intelligent Asset Management (CIAM).

The case study in this research was conducted in collaboration with LKAB (Luossavaara-Kiirunavaara Aktiebolag), a Swedish state-owned company founded in 1890 and headquartered in Luleå. Standing out as one of the global leaders in iron ore mining and processing, the company plays a crucial role in supplying high-quality iron pellets, an essential input in steel production. The company operates mainly in northern Sweden, in Kiruna, Malmberget, and Svappavaara, where the mines are located (Figure 2.2).

Figure 2.1 - Luleå University of Technology, source: www.ltu.se

Figure 2.2 - LKAB, Kirunavaara mountain, source: www.lkab.com

2.2 Research background

In today's highly competitive and environmentally conscious industrial landscape, efficient management of physical assets has become a critical factor for committed organisations to enhance operational performance while minimising their ecological footprint.

This physical assets, face significant challenges related to equipment reliability, unplanned downtime, maintenance effectiveness, and energy consumption. These challenges not only impact production efficiency but also contribute to increased operational costs and adverse environmental effects due to wasted energy and resource utilization. Unplanned downtime and inefficient maintenance not only reduce production but also result in significant energy losses.

2.3 Research approach

The study adopts a case study methodology combined with a mixed-methods approach, integrating both qualitative and quantitative methods to provide a comprehensive analysis of existing challenges and opportunities [7], [8].

The quantitative component involves acquiring asset data from the company and analysing it using defined performance metrics, including a statistical comparison of the mill's operational performance.

The qualitative component includes semi-structured interviews[1] with experts and a Failure Modes, Effects, and Criticality Analysis (FMECA), based on expert input and structured risk prioritisation.

2.4 Research purpose

The purpose of this thesis is to explore how Intelligent Asset Management (IAM) can be leveraged to improve the operational performance, resilience and sustainability of physical assets within industrial environments. By integrating strategic frameworks and aligning with emerging Industry 5.0 principles, the research aims to demonstrate how advanced asset management approaches can enhance decision-making, reduce downtime, and promote environmentally responsible operations.

Through a case study, the thesis seeks to provide practical insights into the application of data-driven maintenance strategies and sustainable asset practices in real-world industrial settings,

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[1] Are guided conversations that use a set of prepared open-ended questions, while allowing flexibility to explore new topics that emerge during the discussion

offering a forward-looking perspective on asset management evaluation as industries adapt to technological advancements and broader societal changes.

2.5 Research strategy

The research proposes a new conceptual framework that bridges the gap between IAM and the emerging Industry 5.0 paradigm. While IAM has traditionally been analysed from technological and operational perspectives, Industry 5.0 remains a relatively recent concept, and current literature lacks a structured integration of these domains.

To address this gap, the study adopts a case study methodology supported by a mixed-methods research approach. The conceptual framework is developed through a comprehensive literature synthesis, and its practical relevance is examined through an in-depth case study at LKAB. This includes qualitative methods such as FMECA, alongside quantitative analysis of operational data. This combined approach enables both theoretical contributions and practical insights grounded in real-world data.

2.6 Data collection and analysis

Data were collected through semi-structured interviews and document analysis within a single case study organisation. The collected data were analysed thematically to evaluate how the proposed conceptual framework aligns with real-world asset management practices.

First, the conceptual framework was developed through a structured literature review, focusing on key international standards (ISO 5500X series, 55011, 55012, 55013, ISO14001, ISO13306, ISO15341) and relevant academic models in AM, IAM, Industry 5.0, and related fields. Sources were selected based on publication year, relevance, and academic credibility from Google Scholar and Scopus.

Second, a case study was conducted to assess the framework's practical applicability. Data were collected from maintenance records detailing unplanned maintenance interventions, as well as through expert consultations and discussions with engineers to understand operations, management practices, and root causes of failures. Data processing and analysis were performed using Excel, Spyder Editor (through *Python* coding) and PowerBi Desktop.

2.7 Research validity and reliability

Reliability and validity are fundamental concepts for assessing research quality, particularly in the selection of data collection and analysis techniques for studying measured parameters.

Validity refers to the accuracy of results, while reliability refers to the consistency of results [9], [10].

Regarding content validity, the research instruments – such as interviews and data analysis methods – were carefully designed to capture all relevant factors, ensuring they accurately represent key aspects of operational efficiency and environmental impact.

To maintain internal validity, this study controls for potential confounding variables by focusing on data from LKAB and applying a structured analysis methodology. The use of both qualitative and quantitative data sources strengthens internal validity by providing a comprehensive view of asset management practices.

In terms of external validity, the conclusions drawn are applicable not only to LKAB but also to other industrial sectors facing similar operational and sustainability challenges.

To enhance reliability, all data collection followed standardised procedures to ensure consistency. Additionally, the study uses established key performance indicators (KPIs) that are widely recognised in asset management research, further reinforcing the reliability of the measurements.

2.8 Research process

This research followed an eight-phase process combining theoretical and empirical approaches, including:

1) Problem definition and objectives: Identify research gaps, define the research problems, and formulate clear research questions and objectives to guide the study;
2) Literature review: Conduct a structured review of academic and industry sources to understand existing frameworks, concepts, and best practices related to asset management in the context of Industry 5.0;
3) Conceptual framework development: Based on insights from the literature, design a new conceptual framework that addresses the identified gap and supports value creation in physical asset management through IAM interconnected with Industry 5.0 principles;
4) Case study: Select a relevant organisation to evaluate and explore the proposed framework, defining the case scope, data sources, and methods for collecting qualitative data;
5) Data collection: Gather empirical data from the selected case using tools such as semi-structured interviews, internal documents, and reports;
6) Data analysis: Analyse the collected data thematically or comparatively, linking findings to elements of the proposed framework;

7) Framework validation and refinement: Evaluate how the framework fits the real-world context and refine it accordingly;
8) Conclusions and contributions: Summarize key findings, articulate the theoretical and practical contributions of the research, and reflect on its implications, limitations, and suggestions for future work.

3 THEORETICAL FRAMEWORK

The theoretical framework establishes the foundation for understanding intelligent physical asset management, focusing on strategies aimed at maximising operational efficiency and minimizing environmental impact. This chapter defines and explores the key concepts central to the thesis, organising them into relevant subsections to ensure clarity and consistency.

3.1 Physical Assets Management (PAM)

Physical assets are tangible items that have a physical presence and are utilized by organisations to generate value through their operation, production, or service delivery activities. These assets include a wide range of categories such as machinery, equipment, buildings, infrastructure, vehicles, tools and natural resources. In many industrial sectors physical assets represent significant capital investments [1], [11].

Asset performance and availability are linked to an organisation's ability to achieve operational reliability, efficiency, safety, environmental compliance, and long-term competitiveness. The performance of an asset refers to how well it fulfils its intended function, including production quantity, quality, speed and responsiveness under normal operating conditions. On the other hand, availability is the percentage of time that an asset is available for use when needed, considering downtime due to failures, maintenance, or other delays [12].

A failure is when an asset cannot perform its intended function. A fault is an abnormal condition that may lead to a failure or is already causing degraded performance. Among failures, a critical failure is one that has a significant impact on safety, environmental compliance, production continuity, or cost, and typically involves assets that are essential to operational or strategic outcomes.

Physical assets need to be well managed, which implies a set of practices and organisational processes that aim to maximise the value and performance of assets throughout their lifecycle [13]. This involves not only the maintenance and operation of assets but also the strategic management of a company's resources in the way that supports organisational goals and improves efficiency and competitiveness [14], [15].

The five stages of asset management lifecycle, include:

- Plan: Define the strategic direction, asset requirements, and management objectives based on organisational goals, stakeholder[2] expectations, and lifecycle cost considerations;

[2] Anyone affected by or involved in an organisation, such as employees, customers, suppliers, communities, and regulators

- Acquisition: Acquiring assets in alignment with the defined plan. This includes selecting, designing, purchasing, and commissioning assets to meet performance and value objectives;
- Operation: Using assets in a way that ensures optimal performance, safety, and efficiency. This stage focuses on delivering the expected service or production levels while meeting compliance and cost targets;
- Maintenance: Perform preventive, predictive, and corrective maintenance activities to sustain asset condition, minimise downtime, and extend useful life;
- Replacement or disposal: Decide when to upgrade, replace or dispose of assets that have reached the end of their useful life, considering economic, environmental, and operational factors.

An effective management of the asset ensures that they consistently deliver the expected performance throughout their lifecycle, from acquisition to decommissioning, while minimising risks and optimising costs. Poor asset management can lead to frequent failures, high maintenance costs, operational disruptions, safety incidents, and significant financial losses [16]. Figure 3.1 shows the asset lifecycle stages [17].

Figure 3.1 – Asset lifecycle stages.

The development and implementation of international standards have been essential in promoting a unified and globally consistent approach to asset management. These standards provide comprehensive frameworks that help organisations establish, document, monitor, and continuously improve asset management practices across different industries and asset types.

3.2 Intelligent Asset Management (IAM)

Intelligent Asset Management (IAM) is a strategic approach to manage physical assets using advanced technologies and methodologies. Unlike traditional asset management, IAM incorporates advanced technologies, real-time monitoring, and predictive analytics to optimise asset performance, improve operational efficiency, and extend asset life [18]. At its core, IAM systems continuously collect, process, and analyse real-time operational data from physical assets to detect anomalies, forecast potential failures, and recommend optimal maintenance actions before breakdowns occur. By proactively identifying issues at an early stage, IAM helps reduce unplanned downtime, lowers maintenance costs, enhance safety, and maximise production output[18], [19].

The implementation of IAM leverages a combination of advanced technologies and methodologies, including Artificial Intelligence (AI), with algorithms that analyse historical and real-time data to identify failure patterns and Predict Maintenance (PdM) needs, and the Internet of Things (IoT), through networked sensors monitoring critical asset parameters such as vibration, temperature, and load conditions. In addition, big data analytics, data visualisation, and large-scale data processing are used to extract meaningful insights from operational datasets [18], [19].

While the People – Process – Technology (PPT) model was originally developed in the fields of Information Technology (IT) and cybersecurity, it has become a widely accepted framework in digital transformation across various industries. In the context of IAM, this triad is highly relevant because technology alone does not ensure success and must be embedded within structured asset management processes and supported by skilled and engaged people, as illustrated in Figure 3.2 [20].

These elements must operate in harmony to deliver value throughout the entire lifecycle of physical assets. Their alignment ensures that data-driven decision-making, human expertise, and structured methodologies are mutually reinforcing, resulting in improved performance, resilience, and sustainability [20].

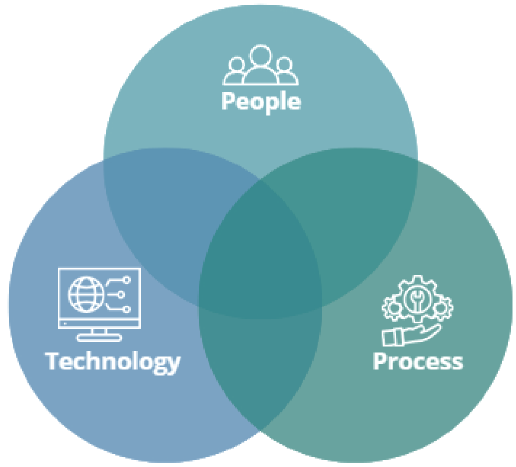

Figure 3.2 - People – Process - Technology model.

3.3 International Standards

The international standards play a crucial role in establishing structured, efficient, and sustainable approaches to asset management across industries.

The ISO 55000 family is the global standard for asset management, offering guidance on structuring, implementing, and improving asset management systems. It consists of three core standards, ISO 55000, ISO 55001, and ISO 55002.

The ISO 55000:2024 provides the fundamental principles, concepts, benefits, and terminology of asset management. It establishes the strategic importance of asset management in achieving organisational objectives, highlights the importance of risk-based decision-making for asset-related activities, and ensures consistency in terminology and application across diverse industries. This standard emphasizes the key principles of asset management for the realization of value from assets, the alignment of asset-related actions to support strategic goals, and strong leadership and culture. Figure 3.3 illustrates the interconnection between asset management, the organisation's asset management system, and the assets being managed [21], [22].

Asset management principles form the core of an organisation's culture and guide its value and behaviours. These principles are integrated throughout governance structures, ethical standards, and operational processes, ensuring consistency in how challenges are addressed, and decisions are made.

The key principles, as outlined in ISO 55000 are:

- Value: Asset management aims to maximise value from assets to the organisation over their entire lifecycle;
- Alignment: Ensures that the asset management activities are strategically and operationally coordinated with the organisation's goals. These principles involve asset management policies, objectives and day-to-day operations (vertical alignment) and collaboration across departments, functions, and disciplines (horizontal alignment) ensuring consistent management across all stages of the lifecycle;
- Leadership and Commitment: Effective asset management relies on strong and sustained leadership at all levels of the organisation. Leaders are responsible for defining clear roles, responsibilities, and lines of authority. A collaborative environment, guided by a common direction, is essential to achieve long-term asset performance and organisational success.

Implementing a structured asset management system provides multiple organisational benefits. It enhances financial performance by increasing returns and reducing operational costs without compromising strategic goals. Decision-making becomes more consistent and data-driven, allowing organisations to better balance costs, risks, and performance. Through systematic risk and opportunity management, asset resilience improves while health, safety, and environmental impacts are minimised. Stakeholder satisfaction increases due to more reliable services, while the organisation's commitment to social responsibility and sustainability becomes more visible. Furthermore, asset management supports regulatory compliance, strengthens reputation, and promotes operational efficiency through improved planning, processes, and teamwork. It also fosters better internal coordination, communication and encourages innovation by focusing on long-term value creation.

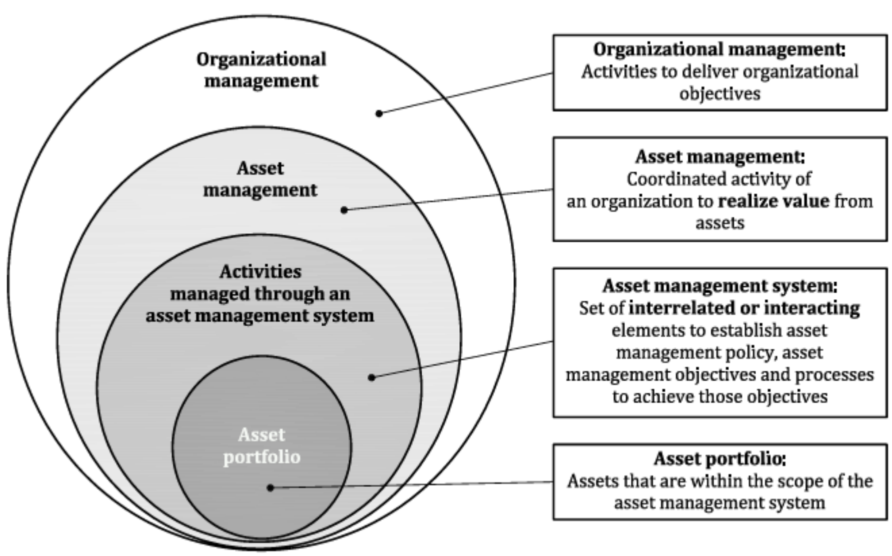

Figure 3.3 – Interconnection among asset management, organisation's asset management system, and the assets being managed.

The international standards ISO 55001 and ISO 55002 are serving as the core standards for system implementation and guidance.

The ISO 55001:2024 outlines the formal requirements for the establishment, implementation, maintenance, and continual improvement of an asset management system. It defines the structural elements necessary for organisations to build effective asset management systems, covering key areas such as organisational context, leadership, planning, support functions, operational control, performance evaluation, and improvement process [23]:

- Context of the Organisation: Requires the organisation to understand internal and external factors that affect its ability to achieve asset management objectives. It must define the scope, identify stakeholders, understand risks and opportunities, and align asset management with the organisation's strategic direction;
- Leadership: Demonstrate commitment and accountability, establish an asset management policy, assign roles, responsibilities, and authorities. Ensure communication and alignment across all levels;
- Planning: Ensures the system is proactive and risk-based, defining objectives aligned with organisational goals, planning actions to address risk and opportunities and develop a Strategic Asset Management Plan (SAMP);
- Support: Refers to the resources and capabilities needed to operate the system, providing adequate resources (human, financial, technological), ensuring competence and training of personnel, facilitating awareness, communication, and documentation;
- Operation: Focuses on the implementation of plans and controls to manage assets throughout their lifecycle. Establishing operational planning and control procedures, managing change and ensuring continuity, coordinating outsourced activities. Also, ensuring effective risk control and performance delivery;
- Performance evaluation: Monitoring, measuring, and analysing asset and system performance, conducting internal audits of the asset management system, and performing management reviews to drive continual improvement;
- Improvement: Organisations must act on nonconformities and implement corrective actions. Embrace continual improvement of the asset management system and encourage innovation and feedback loops to refine practices.

Complementing this, ISO 55002:2018 offers detailed guidance on the practical application of ISO 55001. The 2018 edition provides expanded insights into leadership roles, stakeholder engagement, and decision-making frameworks that aim to balance cost, risk, and performance. It also emphasizes the use of data-driven methods for monitoring performance and driving continuous improvement [24].

Asset management objectives help guide an organisation to ensure its assets deliver the expected outcomes. These objectives are aligned with the overall goals of the organisation and are meant to reflect the value that assets bring to stakeholders. The objectives can exist at different levels – strategic, tactical, and operational – and can vary in scope and time horizon.

When setting asset management objectives, they should be SMART – specific, measurable, achievable, realistic, and time-bound. These objectives must be expressed in either quantitative terms or qualitative terms, and they should be clearly documented in the Strategic Asset Management Plan (SAMP). Progress toward these objectives must be monitored and review regularly. During the planning process, organisations should also consider:

- Risks and opportunities related to asset performance or management practices;
- Asset criticality, or the importance of specific assets to achieving desired outcomes.

Within this framework operation and performance evaluation play a central role in ensuring that an asset management system is not only implemented effectively but also continuously monitored and improved. Emphasizing the need for structured operational planning and control, requiring organisations to conduct asset-related activities in a coordinated, consistent, and controlled manner. This includes establishing criteria for operational processes, managing planned changes, and minimising the impact of unexpected deviations.

A critical aspect of this is the management of change, which ensures that technical, organisational, or contextual changes – such as asset upgrades, new technologies, or process adjustments – are systematically evaluated and controlled. In cases where activities are outsourced, it is essential that organisations establish procurement and oversight mechanisms that ensure external providers comply with asset management requirements.

Equally important is to regularly evaluate how well both the asset management system and the assets are performing. Organisations need to clearly decide what aspects of performance will be measured and how. This involves using the right methods and indicators to check whether asset management goals are being achieved. Key performance indicators (KPIs) such as asset availability and reliability are commonly used for this purpose. In addition, internal audits should be carried out to review system performance, stakeholder feedback, and identify areas for improvement.

As asset management practices mature, organisations increasingly rely on high-quality data and well-structured strategies to make informed decisions and extract long-term value from their assets. In response to these needs, were added two standards ISO 55012, which focuses on asset data management, and ISO 55013, which provides guidance on developing asset management strategies.

The ISO 55012:2024 is intended to support organisations in establishing effective processes for managing asset-related data throughout the asset lifecycle. Data is a critical enabler of informed decision-making, particularly in areas such as maintenance planning, risk management, lifecycle costing, and performance evaluation. This standard address key topics such as data governance, data quality, structure and classification, integration across systems, and the use of digital technologies [25].

The guidance in ISO 55013: 2024 includes identifying and prioritizing strategic objectives, evaluating risks and opportunities, understanding asset criticality, and defining performance targets. It also emphasizes the integration of sustainability, resilience, and value delivery into strategic planning [26].

3.4 Maintenance

Maintenance is defined as the combination of all technical, administrative, and managerial actions throughout the entire life cycle of an asset, with the aim of ensuring that the asset remains or is restored to a condition in which it can perform its intended functions. These actions aim to sustain or recover the functional condition, reliability, and safety of equipment and systems. The condition refers to the physical and functional state of an asset at a given time. Reliability is the probability that an asset will perform its required function without failure for a specified period under stated conditions. Also, safety means that the asset operates without posing unaccepted risk to people, the environment, or property [17], [20].

Maintenance is not limited to fixing broken equipment. It includes various strategies to prevent, predict, and even optimise the timing of interventions.

The main types of maintenance are:

- Corrective (Reactive): Performed after a failure occurs, with the purpose of restoring the asset to working condition;
- Preventive: Involves regularly scheduled inspections, servicing, or part replacements based on time or usage intervals (regardless of the asset's current condition);
- Predictive: Uses real-time condition monitoring and data analysis to detect early signs of wear or failure. Interventions are performed only when needed, based on the actual condition of the asset rather than a fixed schedule;
- Proactive: Aims to eliminate the root causes of failures before they occur. It focuses on improving asset design, operating conditions, and maintenance practices to prevent failures from developing in the first place.

Effective maintenance management contributes directly to increase equipment availability, improve operational efficiency, reduce costs, extend asset lifespan[3], and enhance safety performance. It involves careful planning, execution, and continuous improvement, supported by data, standards, and performance measurements [27].

[3] Useful life

Maintenance activities can generally be categorized into two broad groups:

- Planned Maintenance: Activities scheduled in advance, whether time-based (preventive), condition-based (predictive), or design/engineering-driven (proactive). The goal is to minimise disruptions and maintain optimal asset performance;
- Unplanned Maintenance: Conducted in response to unexpected failures. While sometimes unavoidable, excessive unplanned maintenance often indicates poor planning or ineffective maintenance strategies.

The EN 13306:2017 – Maintenance Terminology – norm provides internationally recognized and harmonized definitions for terms used in maintenance and asset management. This European Norm aims to establish a consistent technical language across different industries, sectors, and organisations involved in maintenance activities. This consistency is essential for developing clear maintenance policies and procedures, ensuring accurate data recording, facilitating communication between stakeholders, and enabling effective performance analysis and benchmarking [28].

3.4.1 eMaintenance

The new concept eMaintenance (electronic maintenance) integrates digital technologies, such as internet-based systems, data analytics and automated tools, to manage and perform maintenance activities for assets and equipment. It integrates real-time data collection, monitoring, diagnostics and reporting to optimize maintenance processes, improve asset reliability and reduce downtime [29].

By leveraging technologies like Industrial Internet of Things (IIoT), Artificial Intelligence (AI) and Machine Learning (ML), eMaintenance enhances predictive and prescriptive maintenance strategies. It allows for Condition-Based Maintenance (CBM) by continuously analysing operational data, detecting anomalies, and predicting failures before they occur. Additionally, eMaintenance supports remote maintenance, enabling technicians to diagnose and resolve issues without physical intervention, reducing costs and increasing efficiency.

By implementing eMaintenance, organisations can achieve reduced maintenance costs, minimised downtime, extended asset life, improved safety and compliance, and enhanced sustainability. Especially in industries such as manufacturing, transportation, energy, and healthcare, where asset reliability and operational efficiency are critical. As digital transformation advances, eMaintenance continues to evolve, integrating Augmented Reality (AR) and Digital Twins (DT) to further enhance maintenance efficiency and decision-making.

3.4.2 Maintenance Key Performance Indicators

Maintenance Key Performance Indicators (KPIs) are essential metrics used to assess the performance and effectiveness of asset management and maintenance practices. KPIs provide a structured means of monitoring equipment reliability, maintenance efficiency, and cost effectiveness, enabling informed decision-making and continuous improvement of operations. The selection, calculation, and application of maintenance performance indicators should follow a systematic methodology to ensure their relevance and accuracy [30].

According to the methodology for selecting and using maintenance performance indicators, the process involves:

1) Definition of the objectives that characterise the maintenance management process, ensuring alignment with organisational goals and operational requirements;
2) Selection of relevant indicators based on the defined objectives, taking into consideration the nature of the assets, operational context, and data availability;
3) Definition and collection of baseline data, which serve as reference points for monitoring and comparison over time;
4) Calculation of indicators and choice of representation, including:
    - determining the frequency of indicator calculation;
    - selecting appropriate data presentation formats (graphs, dashboards, trend analyses);
    - performing testing and validation of the data to ensure accuracy;
    - analysing the results to identify trends, deviations, and areas requiring corrective actions.

In addition to this methodology, this thesis also applies the principles outlined in the European Norm EN 15341:2009. This norm provides a comprehensive framework for defining, selecting, and applying KPIs specially within the context of maintenance management. EN 15341 categorizes KPIs into several hierarchical levels, such as strategic, tactical, and operational indicators, and covers multiple performance dimensions [31].

In this thesis, a set of technical and operational KPIs was selected to evaluate the maintenance performance and operational reliability of the autogenous mills. These include Downtime, Uptime, Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), Standard Deviation of Downtime, Availability, Failure rate, and Unplanned Maintenance Percentage. Each KPI plays a specific role in capturing different aspects of asset performance. Table 3.1 present this KPIs and the formulas to calculate them [32].

Table 3.1 – Key performance indicators used in the case study.

KPI	Formula		Purpose
Downtime	$Downtime = \sum Stop\ time\ duration$	(3.1)	Total time system is not operating.
Uptime	$Uptime = Total\ Time - Downtime$	(3.2)	Total time system is operating.
MTBF (Mean Time Between Failures)	$MTBF = \frac{Total\ Operating\ Time}{Number\ of\ Failures}$	(3.3)	Measure reliability, how often failures happen.
MTTR (Mean Time To Repair)	$MTTR = \frac{Total\ Downtime}{Number\ of\ Failures}$	(3.4)	Measures maintainability, how quickly the failures are fixed.
Standard deviation of downtime (σ)	$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(T_i - \mu)^2}$ • T_i – each individual downtime • μ – MTTR • N – number of failures	(3.5)	Measures consistency of repairs.
Availability (%)	$Availability = \left(\frac{MTBF}{MTBF + MTTR}\right) \times 100$	(3.6)	Measures the percentage of time system is available for production.
Failure rate (λ)	$Failure\ rate\ (\lambda) = \frac{1}{MTBF}$	(3.7)	Another way to express failure frequency.
Unplanned Maintenance (%)	$UM = \frac{Unplanned\ Maintenance\ Hours}{Total\ Maintenance\ Hours} \times 100$	(3.8)	Shows proportion of unplanned vs planned maintenance.

Downtime refers to the total period during which the asset is non-operational due to failures or maintenance activities. In contrast, Uptime represents the time the asset is functioning as intended. Monitoring these indicators provides a basic yet critical understanding of the asset's operational reliability. In the context of unplanned failures, high downtime can signify inefficiencies in maintenance processes or severe reliability issues, whereas high uptime reflects operational stability and reliability.

MTBF is the average time interval between two consecutive failures of the asset. It is a key indicator of reliability. Higher MTBF suggests that the asset is less prone to failures, and thus, more reliable. In failure analysis, MTBF provides insight into how frequently unplanned failures are occurring and serves as a foundation for preventive maintenance planning.

MTTR measures the average time required to diagnose, repair, and restore the asset to operational status following a failure. It directly reflects the efficiency of maintenance teams and the maintainability of the equipment. A low MTTR indicates swift recovery from failures, which is essential for minimising the impact of unplanned downtime.

While average downtime offers a general view of performance, the standard deviation of downtime provides information about the variability of downtime events. High variability can suggest inconsistency in failure types, repair procedures, or severity. Understanding this variability is important in identifying systematic issues or irregularities in maintenance practices.

Availability is the proportion of total time that the asset is capable of performing its intended function, typically expressed as a percentage. Also, serves as a composite indicator that incorporates both failure frequency (MTBF) and repair effectiveness (MTTR), making it a holistic measure of asset performance.

The failure rate represents the frequency of failures over a given operational period. It is fundamental indicator for quantifying how prone the asset is to unexpected breakdowns. A high failure rate is a clear signal of reliability issues and often prompts further root causes analysis or design improvement efforts.

Finally, the unplanned maintenance percentage indicates the share of maintenance activities that are reactive rather than scheduled. A high percentage of unplanned maintenance is typically undesirable as it implies a lack of predictability and control, leading to production disruption, increased costs, and potential safety hazards.

3.5 FMECA Analysis

Failure Modes, Effects and Criticality Analysis (FMECA) is a structured and systematic method used to evaluate and prioritise potential failures in a system, process, or equipment. It is an extension of Failure Modes and Effects Analysis (FMEA), incorporating an additional dimension: criticality analysis, which enables the evaluation of the relative importance of different failure modes based on their risk level [33].

The primary objective of FMECA is to proactively assess potential failures, their causes, and their consequences, allowing organisations to implement preventive and corrective actions that enhance system reliability, optimise maintenance strategies, and improve operational safety and efficiency. This analysis is widely applied across various industries, including manufacturing, aerospace, automotive, energy, and mining operations [34].

The International Electrotechnical Commission IEC 60812:2018 provides comprehensive guidance and methodology for conducting FMEA and FMECA studies in a consistent and systematic manner. According to this standard, the process involves identifying all credible failure modes, analysing their effects on system performance, determining root causes, evaluating the criticality of each failure mode, and developing actions to mitigate unacceptable risks [35].

The analysis typically includes the following key elements:

- Failure type: The classification of the failure, typically based on its nature, helps categorize failures for better understanding and analysis;
- Component: The specific item, subsystem or process being analysed that could potentially fail. This can be a mechanical part, an electronic component, or a software module;
- Failure mode: Description of the specific ways in which components or processes can fail, such as mechanical wear, material fatigue, corrosion, or electrical malfunction;
- Cause of failure: The root cause or initiating mechanism that leads to the failure mode. Causes may include design flaws, manufacturing defects, environmental conditions, human error, or aging of materials;
- Failure effects: Can be with local effects when the impact of the failure is at the location where it occurs, while the global effects are the broader consequences on the entire system or operation, such as degraded performance, system shutdown, or safety hazards;
- Recommended actions: Proposed measures to reduce or eliminate the risk associated with the failure mode, such as redesign, process changes, additional inspections, or updated procedures;

The criticality is the combined assessment of the severity of the effect, the likelihood of occurrence, and the probability of detecting the failure before it leads to adverse consequences. Each identified failure mode is systematically evaluated using three core criteria:

- Severity (S): The seriousness of the failure’s effect on system performance, safety, environment, or regulatory compliance;
- Occurrence (O): The estimated likelihood or frequency with which the failure mode may occur;

- Detection (D): The probability that existing controls will detect the failure before it results in system impact.

These factors are combined to calculate the Risk Priority Number (RPN), typically using the following equation (3.9):

$$RPN = S \times O \times D \qquad (3.9)$$

The RPN provides a quantitative ranking of failure modes, enabling prioritization of mitigation efforts based on the relative risk posed by each mode. While RPN calculation is widely used, IEC 60812:2018 emphasizes that criticality assessment may also be performed using other qualitive or quantitative techniques depending on the complexity of the system and organisational requirements.

The scales created for the 3 criteria's Severity (S), Occurrence (O) and Detection (D) are the presented in Table 3.2, Table 3.3 and Table 3.4 [33] .

Table 3.2 – Occurrence scale.

Occurrence (O)	
Value	**Frequency**
1	Unlikely (Preventive control)
2	Very remote
3	Remote
4	Very low
5	Low
6	Moderate
7	Moderately high
8	High
9	Very high
10	Extremely certain

Table 3.3 – Severity scale.

Severity (S)	
Value	**Level**
1	None
2	Very minor
3	Minor
4	Very Low
5	Low
6	Moderate
7	High
8	Very high
9	Hazardous with warning
10	Hazardous without warning

Table 3.4 – Detection scale.

Detection (D)	
Value	**Detectability**
1	Extremely certain
2	Very high
3	High
4	Moderately high
5	Moderately high
6	Low
7	Very low
8	Remote
9	Very remote
10	Unlikely

The rank of failure risk is presented in Table 3.5.

Table 3.5 – Rank of failures risk, in FMECA analysis.

RPN Range	Risk Level	Action	Color Code
1-100	Low Risk	Acceptable – monitor only	Green
101-200	Moderate Risk	Review and plan corrective action	Yellow
201-500	High Risk	Take corrective action soon	Orange
501-1000	Critical Risk	Urgent action required	Red

3.6 Ishikawa diagram

The Cause-and-Effect diagram (or Fishbone diagram) is a visual tool used for root cause analysis. It helps to identify, sort, and display potential causes of a specific problem or effect. It is called a "fishbone" because it resembles the skeleton of a fish [36], [37].

- Head: Represents the effect/ problem in analysis.
- Spine: Represents a horizontal line extended from the head.
- Bones/ Categories: Diagonal lines branch off the spine, representing major categories of potential causes. The most common ones are:
    - Machine/Equipment: Issues with machinery, tools, or equipment itself;
    - Methods: Problems with procedures, processes, or work instructions;
    - Manpower/ People: Issues related to human error, training, or skills;
    - Material: Problems with raw materials, components, or consumables;
    - Measurement: Issues with data collection, sensors, or calibration;
    - Environment: Factors related to the working environment (temperature, humidity, noise, etc.).
- Sub-Bones: Smaller lines branch off the major bones, representing more specific causes within each category.

3.7 Operational Efficiency and Sustainability Goals

Maximising operational efficiency in asset management refers to the ability to extract the highest possible value from physical assets while ensuring reliability, safety, and cost-effectiveness. This involves implementing integrated strategies that enhance asset productivity, minimise downtime, reduce resource waste, and optimise both operational and maintenance expenditures throughout the asset lifecycle [38].

The concept of "maximising" implies more than just increasing output, and it emphasizes optimising[4] asset performance and availability. Achieving this balance requires aligning operational activities with maintenance strategies, technological innovations, and sustainability objectives.

Key strategies for maximising operational efficiency include:

- Real-time monitoring and predictive analytics: Utilising sensors, and data analysis tools to continuously track asset conditions and performance parameters. Early detection of anomalies enables timely interventions and prevents unexpected failures;
- Proactive maintenance to extend asset lifespan: Transitioning from reactive to preventive and predictive maintenance practices reduces wear and tear, minimizes equipment degradation, and increases overall service life;
- Energy efficiency and failure prevention: Optimising equipment operation and maintenance reduces unnecessary energy use and operational interruptions, directly contributing to cost savings and environmental sustainability.

In this context, operational efficiency refers to the ability to achieve desired outputs, such as production volumes or service delivery, while minimising the input of resources such as time, labour, energy, and materials. This includes optimising equipment utilisation, reducing downtime, eliminating non-value-adding activities, and lowering environmental waste [39].

Integrating operational efficiency with sustainability objectives is essential for contemporary organisations, especially those in resource-intensive sectors. This integration ensures not only immediate profitability but also long-term environmental and social responsibility [40].

Sustainability asset management expands the traditional focus on technical and economic performance to include environmental and social dimensions. It promotes resilience, resource efficiency, and regulatory compliance, and is increasingly recognised as a foundational strategy for responsible and future-ready industrial operations. Companies are adopting asset management models that reduce waste and energy consumption and optimise resource utilization throughout the asset lifecycle.

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[4] Optimise means to make the best or most effective use of something.

One of the most impactful approaches is the adoption of circular economy principles, which aim to extend the useful life of physical assets through repair, refurbishment, reuse, and recycling. Rather than following a linear "take-make-disposal" model, circular economy strategies encourage resource loops that reduce environmental impact and dependence on raw material extraction. By embracing circular practices, organisations not only reduce their environmental footprint but also enhance operational efficiency and financial performance [40].

Energy efficiency is another critical lever for reducing environmental impact. Organisations can achieve substantial reductions in greenhouse gas emissions[5] and operating costs by:

- Investing in energy-efficient technologies equipment;
- Optimisation of operational processes to reduce energy waste;
- Integrating renewable energy sources into asset operations.

Aligning asset management with sustainability objectives offers multiple benefits [41]:

- Reduce emissions and waste;
- Improve environmental regulatory conformity;
- Enhance organisational resilience and social license to operate;
- Creation of long-term stakeholder and shareholder[6] value.

The integration of the international standard ISO 14001:2015 – Environmental Management System – into asset management frameworks reinforces sustainability efforts. ISO 14001 provides a systematic approach to identifying and managing environmental aspects, setting and monitoring objectives, implementing controls, and continuously improving performance across the asset lifecycle [42], [43]. It also supports circular economy practices and helps companies align environmental goals with broader corporate strategies [44].

3.8 Impact of Unplanned Failures in Production

Unplanned failures in production systems occur when equipment or processes cease to function unexpectedly, leading to immediate and often severe operational disruptions. In asset-intensive industries, such as mining, where equipment availability is directly linked to production throughput and profitability, unplanned failures represent one of the most critical challenges to operational efficiency [45].

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[5] GHGs are atmospheric gases such as carbon dioxide (CO_2) and methane (CH_4)

[6] A person or entity that owns shares in a company and has a financial interest in its performance

These failures can stem from a range of causes including mechanical wear, improper maintenance practices, poor lubrication, material fatigue, or undetected anomalies. Regardless of the root cause, the consequences are multifaceted and typically include:

- Production losses: Equipment downtime during unplanned failures halts the entire production flow, especially in continuous operations. This leads to loss of output, delays in meeting production targets, and, in some cases, contract penalties or missed delivery windows;
- Increased maintenance costs: Emergency repairs often require overtime labour, expedited parts procurement, and unplanned allocation of resources, significantly raising maintenance expenditures compared to planned interventions;
- Reduced equipment lifespan: Frequent unplanned failures can pose serious risks to personnel safety and environmental compliance, particularly in operations involving high-energy equipment, pressure systems, or hazardous materials;
- Safety and environmental risks: Unexpected failures can pose serious risks to personnel safety and environmental compliance, particularly in operations involving high-energy equipment, pressure systems, or hazardous materials;
- Operational instability: Recurrent unplanned stops disrupt scheduling, inventory control, and resource planning, leading to inefficiencies throughout the production system.

For the case study, to analyse the lost production was used the Equation (3.10) [45].

$$Lost\ Production\ (ton) = Downtime\ (h) \times Production\ Rate\ (ton/h) \tag{3.10}$$

Many equipment failures or accidents are caused or worsened by human errors. Understanding and managing human factors help reduce downtime, improve safety, and boost overall operational efficiency.

It is a key part of modern reliability management and Industry 5.0, which emphasizes the collaboration between humans and intelligent machines.

This human factors can include:

- Operator errors: Mistakes or slips made by machine operators during routine or emergency operations (e.g. missed checks);
- Training and skills: The level of knowledge and competence of personnel operating or maintaining the equipment;

- Communication: How well information is shared between shifts, teams, or departments;
- Work environment: Conditions affecting humans, such as fatigue, stress, shift length, ergonomics, distractions;
- Decision-making: How humans make judgments under pressure or uncertainty;
- Procedures and compliance: Whether operators follow standard operating procedures correctly or if procedures are unclear or missing;
- Supervision and support: Availability and quality of leadership, coaching, and technical support.

3.9 From Industry 4.0 to Industry 5.0

Industry 4.0, also known as the Fourth Industrial Revolution, refers to the ongoing transformation in manufacturing and industrial sectors driven by the integration of advanced digital technologies. It builds upon the previous industrial revolutions, which saw the advent of steam power, mass production, and automation. Industry 4.0 represents the fusion of physical production with smart, digital technologies, creating a highly connected, automated, and data-driven industrial ecosystem [46], [47], [48].

Industry 4.0 has revolutionized how businesses operate. It enables real-time data collection and analysis, improving decision-making and enabling predictive maintenance, customisation, energy efficiency, and resource optimisation.

Industry 5.0 builds upon the technological advances of Industry 4.0 but introduces a transformative shift in focus from purely automation and efficiency to human-centricity, sustainability, and resilience. It is not simply the next stage in digital transformation, it represents a paradigm shift in how industry interacts with people, society, and environment [49]. Figure 3.4 shows a comparative diagram of Industry 4.0 and Industry 5.0.

The three main pillars of Industry 5.0 are human-centricity, sustainability and resilience. Unlike Industry 4.0, which prioritizes machine autonomy and data-driven automation, Industry 5.0 places the human being at the centre of the industrial process. It emphasises collaboration between humans and machines, where intelligent systems support human intelligence, creativity and decision-making, and not replace. It also promotes environmentally responsible practices, recognising that economic growth must go hand-in-hand with climate action and resource efficiency. It encourages industries to reduce emissions, optimise energy usage, and adopt circular principle [50].

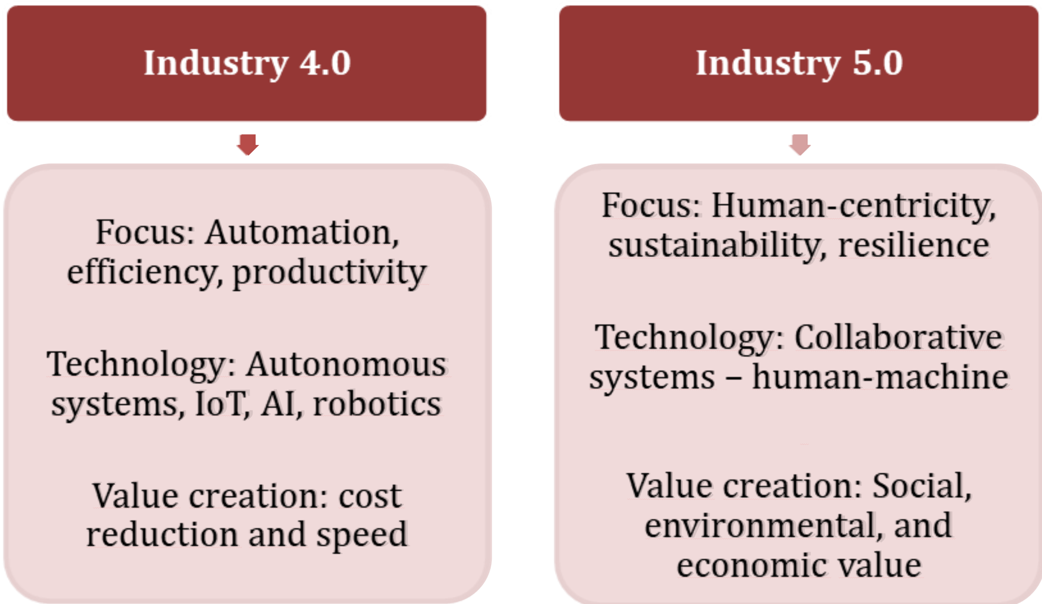


Figure 3.4 – Scheme of Industry 4.0 to Industry 5.0.

Global disruptions (e.g. COVID-19) highlighted the need for robust and flexible industrial systems. Industry 5.0 fosters resilience by creating systems that can withstand shocks, adapt quickly, and maintain functionality under stress [50].

Sustainability in the context of Industry 5.0 refers to the development and operation of industrial systems that reduces environmental impact, optimise the use of resources, and actively contribute to ecological regeneration and long-term planetary health [51].

It encourages the use of green technologies, renewable energy integration, and sustainable design throughout the entire lifecycle of products and assets. The goal is not only to do less harm but to actively improve environmental outcomes through innovation, data-driven optimisation, and long-term thinking [52].

Resilience refers to the capacity of industrial systems, organisations, and value chains to adapt to disruptions, recover from crises, and maintain continuity under stress, where from global shocks, market volatility, cyber threats, supply chain disruptions, or climate-related events.

In Industry 5.0, resilience is not merely about surviving disruptions but about designing systems that are robust, flexible, and adaptable by default. This includes investing in risk management, decentralised production, predictive maintenance, and scenario planning. Resilience also encompasses social and organisational resilience, where companies foster agile workforces, responsive leadership, and knowledge-sharing cultures that can respond quickly and effectively to change [53].

Human-centricity is another well-defined pillar of Industry 5.0, placing human well-being, creativity, and empowerment at the centre of technological and industrial development. Human-centricity also means involving stakeholders in innovation processes, ensuring that technological change is socially acceptable, ethically guided, and democratically governed [54].

Industry 5.0 aims to create technology that serves people, rather than replacing them (Figure 3.5). This includes the design of workplaces that enhance human-machine collaboration, the use of AI and robotics to support (not displace) human workers, and the prioritisation of ergonomics, safety, inclusion, and lifelong learning [55].

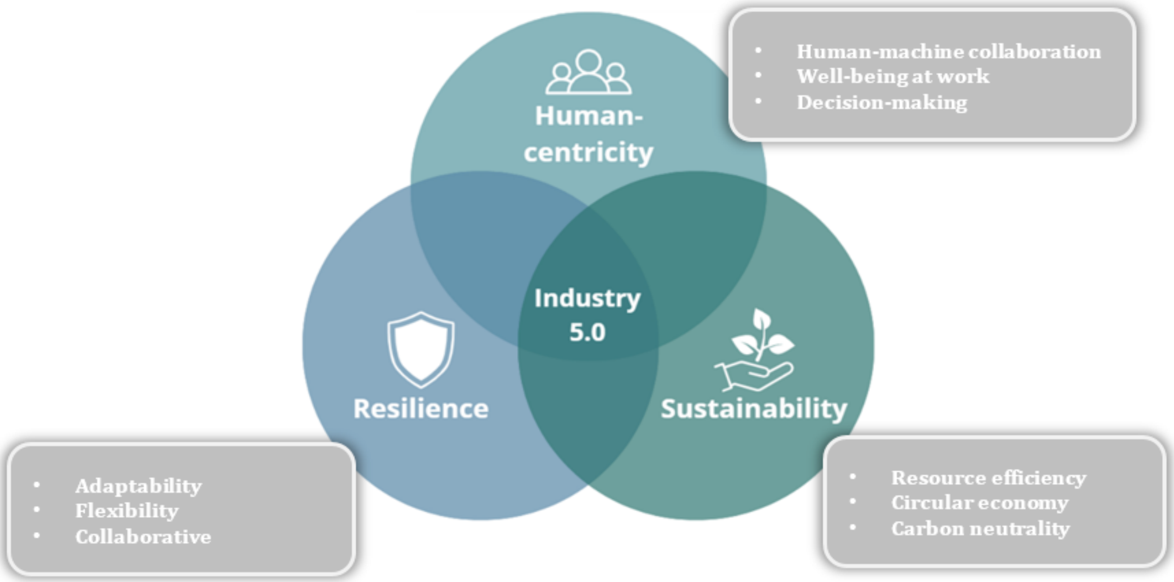


Figure 3.5 – Main principles of Industry 5.0.

3.10 Relevant References

This section provides some relevant references about the integration of technology, sustainability, and strategic frameworks in intelligent physical asset management. By examining trends, challenges and opportunities since 2020, it aims to identify gaps in operational efficiency, environmental sustainability, and risk management. These insights lay the groundwork for innovative solutions in the field.

The management of physical assets has evolved from traditional practices to a more dynamic field driven by digitalisation, emerging technologies and an increasing focus on sustainability. The quest for operational efficiency and minimising environmental impact has led companies to adopt more strategic and innovative approaches such as the use of AI and IoT.

Franciosi *et al.* [56] highlight that maintenance in manufacturing industries has a significant impact on sustainability, emphasising the need to integrate maintenance practices within a holistic approach that considers both operational performance and environmental impacts. The study proposes a framework aligning maintenance with sustainable practices, providing a basis for optimising the asset life cycle.

The integration of Industry 4.0 technologies has been a growing trend. Bokrantz *et al.* [57], [58], [59] explore the evolution of smart maintenance practices that use real-time data and predictive technologies to reduce failure and optimise cost efficiency. Similarly, Weerasekara *et al.* [46] discuss how the transformative potential of applying AI and IoT can significantly increase visibility and control over assets, leading to more informed decision-making and proactive actions. Moreover, Kolasani [60] research suggests that incorporating advanced technologies such as AI and Machine Learning (ML) can enable predictive analysis of asset performance, which can lead to greater operational efficiency and the reduction of unexpected failures.

The evolution from Industry 4.0 to Industry 5.0 marks a shift from automation-centric systems to human centric, adaptive, and sustainable industrial ecosystems. Central to this transformation is the integration of advanced technologies that enables real-time responsiveness, personalisation, and enhanced collaboration between humans and machines.

Murtaza *et al.* [4] highlight how predictive maintenance and condition monitoring are evolving through AI and sensor-based architecture, now tailored to include human oversight and cognitive diagnostics. Similarly, Bongomin *et al.* [61] emphasize digital twin technology as a cross-sectoral enabler that enhances real-time decision-making and system resilience, key attributes of Industry 5.0 environments.

Building on this, Leng *et al.* [62] explore the convergence of industrial AI with edge computing and robotics to support cognitive automation and ethical machine behaviour, enabling smart factories to become more adaptive and human aligned. Complementing this view, Sharma *et al.* [3] identify edge computing as a critical infrastructure that supports decentralized intelligence and responsive systems, essential for meeting the latency, security, and personalization demands of Industry 5.0.

Together, these studies demonstrate that Industry 5.0 technologies are not merely enhancements of Industry 4.0 tools, but represent a strategic redirection, integrating intelligence, empathy, and sustainability into the core of industrial systems.

Interoperability between asset management systems and circularity in the manufacturing process are also emerging areas in asset management. Polenghi *et al.* [63] explore how enterprise information systems interoperability can facilitate asset life cycle management and enhance circular manufacturing. The research highlights that by integrating asset management systems with smart manufacturing platforms, it is possible to optimise resource use and reduce waste, thereby contributing to long-term sustainability. Also, Peña *et al.* [64] offer innovative pathways to extend asset lifecycles and minimise waste. Strategic frameworks, such as ISO

55000 and ISO 14001, play a pivotal role in aligning asset management practices with sustainability objectives.

Another area where research is lacking is the role of human factors and organisational readiness in the successful implementation of intelligent asset management systems. While technical advancements like AI and IoT are crucial, the ability of organisations to embrace these technologies often depends on factors such as culture, training and leadership. Adshirinpour *et al.* [13] and Alsyouf *et al.* [22] discuss the influence of organisational performance, but more research is needed on how human and organisational factors can impact the effectiveness of asset management systems.

Li and Duan [54] emphasize that human-centric innovation must move beyond rhetoric, confronting challenges such as algorithmic bias, digital exclusion, and ethical governance. Their work frames Industry 5.0 as a socio-technical paradigm that demands inclusive design and responsible innovation. In parallel, Piccarozzi *et al.* [50] identify strategic gaps in workforce readiness, leadership alignment, and resistance to change, advocating for a roadmap that blends technological adoption with cultural transformation.

From an environmental perspective, Rame *et al.* [51] argue that the goals of personalisation and sustainability may conflict without proper regulation, especially in resource-intensive industries. They stress the need for systemic alignment between Industry 5.0 practices and global sustainability frameworks.

4 CASE STUDY

This chapter presents an analysis of the maintenance activities conducted on two primary autogenous mills. The objective is to assess recuring issues, identify root causes, and recommend improvements to enhance operational efficiency and reduce environmental impact.

The plant under study operates two primary autogenous (AG) mills, configured in a flowchart, as shown in Figure 4.1. The process begins with raw iron ore being fed into these AG mills. Acquired in 2008, and mills are Metso models with an expected lifespan of 25 to 30 years. At 17 years old, they are beginning to show signs of degradation.

The dimensions of this machines are 6.5m in diameter and 6.0m in length. These mills are designed to perform griding using the ore itself as the griding media, where larger ore particles break down smaller ones through impact and abrasion. The feed material consists of fractionated ore with particle sizes ranging from 0 to 30 mm and from 30 to 100 mm.

4.1 Framework

The selection of autogenous grinding for this operation is consistent with practices observed in iron ore processing, particularly for itabirite ores, as described by Rodrigues *et al.* [65]. In their study, the authors demonstrate the effectiveness of autogenous and semi-autogenous grinding circuits in processing low-grade iron ores, where ore hardness and particle competency play critical roles in achieving efficient size reduction and mineral liberation. The autogenous grinding process allows for efficient ore breakdown while minimising the need for additional grinding media, which simplifies circuit design and reduces operating costs.

Upon leaving the primary autogenous mills, the processed material follows two distinct pathways:

- First Stream: Part of the discharge flows directly to a spiral classifier, which separates the particles based on size and density. The classified material then passes through a magnetic separator to extract the iron-rich fraction before being sent to the secondary grinding stage, which utilizes pebble mills. The use of early-stage separation and classification is aligned with the approach suggested by Ji *et al.* [66], who advocate for the incorporation of pre-concentration and intermediate separation stages in mineral processing circuits. Such integration helps to reduce the downstream grinding load, improve the efficiency of separation processes, and optimise the overall energy consumption of the plant;
- Second Stream: The remaining portion of the primary mill discharge is directed to a pebbles screen. In this stage, part of the screened material, depending on size and

quality, is sent directly for sale as a final product. The undersized or non-conforming material is recycled back into the secondary pebble mills for further size reduction, ensuring the product meets the required specifications.

The pebble mills operate in a similar manner as primary ones but typically handle a narrower size range, processing the coarser fractions that require additional grinding. Their size is 6.5m in diameter and 9.0m in length, because the finer ore requires longer grinding to achieve the target size, being more effective at reducing smaller particles.

By incorporating pre-classification, magnetic separation, and staged grinding using both autogenous and pebble mills, the plant design reflects a hybrid flowsheet supported by both industrial practice and recent academic research [67]. In Figure 4.1 is represented the complete flowchart of the processing plant.

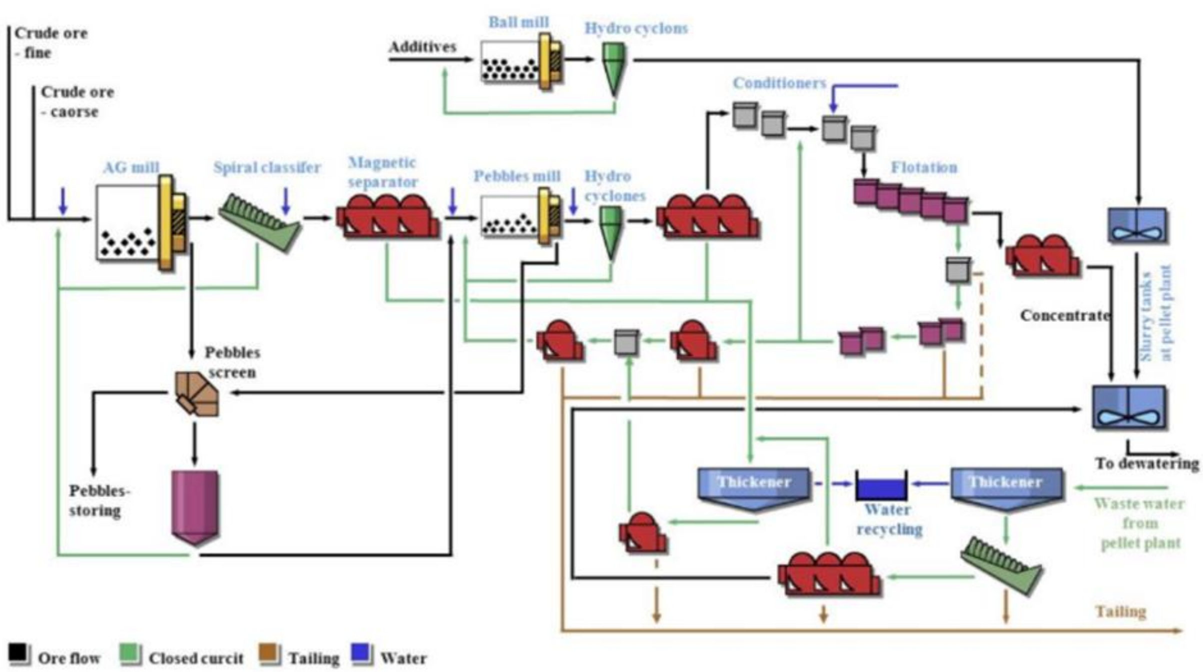


Figure 4.1 – Complete flowchart of the processing plant.

Autogenous (AG) mills are a critical component in the mineral processing industry, widely used in the initial stages of ore grinding. The performance and reliability of an AG mill depend heavily on the integrity of its main components and the availability of essential spare parts. In Figure 4.2 is presented a scheme illustrating those spare parts.

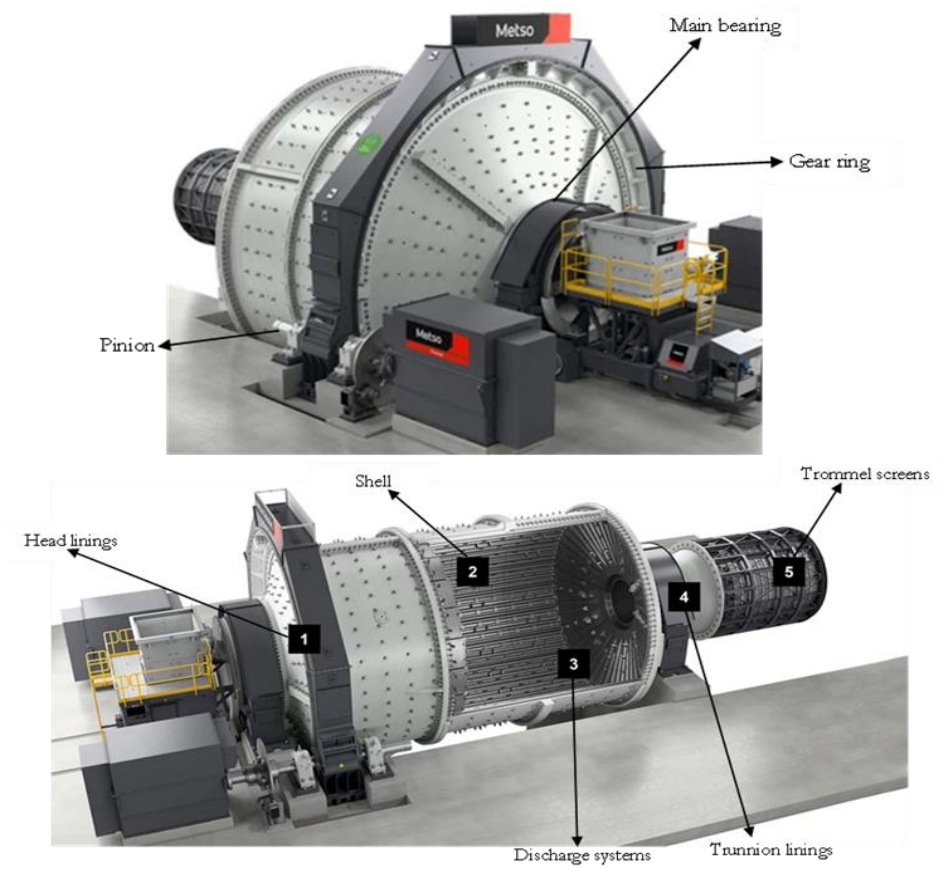


Figure 4.2 – Scheme of the autogenous mills, source: www.metso.com, Metso.

- Main bearing: Support the rotating mill shell and are typically hydrodynamic or hydrostatic in design. These components bear the full static and dynamic loads of the mill and require precise alignment;
- Gear ring and Pinion: The gear ring, mounted on the outer circumference of the mill shell, and the pinion connected to the drive motor constitute the primary transmission mechanism. This assembly transmits rotational power to the mill and must operate with exact tooth alignment and minimal backlash to ensure long service life and energy efficiency. Wear of the gear teeth or misalignment can lead to severe mechanical issues and production losses;
- Mill Shell: Cylindrical structure that houses the grinding process. It is fabricated from heavily-duty steel plates and designed to withstand the internal forces generated during grinding. Shells are often lined internally with wear-resistant liners and are subject to fatigue over time;

- Mill liners: Liners are critical for protecting the internal surfaces of the mill and for optimising grinding efficiency. Liners are typically made from rubber, steel, or composite materials, they include:
    - Shell liners: Mounted along the cylindrical shell to absorb impact and wear;
    - Head liners: Installed on the mill ends to protect the inner surface of the heads;
    - Trunnion liners: Protect the mill's inlet and outlet trunnions from wear due to slurry and ore impact.
- Discharge system: The discharge end of the mill regulates the flow of the ground material. It commonly includes discharge grates, pulp lifters, and discharge cones, which together control the slurry extraction rate and minimise backflow;
- Trommel screens: Positioned at the mill discharge, the trommel screen separates oversize particles from the slurry. Oversize material is redirected for regrinding, ensuring product consistency and preventing downstream processing issues;
- Lubrication system: Proper lubrication is critical for the operation of main bearings, gear systems, and drive assemblies. The lubrication system typically includes pumps, filters, reservoirs, cooling units, and piping;
- Motor: The mill is powered by a high-capacity electric motor for powering the rotation of the mill shell and enabling the ore comminution process.

Together, these parts form the backbone of a reliable autogenous grinding system. Regular inspection, timely replacement of worn components, and adherence to the Original Equipment Manufacturers (OEM) specifications are essential to maximise mill availability and performance.

4.2 Reliability Analysis of Autogenous Mills

This study presents a comprehensive analysis of the operational performance of two primary autogenous mills over a five-year period. The objective was to identify critical failure modes, evaluate equipment reliability, and explore opportunities for performance improvement through data analysis.

The dataset, provided by the company, spans from May 2020 to May 2025 and includes records of maintenance interventions. These records comprise failure causes, downtime durations, timestamps, and maintenance classifications. This mills are designed to operate 24 hours per day, yielding a theoretical maximum of 44094 operating hours over the five-year period. Their annual production target is 5.7 million tonnes (Mton).

To prepare and process the data, first was employed the Python Script, executed using the Spyder Editor. The scripts facilitated filtering, cleaning, processing, representation and visualisation of the data. Key Python libraries included *pandas, NumPy*, *Matplotlib* and *Seaborn* for modelling and visualisation.

The analysis was structured in five phases:

1. Descriptive analysis

    - Quantification of stoppage frequency and total downtime;
    - Visualisation of downtime distribution over time to detect patterns and anomalies.

2. Reliability Assessment

For the machine to stop, it is necessary to analyse the type of interference, and the factors that disrupt a machine from operating normally. Failures were classified based on the source of interference:

- Internal interference: Machine-related issues that originate within the equipment (e.g., mechanical wear, malfunctions);
- External interference: External conditions or events that disrupt the machine's operation but are not caused by the machine itself (e.g., human error, power supply).

A set of reliability KPIs (see Table 3.1) were calculated, including Downtime, Uptime, MTBF, MTTR, Standard deviation, Availability, Failure rate and Percentage of unplanned maintenance.

Downtime data were analysed with a focus on critical failures, defined as events that cause significant production losses, safety risks, or environmental impacts. The objective was to quantify the total downtime attributable to such failures and assess their contribution to overall operational interruptions.

A comparative analysis between the two mills was conducted to highlight operational differences as well as shared failure patterns.

3. Simulation model

To quantify potential performance improvements, a simulation model was developed to assess the impact of incremental reductions in critical failures. A 30% reduction scenario was simulated to estimate potential gains in production, in line with industry benchmarks and realistic improvement targets [68], [69].

4. Failure Mode Analysis

A Failure Modes, Effects, and Critically Analysis (FMECA) was performed in collaboration with domain experts to prioritize high-risks failure modes.

To complement this, a Fishbone diagram was constructed to support root cause identification and facilitate the formulation of strategies for reducing unplanned stoppages.

5. Visualisations and Reporting

An interactive Power Bi dashboard was developed to communicate results effectively to stakeholders. The dashboard integrates the raw data and analysis outputs from Excel, providing real-time insights into failure frequency, downtime duration, failure initiation patterns and maintenance KPIs, and a word cloud visualization highlighting the most recurrent themes and operational issues.

5 RESULTS AND DISCUSSION

This chapter presents detailed results from the case study and answer the three research questions RQ1, RQ2 and RQ3. Also presents the detailed explanations of the proposed framework for Intelligent Asset Management (IAM).

5.1 Results from the case study

This case study presents the operational and maintenance performance of two primary mills, P1and P2, over a five-year period. The objective was to evaluate the unplanned stoppages, downtime trends, failure causes, and overall impact on production, while also identifying key opportunities for improvement through reliability analysis.

Table 5.1 show the definition of each failure present in the dataset.

Table 5.1 – Description of the failures that occur for both mills.

Failure Type	Description
Automation Failure	Control system errors leading to poor mill control: wrong feed rate, incorrect speed, water flow issues, or unresponsive interlocks.
Barring Motor	Malfunction of the auxiliary motor used to slowly rotate the mill during maintenance or inspections.
Bolt (loosening, leakage, breakage)	Loose or broken bolts on liners, trunnion housings, or girth gear segments causing leaks or mechanical instability.
Clogging/ Blockage	Accumulation of coarse material inside the mill, trommel, chute, or discharge pipe blocking material flow.
Cooling Water	Failure in water cooling circuits for motor, gearboxes, or oil cooling, risking thermal overload of components.
Feeding/ Input	Irregular feed rate, oversized particles, or no material supply to the mill feed chute affecting grinding stability.
FRO/ VFD[7] (Variable Frequency Drive)	Failure of the variable speed drive controlling the mill's rotation speed, affecting grinding performance and mill load control.

[7] Frequency Converter

Full/ Stop Forward	Mill is full due to overloaded grinding chamber or blockage at the discharge end (trommel or sump).
Gearbox	Internal damage to gear reduction units transmitting motor torque to the mill, often due to lubrication or overload issues.
Girth Gear Lubrication	Failure of the girth gear lubrication system (spray nozzles, oil film issues, or pump failures) risking tooth damage.
High Load/ Running Heavily	Excess mills charge or high ore hardness causing abnormal power draw, high torque, and accelerated liner and bearing wear.
Hydraulic Failure	Malfunction in hydraulic systems operating bearing lubrication, discharge mechanisms, or auxiliary equipment.
Hydrostatic Bearing	Failure of high-pressure oil system for hydrostatic trunnion bearings during start or operation, risking bearing damage.
Leakage	Loss of oil (from trunnion seals, lubrication systems), slurry (from discharge seals), or cooling water inside or around the mill.
Liner (Mill lining)	Wear, cracking, or detachment of internal liners exposing shell to impact and reducing grinding efficiency.
Lubrication Failure	Problems in trunnion bearing oil system, girth gear lubrication, or gearboxes causing overheating and component wear.
Mechanical Failure	General failures in structural or rotating components: drive shaft, couplings, trunnions, supports, or frame cracks.
Other	Rare or complex failures not falling into standard categories.
Overload/ Side Load	Uneven charge distribution causing lateral forces, trunnion misalignment, or bearing overload.
Positioning Error	Incorrect alignment or positioning of mill shell, trunnions, feed chute, or auxiliary equipment leading to abnormal operation.
Product Change	Mill stoppage to change ore type, adjust grinding parameters, or modify downstream plant setup.
Scrap	Contamination, or rejected material during processing.

Screen Cloth Issue	Wear or breakage of screen cloth on classifiers or dewatering units downstream of the mill, affecting final product sizing.
Sensor Error	Malfunction of mill-specific sensors (bearing temperature, oil pressure, torque, vibration, speed).
Start-up Problems	Failures during mill start (frozen charge, trunnion bearing pressure issues, incorrect speed ramp-up).
Trommel Screen/ Return Pipe	Blockage or damage in trommel discharge piping or return circuit causing restricted flow or recirculating load issues.
Valve Failure	Failure of process valves controlling slurry flow, lubrication circuits, cooling systems, or hydrostatic lubrication.
Work on External Equipment Preventing Operation	Mill stoppages caused by maintenance or failures in conveyors, feeders, pumps, or plant utilities outside the mill itself.

Figure 5.1 and Figure 5.2, show the failures frequency for both mills, respectively.

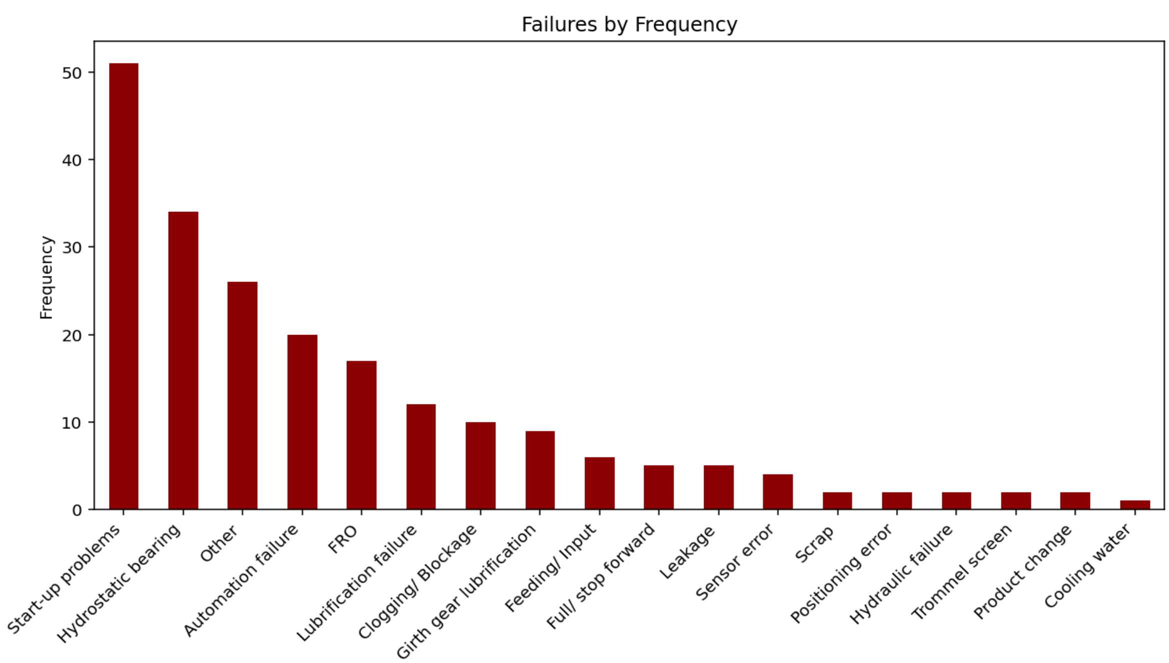


Figure 5.1. Graph of the failure's frequency for mill P1.

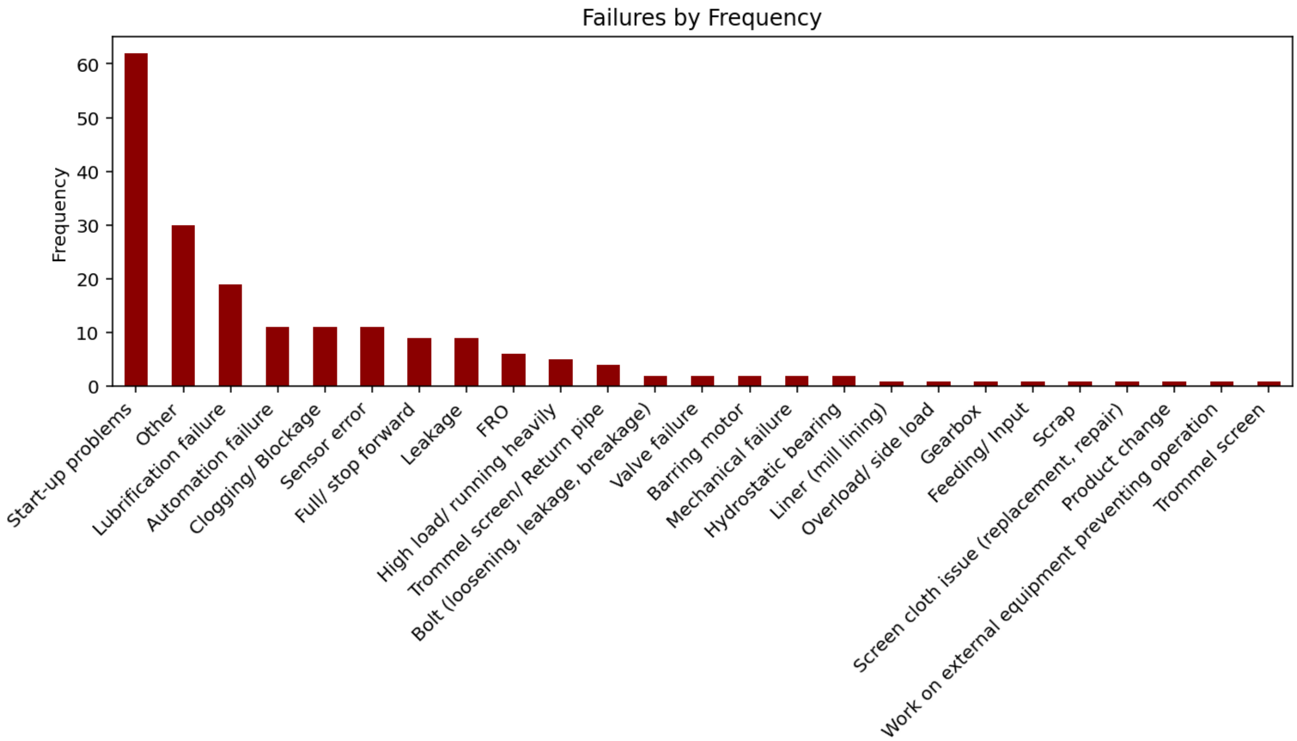


Figure 5.2. Graph of the failure's frequency for mill P2.

During the five-year analysis, mill P1 recorded a total of 217 stoppages and mill P2 registered 199. Despite these interruptions, both mills maintained an average utilization rate of approximately 78% of their total capacity, indicating a relatively balanced production load between the two units.

The mills undergo annual preventive maintenance, complemented by approximately four shorter maintenance stops per year, each lasting between 10 and 24 hours.

Figure 5.3 illustrates the monthly distribution of failures for both mills. In mill P1, significant peaks occurred in October (40 stops) and August (34 stops). The lowest frequency of stoppages was observed in July, March and May. Mill P2 experienced highest number of failures in August (29 stops), July (25 stops) and April (21 stops), with the lowest numbers reported in March and November.

Notably, both mills experienced the same number of stoppages in March (7), September (11) and December (15), suggesting possible shared operational patterns during these months.

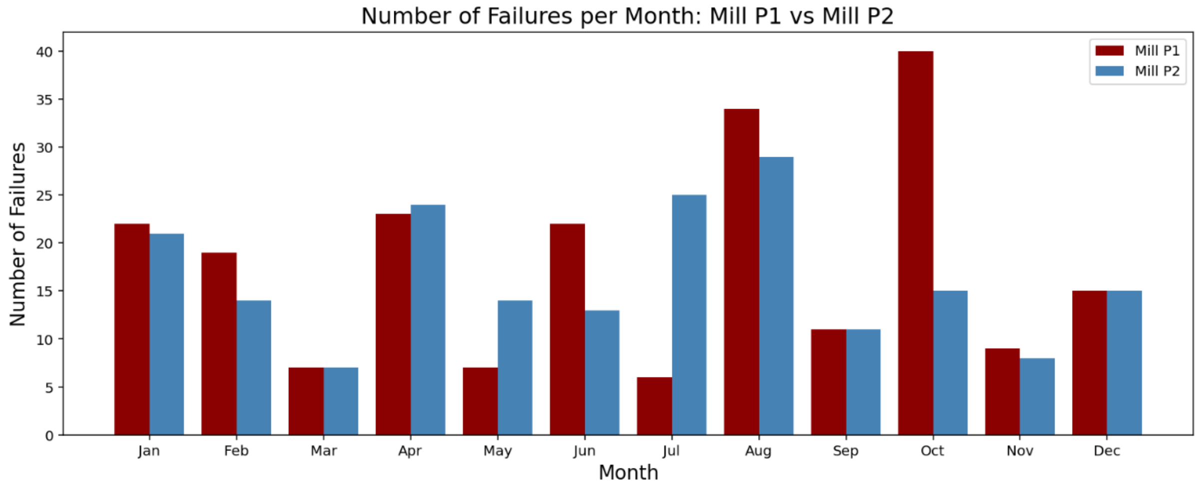


Figure 5.3 – Number of failures per month for Mill P1 and P2.

Monthly downtime, in hours, is shown in Figure 5.4. For mill P1, the most critical months in terms of total downtime were April (158 hours) and August (130 hours). The least severe months were July, October and June. Interestingly, although October had the highest number of failures, they were not associated with significant downtime, implying less severe or more easily resolved issues.

For mill P2, the highest downtime occurred in January (200 hours) and July (150 hours). August, despite having the highest failure frequency, resulted in relatively low total downtime, indicating that those failures were addressed quickly. The lowest downtime for P2 was observed in March and August.

Both mills showed similar downtime values in June and October, highlighting consistent operational behaviour in those months.

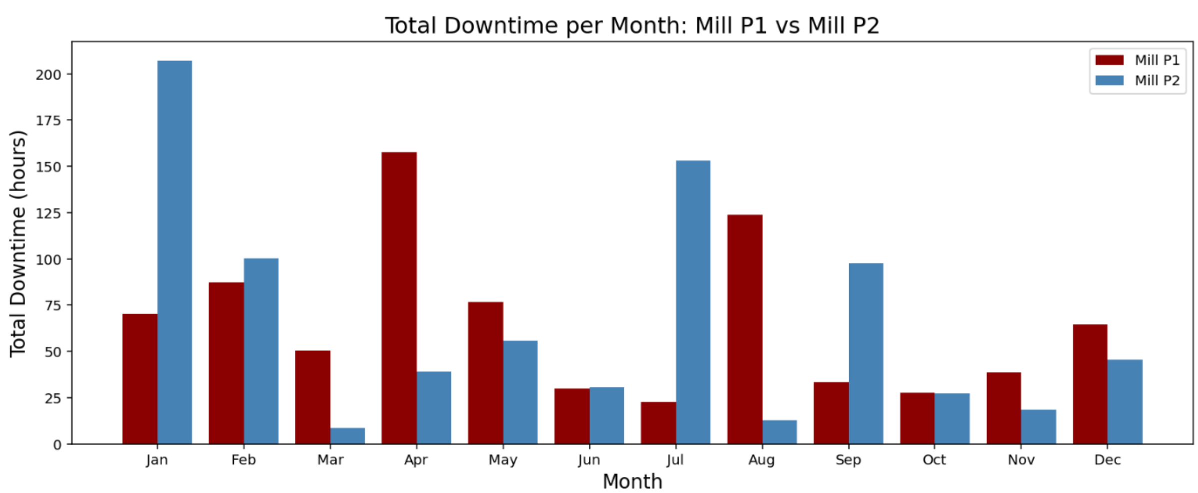


Figure 5.4 – Total downtime per month for mill P1 and P2.

Figure 5.5 summarizes annual unplanned stops for each mill. The final year of analysis recorded the highest total downtime for both units, potentially signalling progressive mechanical degradation or aging equipment.

A notable discrepancy appeared in the second year of the study, where mill P2 recorded 141.9 more hours of downtime than mill P1, making it a particularly critical year for mill P2. In the remaining years, the difference in downtime between the mills remained minor.

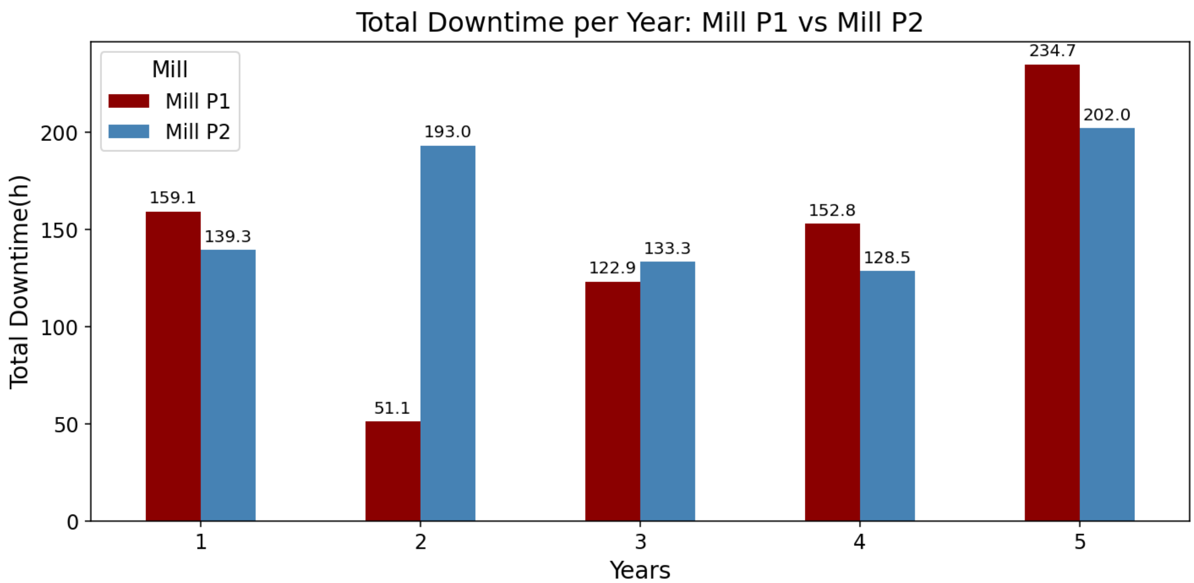


Figure 5.5 – Total downtime per year for each mill.

The company also validated the accuracy of the results, considering external factors that affect mill operations. For instance, January is typically characterized by extreme freezing conditions in Kiruna, often requiring production to be halted. In 2020, a major earthquake in the region further impacted operations, making it a particularly challenging year. Similarly, in 2022, issues at the pelletizing plant contributed to irregularities in mill performance. Overall, the harsh and variable weather conditions in Kiruna present a consistent challenge for the operation of this mills.

To better understand the nature of stoppages, causes were separated as either internal (related to equipment condition or operation) or external (environmental or with influence of third parties).

For mill P1, there were 208 internal stops and 7 instances of external interference. When examining the total downtime associated with each interference type, mill P1 experienced 596.45 hours of downtime due to internal causes and 185.78 hours resulting from external interferences, summing to a total of 782.23 hours of operational disruption.

In contrast, mill P2 experienced 185 internal stops and 11 external interferences. Mill P2, exhibited 418.53 hours of downtime linked to internal interference, with a notably higher

377.60 hours attributed to external factors, bringing the total downtime to 796.13 hours. For this mill external factors played a larger role than expected.

This differentiation between internal and external sources of stoppage was crucial in focusing subsequent analyses. In particular, greater attention was given to internal interference, as these failures are related to the machines condition and performance, thus offering actionable insights for improving maintenance strategies and overall equipment reliability.

In this case study, critical failure refers to the duration of the downtime of each failure that directly affect safety, production targets, and asset health.

According to Table 5.2, the most frequent failure type for both mills was start-up problems. These issues typically arise when restarting equipment after shutdowns, maintenance, or commissioning activities. They may be triggered by mechanical faults, process inconsistencies, electrical or control malfunctions, or human errors. Start-up failures are critical moments due to unstable loads, incomplete system resets, or residual maintenance errors.

In terms of criticality, the "Other" category appeared most often in both mills, encompassing complex or poorly defined failure modes. This category includes all events that do not fit clearly into predefined categories and may result from combined or unclear causes. Other critical failures that appeared consistently in both mills included leakage, lubrication failure and automation failure.

These recurring issues indicate common weaknesses in auxiliary systems and automation reliability across both mills. Leakage failures involve unintended fluid loss due to degradation in seals, gaskets, or piping, often escalating into significant mechanical or environmental issues.

Lubrication failure result in improper lubrication of rotating parts, leading to overheating, wear, or breakdown.

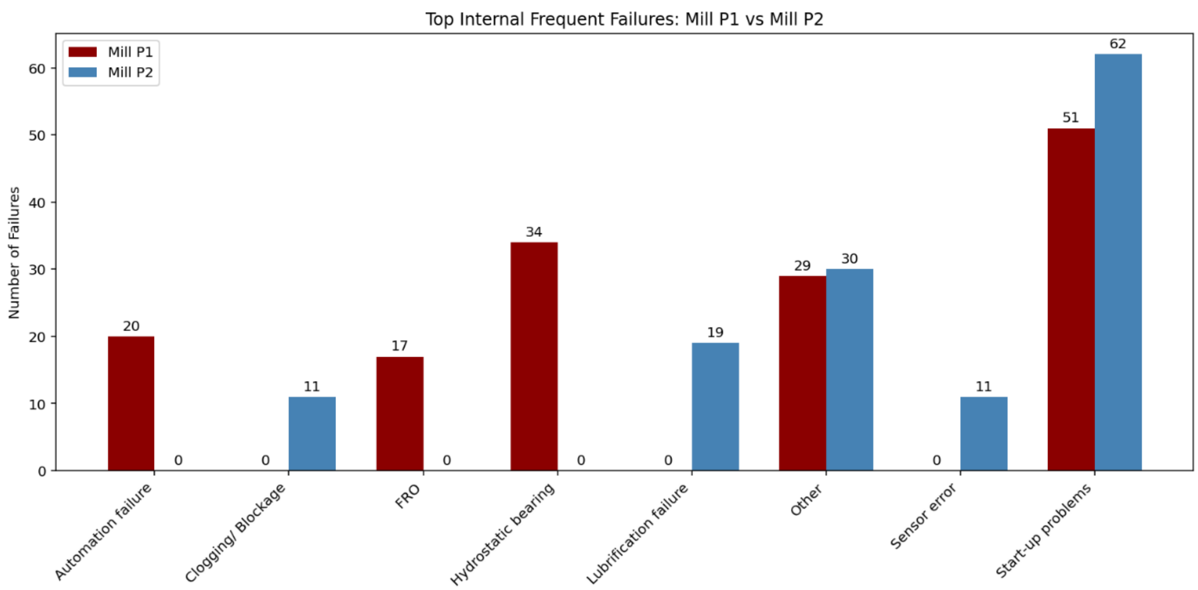
An automation failure covers interruptions in monitoring and control systems that govern essential subsystems such as speed, feed rate and safety interlocks.

Table 5.2 – Top 5 most frequent and most critical failures per mill.

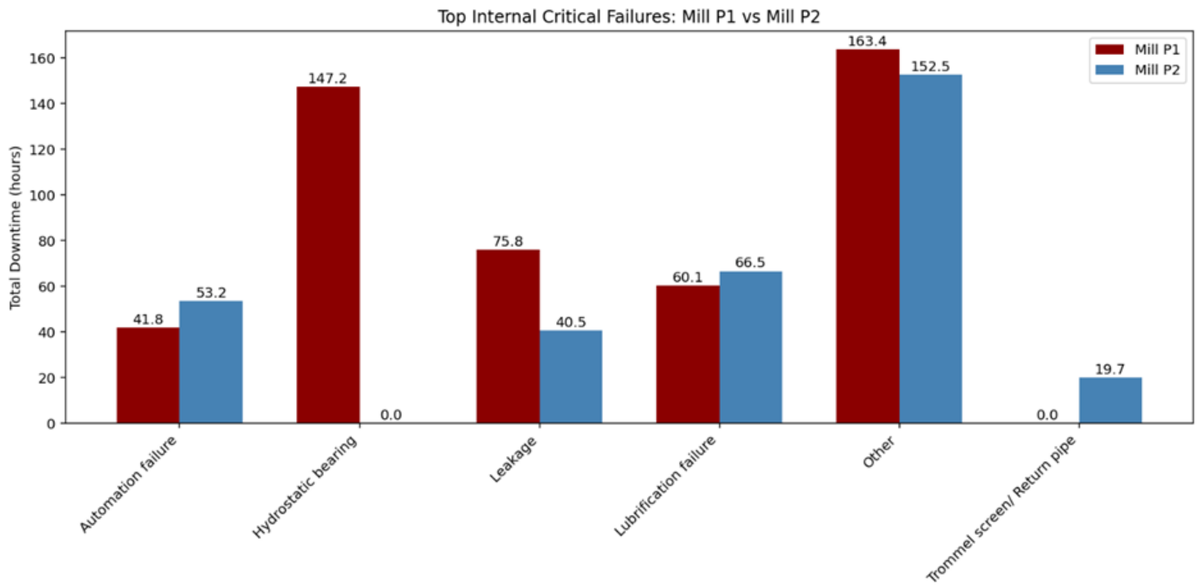
Mill	P1	P2
Frequent Failures	1. Start-up problems 2. Hydrostatic bearing 3. Other 4. Automation failure 5. FRO	1. Start-up problems 2. Other 3. Lubrication failure 4. Clogging/blockage 5. Sensor error

Critical Failures	1. Other 2. Hydrostatic bearing 3. Leakage 4. Lubrication failure 5. Automation failure	1. Other 2. Lubrication failure 3. Automation failure 4. Leakage 5. Trommel screen/ return pipe

Figure 5.6a, and 5.6b graphically confirm that start-up problems is the most frequent cause, while automation, lubrication and leakage dominate the list of most critical failures in both mills.



a)



b)

Figure 5.6 – Top 5 internal interference per mill: a) frequent failures; b) critical failures.

Table 5.3 provides a comparison of key reliability metrics. Mill P2 demonstrated better reliability (higher MTBF), but experienced longer and more variable downtimes, as reflected in higher MTTR and standard deviation.

Mill P1 experienced a total of 215 unplanned stops, while mill P2 had 196, indicating slightly better operational stability for P2. However, despite fewer stoppages, P2 accumulated a slightly higher total downtime of 796.13 hours compared to 782.23 hours for P1. This suggests that while P2 experienced fewer failures, the duration of individual stoppages tended to be longer on average. The standard deviation of downtime duration was higher for P2 (13.35) compared to P1 (8.90), reflecting greater variability in downtime events for P2.

P1 showed a lower MTTR of 3.64 hours, while P2 required 4.06 hours on average to restore operations, indicating that P1's failures were repaired more quickly. P2 performed significantly better, with an MTBF of 222.97 hours compared to 203.52 hours for P1. This means that failures occurred less frequently in P2, suggesting better overall reliability. Also, both mills demonstrated the same failure rate of 0.5% and have high availability with P2 showing a marginal advantage.

Table 5.3 – KPIs results for both mills.

Indicators	P1	P2
Total Downtime (h)	782.23	796.13
MTTR[8]	3.64	4.06
MTBF[9]	202.52	222.97
Standard deviation	8.90	13.35
Uptime[10]	43311.77	43297.87
Availability (%)	98.6	98.7
Failure rate (%)	0.5	0.5
Unplanned Maintenance (%)	1.77	1.81

Table 5.4 and Figure 5.7 show the production losses associated with each mill per year. The final year was the worst in terms of availability and productivity for both mills (1 ton = 10^3 kg).

Mill P1 effective production had been significantly reduced over the past five years and therefore more lost production. Mill P2 maintained more stable values, although the highest production loss occurred in the second and fifth year.

Table 5.4 – Results of lost production for both mills.

Mill	Year	Downtime(h)	Availability (%)	Effective Production ($\times 10^6$ tons)	Lost Production ($\times 10^6$ tons)
P1	**1**	177.10	97.97	5.570	0.115
	2	51.05	99.42	5.650	0.033
	3	122.93	98.59	5.604	0.080

[8] Mean Time to Repair
[9] Mean Time Before Failure
[10] Out of 44094.0 hours

	4	152.85	98.26	5.600	0.099
	5	264.53	96.97	5.512	0.172
P2	**1**	157.35	98.20	5.582	0.102
	2	193.02	97.79	5.560	0.125
	3	133.27	98.47	5.598	0.086
	4	162.45	98.15	5.594	0.105
	5	201.97	97.69	5.553	0.131

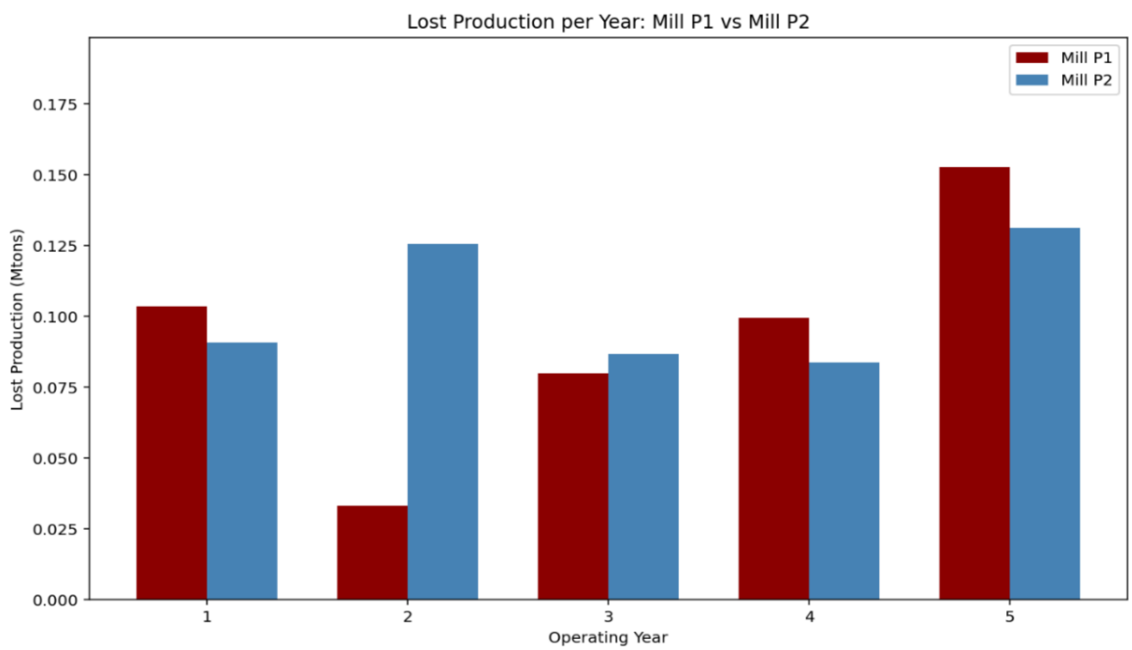
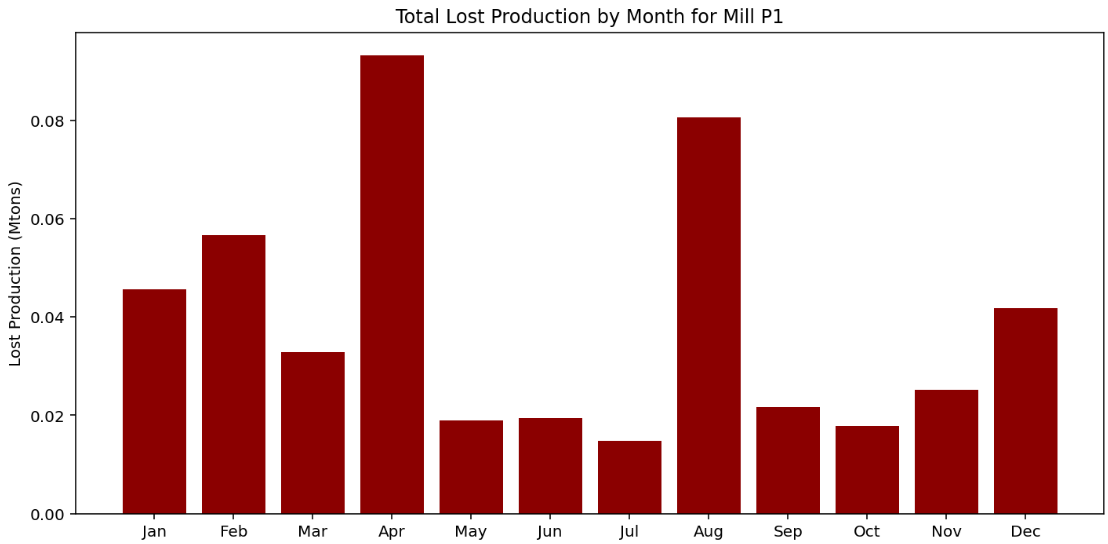


Figure 5.7 – Lost production for each mill per year.

Figure 5.8a, and 5.8b, highlight the worst months per mill. For mill P1 were April and August, while for P2 were January and July.



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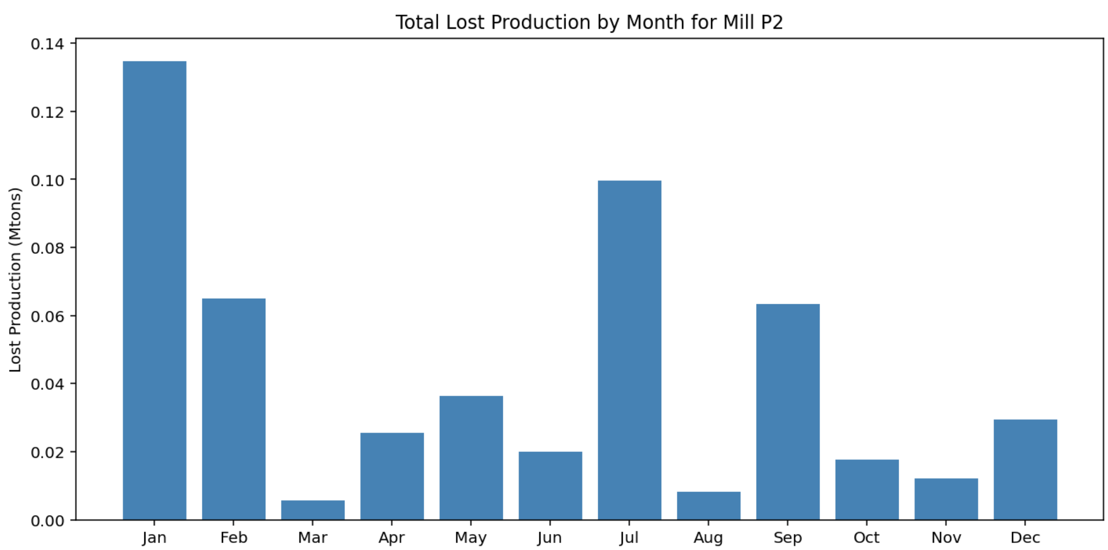


b)

Figure 5.8 – Lost production by month: a) for mill P1; b) for mill P2.

After the results from total lost production, the objective was to analyse in detail the failures that directly affect more the production of this mills. Table 5.5 and Table A.1 (in Annex A) show the most critical failures based in Table 5.2 (top 5 most frequent and most critical failures) and confirmation from the company's engineer. The faults that require the most attention are "leakage", "lubrication failure", "automation failure" and "hydrostatic bearing". Also, was decided to consider the failure "start-up problems" in both machines because of the frequent occurrences.

The worst losses for mill P1 were linked to hydrostatic bearing (95759.13 tons), followed by leakage (49332.76 tons). For mill P2 the leading contributors were lubrication failure (43248.86 tons) and automation failure (34648.97 tons).

Table 5.5 – Total Production Lost for the 5 years period, for mill P1 and P2.

Mill	Year	Production Lost (tons)				
		Start-up problems	**Leakage**	**Lubrication Failure**	**Hydrostatic Bearing**	**Automation Failure**
P1	**1**	260.27	9500.00	0	0	856.74
	2	477.17	2515.98	2158.11	0	15399.54
	3	249.43	0	21244.86	0	0
	4	422.95	0	0	32154.68	6561.07
	5	488.01	37316.78	6528.54	63604.45	4359.59
Total		1897.83	49332.76	29931.51	95759.13	27176.94
P2	**1**	1225.46	10259.13	25127.28	0	13393.27
	2	1735.16	1062.79	2429.22	0	19954.34
	3	336.19	1236.30	3416.10	0	0
	4	2277.40	0	1290.53	867.58	1268.84
	5	347.03	13794.52	10985.73	32.53	32.53
Total		5921.23	26352.74	43248.86	900.11	34648.97

To reduce the production losses, a scenario with a 30% reduction in critical failures was simulated (Figure 5.9). This revealed that targeting hydrostatic bearing issues, for mill P1, and lubrication failure, for mill P2, would deliver the greatest improvements in productivity and equipment longevity.

Although this reduction in critical failures provides a useful initial reference, it is not sufficient to support final decision-making. Future analyses should be completed with tools such as

Pareto analysis and economic indicators to quantify potential impacts, support informed decisions, and reduce the risk of costly investments. These tools would also justify investments in preventive maintenance and enable more comprehensive economic assessments, including payback period and return on investment (ROI) analyses.

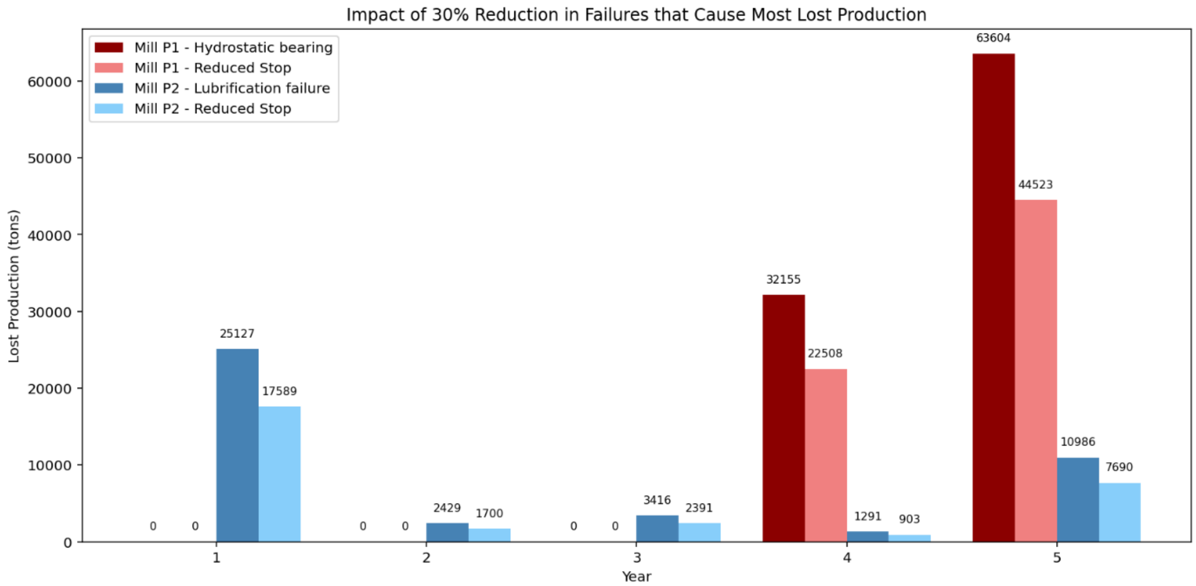


Figure 5.9 – Impact of 30% reduction of a failure in mill P1 and P2.

FMECA analysis was conducted to prioritize failure modes using Risk Priority Numbers (RPN), calculated from Severity (S), Occurrence (O) and Detection (D) ratings (Table 5.6).

In this analysis the failure type was taken from the data provided by the company. The components, failure mode, cause of failure, and failure effect were taken from the engineer's comments given in the data provided by the company.

Table 5.6 – FMECA Analysis

Failure type	Failure mode code	Component	Failure mode	Cause of failure	Failure effect		Recommended actions
					Local effects	Global/ End effects	
Automation Failure	**FM1**	Switchgear	Safety circuit trips	Component fault, faulty monitor	No power delivery	Mill shutdown, production stops	Regular maintenance, quick repairs
	FM2	UPS/ Control System	Power drop or communication loss	Power loss, UPS failure, overload, or battery degradation	Power loss, UPS fail, overload, battery	Downtime	UPS maintenance, regular battery checks, backup power
	FM3	Converter (Accumulator)	Converter failure	Electrical fault	Unexpected stops	Production stops	Signal check, diagnostics, replacement
	FM4	Sensors (pressure/flow)	Unstable or incorrect readings	Sensor fails, miscalibration, signal loss	Process interruption, unreliable data	Reduced throughput, equipment damage risk	Sensor redundancy, filtered alarm logic, validation rules
	FM5	Valves	Wrong position	Valve or wiring issue	Pumps/ feeders stop	Plant halt	Electrical checks, replacements
Clogging/ Blockage	**FM6**	Feed chute	Material blockage	Ore, particles, foreign objects	Flow restricted, chute backup	Mill stop, production loss	Scrap cleaning, monitor chute

	FM7	Mill discharge	Over-discharge at startup	Poor discharge, overfilling, slurry buildup	Risk of chute overflow	Line blockage, equipment stress	Operator training; optimise startup procedure
	FM8	Chute sensors	False/ missed readings	Sensor malfunction or obstruction	Inaccurate blockage detection	Delayed or missed intervention	Sensor calibration; inspect sensors regularly
	FM9	Mill system	Hydrostatic failure on restart	Previous sudden stop, system instability	Restart failure, mill idle	Extended downtime	Controlled stops; validate system status pre-start
Hydrostatic System Failure	**FM10**	Accumulator	Pressure below threshold	Gas leakage, insufficient pre-charge, valve failure	Insufficient pressure in hydrostatic system	Mill cannot start or maintain operation	Regular gas checks, pre-charge logs, backup accumulator
	FM11	Flow sensors	Flow too low	Pump degradation, clogged filters, low flow sensor dips	Drop in system flow and pressure	Trip or shutdown to prevent bearing damage	Flow alarms, backup pump, predictive maintenance
	FM12	Hydrostatic system oil	Overheating	Overheating due to friction, cooling failure	Oil temperature too high (loss of viscosity)	Bearing failure or safety trip	Oil temperature sensors, cooling loop checks, auto shutdown logic
	FM13	Flow and pressure sensors	False readings/fluctuation	Sensor drift or failure	Incorrect alarms or no trips	Unreliable operation	Sensor replacement, calibration routines

	FM14	Filters, valves, pumps	Pressure/flow change	Pressure dips during filter swap, lack of bypass or improper sequencing	Transient flow loss	Unplanned stop during maintenance	Controlled maintenance; override safeguards if safe
	FM15	Interlocks	Emergency stop triggered	Linked to flow/pressure dips	Immediate stop	Production interruption	Investigate triggers; test safety circuits
	FM16	Hydrostatic system	Viscosity too high	Low ambient temperature or preheat failure	Reduced flow, false trips	Start-up delays	Preheat system; monitor oil temperature during start-up
Leakage	**FM17**	Hoses and pipes (water/oil)	Hose or pipe leak	Corrosion, wear, damage	Water/oil loss	Motor damage, short circuit, unplanned stop	Visual inspection, pressure rated hose, automatic shutoff
	FM18	Hydraulic system	Oil leak	Seal failure or overpressure	Oil pooling, safety risk	Stop for cleanup or damage	Preventive maintenance; monitor pressure
	FM19	Chutes and funnels	Holes or cracks	Wear, impact, corrosion	Material leakage	Product loss, safety risks	Patch/ repair; reinforce weak points
	FM20	Valves	Seal or seat failure	Valve failure or broken housing	Flow disruption or loss	Process inconsistency	Valve testing, backup valves
	FM21	Coarse cyclone piping	Joint/pipe failure	Vibration, misalignment	Material spray or spillage	Process inefficiency	Pipe inspection, weld certification, vibration damping

Lubrication failure	**FM22**	Ring gear grease pump	Continuous run without control	Pump motor failure, wear, electrical fault	No grease supply to gear	Alarm flood; potential damage	Check control logic; add auto-shutoff
	FM23	Ring gear lubrication circuit	None or insufficient grease delivery	Faulty/failed grease pump; ran out of grease	Grease not reaching target zones, alarm triggers	Mill stops	Monitor grease level; maintain spares; alarm escalation
	FM24	Lubrication sensors	Ghosting/faulty alarms	Failing sensor or false readings	Confusion, delayed acknowledgment	False shutdown; troubleshooting delays	Sensor diagnostics; timely replacement
	FM25	Valve	Incorrect valve state or actuator failure	Manual error, coil fault, actuator issue	No grease flow; false signals	Shutdown due to safety interlock	Valve state checks; maintenance routines
	FM26	Ring gear/ labyrinth system	Distributor not moving	Distributor not moving due to clogging, mechanical jam, or actuator failure	No lubrication to labyrinth seal	Component wear; safety shutdown	Distributor motion monitoring, alarms, periodic testing
Start-up problems	**FM27**	Mill drive and load system	Excessive torque/power load	Mill full of material after unplanned stop or emergency brake	High torque, heavy load	Repeated shutdowns; equipment strain	Ensure end-run; unload before restart
	FM28	Feed chute/ conveyor/ classifier	Blockage at startup	Material build-up due to poor flow, improper flushing, or backlogged conveyor	Feed disruptions, belt overload	Process interruption	Flush system, verify flow and water valve ops

FM29	Hydraulic system	High viscosity oil	Insufficient warm-up after shutdown	Delayed pressure build-up	Failed start attempts; safety trips	Preheat oil, warm-up procedures
FM30	Water/ flow system	No or poor flushing	Faulty valve, manual closure, control issues	Poor material movement	Mill overloads due to dense material	Repair/replace faulty valves, install flow monitoring, manual override alerts
FM31	Flow sensors	No/false readings	Sensor failure or misconfiguration	No auto-flow detection; alarms	Operator confusion; false stops	Validate instruments; backups; test signals
FM32	Line	System brakes hard	Broken emergencies stop line, sudden stop without discharge	Load spike on restart	Repeated stop/start cycles	Controlled stops; clear material before restart

The Severity (S) was calculated by considering the downtime associated with each type of component failure divided by the total downtime for that failure type. The Occurrence (O) was calculated based on the number of stoppages for each type of component failure and divided by the total number of stoppages for the corresponding failure type. Finally, the Detection (D) was assessed through discussion with the company's engineers and was assigned at each failure type. The detailed calculations used to identify S and O are presented in Annex A.

The RPN results for both mills are presented in Table 5.7. For mill P1, the most critical failures were clogging/blockage in feed chute and at the mill discharge (failure modes FM6 and FM7, respectively). In the case of mill P2, the most critical failures include clogging/blockage in the feed chute and leakage in hoses and pipes (failure modes FM6 and FM17, respectively).

This findings underscore a shared vulnerability in the feed chute systems, which should be prioritizes for maintenance improvements.

The RPN lines shown in grey indicate that no failure mode was identified for that component based on the available data.

Table 5.7 - FMECA results for the two mills (P1 and P2).

Failure mode code	Mill P1				Mill P2			
	S	**O**	**D**	**RPN**	**S**	**O**	**D**	**RPN**
FM1	5	7	9	315	10	6	9	540
FM2	10	5	9	450	10	6	9	540
FM3	5	5	9	225	4	10	9	360
FM4	7	6	9	378	6	7	9	378
FM5	5	5	9	225	10	7	9	630
FM6	8	10	10	800	10	9	10	900
FM7	10	8	10	800	6	7	10	420
FM8	2	7	10	140	9	7	10	630
FM9	10	7	10	700	7	9	10	630
FM10	10	8	5	400	-	-	-	-
FM11	9	9	5	405	-	-	-	-

FM12	3	7	5	105	-	-	-	-
FM13	7	7	5	245	10	9	5	450
FM14	6	7	5	210	-	-	-	-
FM15	5	7	5	175	-	-	-	-
FM16	10	6	5	300	4	9	5	180
FM17	6	9	10	540	10	9	10	900
FM18	-	-	-	-	10	8	10	800
FM19	3	7	10	210	6	7	10	420
FM20	8	7	10	560	-	-	-	-
FM21	10	7	10	700	5	6	10	300
FM22	5	7	3	105	2	8	3	48
FM23	10	9	3	270	6	8	3	144
FM24	8	6	3	144	10	8	3	240
FM25	1	6	3	18	4	5	3	60
FM26	9	7	3	189	9	8	3	216
FM27	10	9	2	180	10	8	2	160
FM28	8	7	2	112	5	7	2	70
FM29	6	6	2	72	10	6	2	120
FM30	6	6	2	72	5	7	2	70
FM31	-	-	-	-	1	4	2	8
FM32	5	6	2	60	4	5	2	40

To deepen understanding of systemic failure causes, Ishikawa (fishbone) diagrams were developed to further investigate the root causes of clogging/blockage issues, and leakage failures (Figure 5.10 and Figure 5.11, respectively).

These diagrams revealed recurring causes across categories such as Machines, Methods, Manpower, Material, Measurements and Environment conditions.

The diagram in Figure 5.10, the machines category refers to the mechanical and electronic components directly involved in the material handling or processing operation. Key components such as the feed chute, mill discharge units, and chute sensors play vital roles in ensuring the proper flow of material. If any of these systems malfunction, whether due to mechanical wear, sensor failure, or design limitations, material flow can become obstructed. For example, a malfunction chute sensor might fail to detect the buildup of material, causing overflows and eventual blockages. Similarly, any dysfunction within the mill system can disrupt normal discharge, leading to backups and stoppages downstream.

The methods section identifies procedural shortcomings that may contribute to clogging. Improper startup procedures are significant issue, as starting the system without first ensuring that all parts are clear can immediately lead to blockage. Additionally, a lack of pre-checks before restarting operations after maintenance or shutdowns can allow residual materials or foreign objects to interfere with the normal flow. Inefficient timing in the discharge process can cause overflows, while poor protocols for detecting and responding to blockages mean problems are often not addressed until they have escalated. The absence of robust, standardized procedures leaves the system vulnerable to inconsistent handling, increasing the likelihood of failure.

Human error is an important factor in many operational failures, and this is captured under the Manpower category. Operator errors at startup, such as neglecting to inspect equipment or bypassing safety protocols, can quickly result in system failure. A lack of training specific to blockage prevention means that operators may not recognise early warning signs or know how to take corrective action. Further exacerbating this problem is a general lack of awareness about hydrostatic risks, such as pressure buildup in pipes or chutes, which can lead to severe consequences if improperly managed. Additionally, delayed responses to false alarms or missed sensor signals can allow a minor issue to evolve into a full blockage.

The properties and conditions of the materials being processed also significantly influence blockage risks. The presence of foreign objects in the feed can cause immediate physical obstruction. High-density slurry is particularly problematic, as it tends to settle and accumulate more readily than lower-density materials. Uneven particle size distribution can exacerbate this by allowing fine particles to compact and bridge within narrow sections of the system. Overfilling during the charging process contributes further, often overwhelming the system's capacity and leading to backup and overflow scenarios.

The Measurements category is related to sensors, monitoring systems, and data validation mechanisms. Sensor miscalibration is a key contributor, leading to inaccurate readings and inappropriate system responses. If sensors fail to detect a blockage, or falsely indicate one, operators may either ignore real issues or react to non-existent problems, both of which can cause system instability. A lack of real-time monitoring of discharge rates or flow dynamics means that the system cannot adapt quickly to changing conditions. Furthermore, if control systems lack built-in validation rules to flag anomalous data, early signs of developing blockages may go unnoticed until it is too late.

Environmental conditions within and around the processing area also play a critical role. Temperature fluctuations can affect the reliability of system restarts, particularly in systems sensitive to expansion, contraction, or thermal cycling. Humidity and slurry splashes can compromise sensors, corrode components, and contribute to the accumulation of sticky residues. Abrasive materials can gradually wear down chute walls, altering flow dynamics and increasing the chances of material buildup.

By breaking down the root causes into these categories, the diagram serves as a good diagnostic tool to identify, prioritize, and mitigate issues. Addressing these contributing factors significantly enhances system performance.

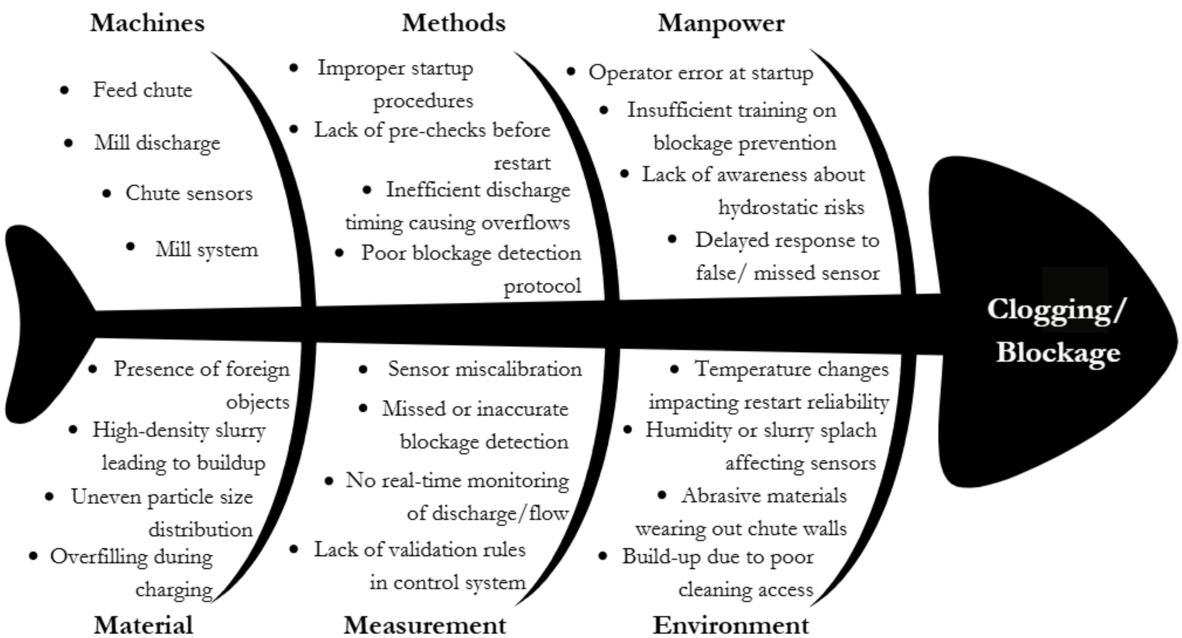


Figure 5.10 – Fishbone diagram of interrelated causes of clogging/blockage.

In Figure 5.11, the Machines category focuses on mechanical and equipment-related issues that can cause leakage. Components such as hoses and pipes, hydraulic systems, chutes and funnels, valves and coarse cyclone piping are highlighted. Failures in these components, such as cracked or poorly maintained hoses, faulty valves, or improper funnel design, can result in leaks. For instance, damaged hydraulic lines or corroded piping systems often become a direct source of leakage if not maintained properly.

In Methods, the inadequate preventive maintenance routines and improper or delayed repairs are major contributing factors. If regular maintenance is neglected, or if repairs are done without proper standards or timeliness, the risk of leakage increases. Additionally, lack of regular valve testing, poor system pressure monitoring, and inconsistent inspection of vulnerable piping sections can lead to undetected system weakness, eventually resulting in leaks, these procedural lapses indicate systemic issues in maintenance methodology.

Manpower category show that improper visual checks by technicians or operators can result in missed early signs of leakage. Many operators may also be inexperienced in recognising the early signs of leakage, such as subtle oil stains or slight drops in pressure. Furthermore, delayed responses to early indicators, such as pooling water or oil, and inadequate training in fluid handling systems, compromise the team's ability to detect and address leaks effectively. This category highlights the importance of competent, well-trained personnel and vigilance.

The Material category about leakage, result from degraded seals, corroded components, or contaminants that cause erosion. Materials that are prone to wear or not designed for the operating conditions can accelerate failure. Also, substandard welding or pipe joints that lack proper certification can introduce weak points. The use of worn-out hoses or low-pressure-rated piping in high-pressure systems is also a key contributor, as these materials cannot withstand the operational stresses, leading to rupture or failure.

In Measurements, lack of pressure monitoring may allow overpressure conditions to go unnoticed until failure occurs. The absence of automatic shutoff mechanisms or sensor-based alerts reduce the system's ability to respond to critical failures in real time. Additionally, no vibration monitoring in piping systems can lead to undetected mechanical stress and fatigue. Finally, failure to track wear or the service hours of critical components means maintenance may not occur at optimal intervals, leading to avoidable failures.

In Environmental section, vibration and misalignment from machinery can stress piping and joints, increasing the likelihood of leaks. Operating in harsh environmental conditions, such as high humidity, chemical exposure, or salt-laden air, can accelerate corrosion. Systems exposed to abrasive materials, like slurry or particulate-laden fluids, experience faster internal erosion. Additionally, thermal expansion and contraction due to temperature fluctuations cause stress on joints and pipes, leading to fatigue and eventual leakage.

Understanding each category and its specific causes enables a more targeted and strategic approach to leak prevention and system reliability. By addressing each contributing factor from Cause-and-Effect diagram, through better training, material selection, maintenance planning, environmental controls, and real-time monitoring, this industry (and the general industry sector) can significantly reduce the occurrence of leakage and improve the operational efficiency of fluid systems.

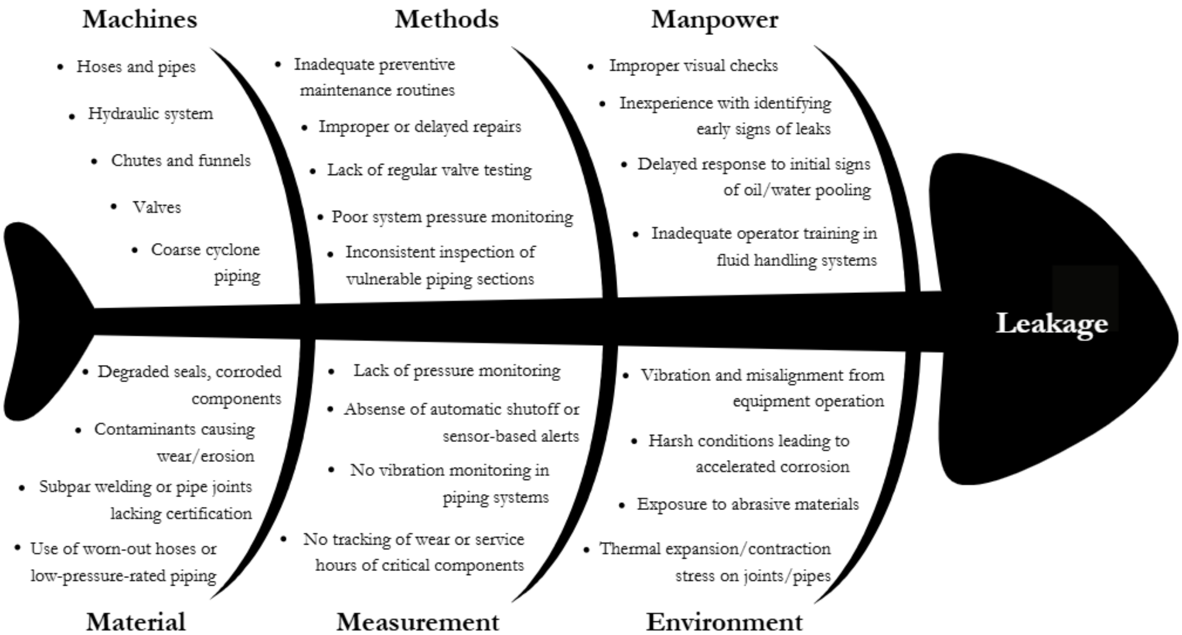


Figure 5.11 – Fishbone diagram of interrelated causes of leakage.

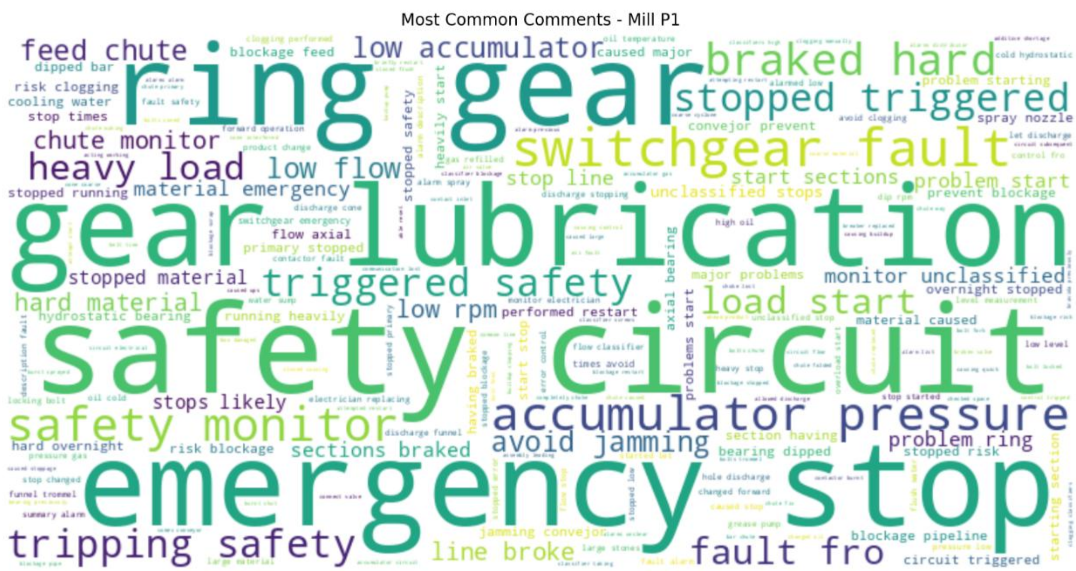
To identify recurring themes and operational issues in mill P1 and P2, a word frequency analysis was conducted on comments from engineers and operators. This analysis focused on bigrams (two-word phrases), revealing patterns in how failures, alarms, and abnormal conditions are reported.

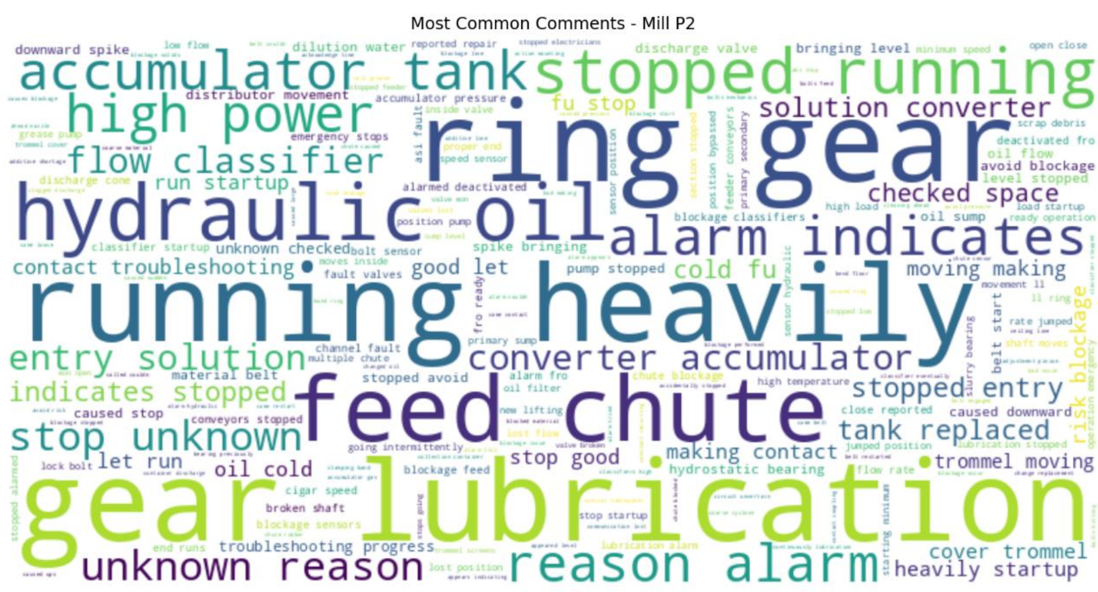
The word cloud for mill P1 (Figure 5.12) highlights operational concerns centred around safety and mechanical reliability. The most frequent bigrams include: "emergency stop", "safety circuit", "gear lubrication", "ring gear", and "braked hard". These indicate that unscheduled shutdowns and safety-related interruptions are major issues in mill P1. The prominence of terms like "emergency stop" and "safety circuit" suggests frequent activation of safety mechanisms, likely due to mechanical or process instability. Terms such as "gear lubrication" and "ring gear" points to chronic issues in the drive system and lubrication loop.

The word cloud for mill P2 (Figure 5.13) reveals that the most prominent terms include "running heavily", "gear lubrication", "ring gear", "hydraulic oil", and "unknown reason". The bigram "running heavily" suggests persistent high mechanical load, potentially linked to throughput or oversizing of material. The recurrence of "hydraulic oil" reflects a strong presence of fluid system issues, particularly in pressure regulation and oil circulation. A notable pattern is the high occurrence of "unknown reason" suggests diagnostic uncertainty in reported stoppages.

Comparing both mills word cloud, P1 shows more frequent comments related to emergency and safety-triggered shutdowns, suggesting greater mechanical or electrical instability. Mill P2 shows stronger emphasis on running under load, alarm diagnostics, and lubrication system, indicating it may be operating under more consistent stress conditions but lacks clarity in failure attribution.

These findings can inform tailored reliability strategies, for mill P1 may benefit from improved real-time monitoring and automated shutdowns prevention, while mill P2 may require enhanced alarm logic, root cause analysis, and operator training to reduce ambiguity in failure reporting.





By focusing on the most critical failure modes and their root causes, the company can significantly improve mill availability, reduce production losses, and extend equipment lifespan. Key recommendations:

- Prioritizing reductions in hydrostatic bearing and lubrication failures;
- Enhancing predictive maintenance and automation system monitoring;
- Addressing human factors through improved training and procedures;
- Improving failure classification to reduce ambiguity in root cause data.

5.2 The proposed framework for Intelligent Asset Management (IAM)

To address the emerging challenges and opportunities in industrial operations, particularly related to sustainability, human-centricity and resilience, this research introduces a novel framework that connects Physical Asset Management (PAM) to an improved Intelligent Asset Management (IAM) within the vision of Industry 5.0. This framework, depicted in Figure 5.14, aims to clarify what, how and why organisations should transform asset management practices to align with the principles of Industry 5.0.

- Why – The Purpose: Industry 5.0

At the top level, the framework aligns with the "why" dimension, overarching goals that drive transformation in industries. These are based on the principal values of Industry 5.0:

  - Resilience: The capacity of anticipate, absorb, and recover from disruptive events;
  - Human-centricity: Placing human well-being and skills at the centre of technology development and industrial processes;
  - Sustainability: Achieving environmental and resource efficiency while minimising negative externalities.

- How – The Strategic Layer: Intelligent Asset Management (IAM)

The "how" level reflects the transition from traditional asset management to a more integrated and intelligent approach. IAM serves as the strategic mechanism that enables value creation through the integration of internal and external factors in the assets management. The internal factors are originated inside the organisation and can be directly managed (e.g., leadership, company culture, financial resources), while external factors are originated outside the organisation and must be adapted to (e.g., regulations, economy, technology trends).

- Internal factors:
    - Technology: Integration of smart technologies such as AI, IoT and digital twins to enhance asset visibility, reduce downtime, and support lifecycle optimisation;
    - People: Promoting collaboration, cross-functional knowledge sharing, and digital literacy among employees. Human expertise remains vital in interpreting insights, setting strategy, and ensuring ethical oversight. A culture that embraces innovation, continuous learning, and co-creation between people and technology strengthens IAM effectiveness;
    - Process: Implementing optimised workflows, standardized asset management practices, and decision-making structures. Intelligent automation of routine tasks, simplified maintenance planning, and data-driven governance processes that support strategic asset performance and value realisation.
- External factors:
    - Regulation and policy: Ensuring compliance, standardisation, and responsible governance.

Together, these factors form a holistic environment for smarter asset governance and decision-making.

- What – The Operational Layer: Physical Asset Management (PAM)

The base of the framework represents "what" organisations do, the operational activities encompassed by PAM. PAM creates value following International Standards, such as ISO 5500X series, and focus only on the internal management of the company. This includes the asset lifecycle stages of planning, acquisition, operation, maintenance and disposal.

Underpinning these stages is the role of data as an enabler of value creation. Data flows through every lifecycle phase in forms such as acquisition, filtering, cleaning, processing, representation, and visualisation:

1. Data Acquisition: The process of collecting or capturing raw data from various sources, such as sensors, machines or databases;
2. Data Filtering: The process of selecting relevant data by removing unnecessary, irrelevant, or low-quality entries based on specific criteria. The objective is to narrow down large datasets to only the values that matter for a particular analysis;
3. Data Cleaning: The process of detecting and correcting/removing inaccurate, corrupted, incomplete, or duplicate data. The purpose is to ensure data integrity and reliability before analysis;

4. Data Processing: The transformation of raw data into a structured, usable format for analysis or visualization;
5. Data Representation: How data is structured and formatted for communication or analysis, can be included tables, graphs, models or coded formats;
6. Data Visualisation: The graphical representation of data to help identify patterns, trends, and insights. To simply data interpretation and support decision-making by stakeholders.

These activities transform raw data into actionable intelligence, supporting the strategic IAM layer and enabling the delivery of Industry 5.0 goals.

The framework is the result of a synthesis between the foundational structure of PAM, advancements in digital technologies and IAM practices, and the philosophical orientation [11]of Industry 5.0. It prioritizes the synergy between humans and machines, emphasizes environmental responsibility, and promotes resilient, adaptable systems that align with societal values.

This paradigm shift emphasises intelligent collaboration between systems and people, ensuring that technological development respects human needs, cognitive limitations and ethical considerations. Tools such as user-centric dashboards, human-in-the-loop systems and adaptive interfaces facilitate more intuitive interactions with complex data, reducing the likelihood of human error and increasing operational transparency.

At the core of this framework is IAM, which facilitates informed, data-driven decision-making. IAM systems allow companies to optimise asset performance, reduce downtime, and extend equipment lifecycles (Figure 5.14). This ensures operational efficiency while supporting broader business goals. Also, enables organisations to solve their main objectives effectively.

[11] Refers to the underlying values, principles, and worldview

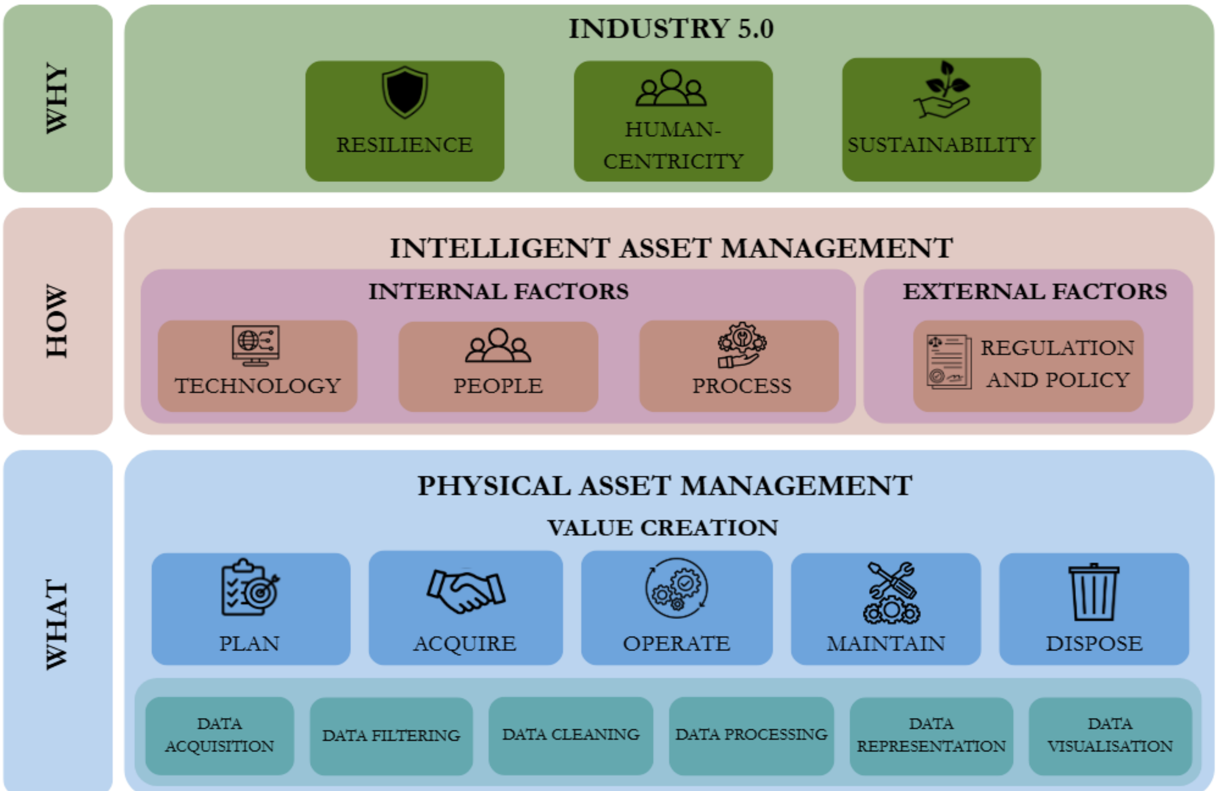


Figure 5.14 – Conceptual model linking physical and intelligent asset management in the context of Industry 5.0.

5.3 Results related to RQ1

The first research question was formulated as: *What are the main challenges associated with managing physical assets in industry?*

To answer RQ1, it was necessary to identify and analyse the core challenges associated with managing physical assets in the industry context. These insights are drawn from literature and the case study.

1) Technical challenges – Focus on technical infrastructure, technology, and systems employed to manage physical assets.

    - Real-time asset visibility: Many organisations struggle to monitor their assets in real time. Without technologies, assets are often misplaced, underutilized, or duplicated. This causes inefficiencies and increases operational risks;

- Technology: Legacy systems and outdated machinery often hinder integration with new digital tools. This gap slows modernization and affects competitiveness;
- Cybersecurity and data privacy: Connected assets are exposed to cyber threats. Older digitalised systems, not designed for digital security, make organisations vulnerable to attacks and data breaches.

2) Organisational challenges – Relate to internal structures, culture, and human resource limitations.
    - Workforce skills: There is a growing need for workers skilled in asset management software and analytics; many employees lack training in these areas;
    - Maintenance strategy: Corrective maintenance is still common, leading to unplanned failures and high repair costs and also has an impact on the operation process;
    - Lifecycle cost planning: Decisions often focus on purchase price, ignoring long-term maintenance and disposal costs.
3) Strategic and compliance challenges - Involve broader policy, risk, compliance, and integration issues that affect long-term planning.
    - Regulatory compliance: Meeting safety, environmental, and industry regulations requires accurate asset records, manual tracking increases the risk of non-compliance.
    - Data fragmentation and system silos: Asset data is often scattered across systems and departments. This prevents a unified view and hampers strategic decision-making.

The analysis of both mills revealed frequent equipment failures, unplanned downtimes, and recurring mechanical issues. Mill P1 suffered from frequent failures with shorter repair durations, while mill P2 had fewer failures but longer repair times, indicating different reliability challenges.

A large portion of downtime was classified under the category "Other", suggesting poor classification systems and lack of detailed failure documentation.

Failures such as leakage, lubrication issues, and overheating were highlighted as key contributors to energy loss. Also, human errors during maintenance (e.g., incorrect part assembly, missing components) were identified as important causes of avoidable stops.

High failure frequency, especially in mill P1, reflects the ongoing struggle with maintaining reliability in aging or heavily used equipment. The high proportion of unclassified downtimes suggests inadequate failure tracking systems, a known limitation in many industrial operations. Additionally, recurring issues, like leaks and overheating, reflect broader inefficiencies tied to poor component health and energy-intensive failure modes. These results reinforce the need for better failure data granularity[12], enhanced workforce training, and stronger root cause analysis capabilities, delivered through a structured maintenance programme.

Answering to RQ1, the main challenges were identified using literature survey and with results from the case study. The findings illustrate several core challenges, consistent with the literature on asset management.

5.4 Results related to RQ2

The second research question is: *What are the key elements that influence the implementation of asset management in industry?*

To answer RQ2, the interconnection between the framework developed in Section 5.2 and the theoretical foundations presented in Section 3 was applied. A successful implementation of asset management within industrial organisations is influenced by a set of interrelated elements that determine the physical assets value creation, risk mitigation, and cost optimisation throughout their lifecycle. These elements encompass strategic, organisational, regulatory, cultural, technological and financial dimensions.

Firstly, asset management needs be anchored in the overall organisational strategy and objectives. This implies that the management of physical assets should not be considered as an isolated operational activity, but rather as an integrated part of the company's mission, vision, and long-term goals.

A second element relates to regulations and governance. Strong commitment from top management is essential to the adoption and institutionalization of asset management practices. This involves defining clear governance structures, roles, and responsibilities for those involved in asset-related activities, as well as ensuring compliance with internationally recognised standards such as the ISO 55000 series (ISO 55000, ISO 55001, ISO55002).

Equally important is the human and cultural dimension. The successful implementation of asset management depends on the skills, competencies, and engagement of the workforce across different levels of the organisation. Training and capacity building are fundamental to ensuring that employees not only possess the necessary technical expertise but also understand the strategic importance of asset management.

Another essential element is risk management, where organisations must be able to identify, assess and mitigate risks associated with asset failure, operational downtime, safety incidents, and environmental impacts.

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[12] The level of detail and specificity in recorded failure data

A further element concerns the adoption of a life cycle perspective. Effective asset management requires that physical assets are managed from the planning and acquisition stages through operation, maintenance, and renewal or disposal.

Technology and innovation represent another key element. The transition towards digitalised and intelligent asset management systems enhances the ability of organisations to anticipate failures, optimise resource utilization, and increase asset availability and reliability.

Finally, the financial dimension underpins all aspects of asset management. Effective capital planning and budgeting processes are necessary to ensure adequate investment in asset renewal, maintenance, and innovation. Financial analysis tools, including life cycle cost and life cycle investment analysis, support decision-making by balancing asset performance, risk, and cost considerations, thereby enabling organisations to maximise value creation over the long term.

In summary, the successful implementation of asset management requires the integration of these interrelated dimensions into a coherent framework, ensuring that physical assets are managed in a manner that optimises performance, minimises risks, and supports value creation.

5.5 Results related to RQ3

The third research question is: *How should intelligent asset management of physical assets be implemented to support Industry 5.0?*

To answer RQ3, the framework developed in Section 5.2 was considered, interconnecting Intelligent Asset Management (IAM) with Industry 5.0.

The transition from Industry 4.0 to Industry 5.0 represents a paradigm shift in how organisations perceive and manage industrial systems. While Industry 4.0 has been predominantly focused on automation, digitalisation and efficiency, Industry 5.0 emphasizes resilience, human-centricity and sustainability.

As outlined in Section 5.2, the implementation of intelligent asset management of physical assets plays a pivotal role in enabling organisations to achieve the vision of Industry 5.0. IAM considers both internal and external factors, connecting technology, people and processes with external drivers such as regulations, policies and societal expectations. This dual perspective ensures that asset management contributes not only to operational excellence but also to broader environmental and social objectives.

From a lifecycle perspective, IAM must ensure that physical assets are intelligently managed from conception to decommissioning, supporting long-term value creation and strengthens organisational adaptability in dynamic environments.

Furthermore, IAM must also address regulatory compliance. Intelligent monitoring systems can track compliance with safety, environmental, and legal requirements.

In summary, the implementation of IAM in the context of Industry 5.0 should integrate human-centric design, advanced data management, sustainability and resilience. By combining emerging digital technologies with the unique capabilities of the human workforce, IAM enables organisations to move beyond efficiency-driven models and towards the creation of sustainable, resilient, and inclusive industrial systems.

5.6 Scientific Contribution: Results

As part of this thesis results, a scientific article titled "Intelligent Asset Management: Bridging Operational Efficiency and Environmental Sustainability" was developed (see Annex D). This article presents the findings of a systematic literature review aimed at identifying how Intelligent Asset Management (IAM) connect with operational efficiency and sustainability, in the context of Industry 5.0. The literature review findings are based exclusively on articles published since 2020.

The findings reveal persistent challenges related to adaptation of legacy systems, organisational resistance, and the need for greater integration between technological solutions and human-centric framework. Few publications connecting IAM explicitly with operational efficiency and sustainability, and complete absence of studies linking IAM directly to Industry 5.0. Similarly, no articles were found addressing the connection between Industry 5.0 and operational efficiency.

Although IAM technologies contribute to predictive maintenance and resource optimisation, there are persistent challenges in aligning these technologies with the strategic principles' human-centric, resilience and sustainability. A key finding of the article is the fragmentation in the existing literature, where studies focus on individual technologies and benefits, without integrating human and sustainability dimensions comprehensively.

Furthermore, the article also highlights organisational barriers, such as resistance to change and the presence of legacy systems, emerging as limitations to IAM implementation in the context of Industry 5.0.

In terms of research contribution, the article proposes future directions that include, empirical studies in real-world industries, and investigation into factors, such as leadership and company culture, which influence the adoption of smart asset management systems.

6 CONCLUSIONS

This thesis aimed to develop and propose a framework to support the transition from traditional Asset Management (AM) to Intelligent Asset Management (IAM) in alignment with Industry 5.0. Using a case study of two autogenous mills in a mineral processing plant, the research investigated unplanned failures, operational performance, and the potential benefits of adopting intelligent maintenance strategies.

The analysis revealed that both mills were affected by critical failure types, particularly hydrostatic bearing, lubrication failure, clogging/ blockage and leakage, which significantly impact production efficiency. Mill P2 demonstrated better reliability, although it experienced longer repair times, while P1 exhibited more frequent failures, though with shorter downtime per event. These differences emphasize the importance of site-specific and asset-specific maintenance strategies rather than one-size-fits-all solutions.

The combined use of Failure Modes, Effects and Criticality Analysis (FMECA) and the Ishikawa diagram proved effective in identifying root causes. These tools also facilitated clearer communication of risks between technical and managerial stakeholders. However, some challenges were observed, including inconsistencies in data quality.

Although the proposed IAM framework could not be fully implemented due to lack of data, the case study generated meaningful insights that supports its practical value. The framework presents a strategic direction for industrial organisations seeking to improve asset management and achieve Industry 5.0.

Limitations in data availability and scope constrained the depth of some analyses, particularly regarding sustainability metrics and cost evaluation. These limitations point to promising avenues for future research, including more detailed reliability modelling, integration of sustainability considerations, and economic assessments.

In conclusion, this research contributes both theoretically and practically to the evolution of asset management. It highlights the need to combine intelligent asset management with advanced technologies, human-centricity and sustainable practices to meet the complex demands of modern industrial systems, in the context of Industry 5.0.

6.1 Contributions

This thesis makes important contributions to the scientific and academic body of knowledge in the field of asset management. One of the key scientific advances is the development of a new framework that guides the transition from traditional Asset Management (AM) to Intelligent Asset Management (IAM), specifically aligned with the values and objectives of

Industry 5.0. By defining IAM in two main factors (internal and external) and considering four key elements: Technology, People, Process, and Regulations and Policies.

This thesis contributes both theoretically and practically to the advancement of AM, transitioning to IAM aligned with Industry 5.0 principles. This framework provides a strategic roadmap that industrial organisations can adopt to enhance resilience, human-centricity and sustainability.

Simultaneously, this research delivers industrial contributions by applying the proposed framework to a real-world case. The detailed analysis of operational data identifies failure patterns, quantifies production losses, and assesses the benefits of targeted improvements – offering actionable insights for maintenance planners and reliability engineers. The study emphasizes the importance of structured failure classification, improved data quality, and intelligent diagnostics, directly supporting the adoption of predictive and sustainable maintenance practices in Industry.

By connecting theory with practice, this thesis helps shape the foundation for future implementations of intelligent asset management aligned with Industry 5.0 objectives.

6.2 Future Research Directions

This research proposed a conceptual framework to support the transition from traditional physical asset management to Intelligent asset management, aligned with the Industry 5.0 principles.

While the case study conducted on two autogenous mills provided valuable insights and partially validated the framework, it did not fully explore all its dimensions due to constraints in data availability, and operational complexity.

To further develop and refine this framework, several opportunities for future research are recommended:

- For future work, Weibull Distribution and Pareto Principle could apply statistical reliability methods to model failure distributions more accurately. This would enhance understanding of failure behaviours and enable more precise maintenance interval optimisation (see short analysis in Annex C);
- A more detailed FMECA with enhanced quantification of detection, occurrence, and severity, could improve prioritization of failure modes and strengthen decision-making;
- Including a cost-based perspective (cost of downtime, maintenance interventions, etc.) would allow for a clearer business case for IAM implementation (Life Cycle Cost, LCC, and Life Cycle Investment, LCI);

- Future studies could also incorporate sustainability indicators such as energy efficiency, emissions reduction, and material waste. This would align the framework more closely with Industry 5.0's emphasis on environmental responsibility;
- Analysing the company's current level of data maturity, digital infrastructure, and IAM readiness could support the phased implementation of the framework. Tools such as condition monitoring systems, and machine learning could be progressively introduced;
- Applying the proposed framework in different industrial settings, or across a larger asset base, would help generalize its utility and reveal scalability challenges or adaptability needs.

Although the case study in this work was not able to fully implement the proposed framework due to practical limitations, it successfully highlighted the need and potential for such a transition. Future research can build on this foundation to create more robust, data-driven, and sustainable IAM strategies that support long-term value creation and strategic alignment with Industry 5.0 principles.

REFERENCES

[1] G. Sandu, O. Varganova, and B. Samii, "Managing physical assets: a systematic review and a sustainable perspective," *International Journal of Production Research*, vol. 61, no. 19, pp. 6652–6674, Oct. 2022, doi: 10.1080/00207543.2022.2126019.

[2] E. Gavrikova, I. Volkova, and Y. Burda, "Strategic Aspects of Asset Management: An Overview of Current research," *Sustainability*, vol. 12, no. 15, p. 5955, Jul. 2020, doi: 10.3390/su12155955.

[3] M. Sharma, A. Tomar, and A. Hazra, "Edge Computing for Industry 5.0: fundamental, applications, and research challenges," *IEEE Internet of Things Journal*, vol. 11, no. 11, pp. 19070–19093, Mar. 2024, doi: 10.1109/jiot.2024.3359297.

[4] A. A. Murtaza, A. Saher, M. H. Zafar, S. K. R. Moosavi, M. F. Aftab, and F. Sanfilippo, "Paradigm Shift for Predictive Maintenance and Condition Monitoring from Industry 4.0 to Industry 5.0: A Systematic Review, Challenges and Case Study," *Results in Engineering*, p. 102935, Sep. 2024, doi: 10.1016/j.rineng.2024.102935.

[5] S. Zeb *et al.*, "Towards defining industry 5.0 vision with intelligent and softwarized wireless network architectures and services: A survey," *Journal of Network and Computer Applications*, vol. 223, p. 103796, Dec. 2023, doi: 10.1016/j.jnca.2023.103796.

[6] S. Abutabenjeh and R. Jaradat, "Clarification of research design, research methods, and research methodology," *Teaching Public Administration*, vol. 36, no. 3, pp. 237–258, May 2018, doi: 10.1177/0144739418775787.

[7] H. Taherdoost, "What are Different Research Approaches? Comprehensive Review of Qualitative, Quantitative, and Mixed Method Research, Their Applications, Types, and Limitations," *Journal of Management Science & Engineering Research*, vol. 5, no. 1, pp. 53–63, Apr. 2022, doi: 10.30564/jmser.v5i1.4538.

[8] M. Özden, "Content and thematic analysis techniques in qualitative research: purpose, process and features," *Deleted Journal*, vol. 2, no. 1, pp. 64–81, Aug. 2024, doi: 10.59455/qietp.20.

[9] V. T. T. Nha, "Understanding validity and reliability from qualitative and quantitative research traditions," VNU Journal of Foreign Studies, vol. 37, no. 3, Jun. 2021, doi: 10.25073/2525-2445/vnufs.4672.

[10] H. Noble and J. Smith, "Issues of validity and reliability in qualitative research," Evidence-Based Nursing, vol. 18, no. 2, pp. 34–35, Feb. 2015, doi: 10.1136/eb-2015-102054.

[11] A. Alquraidi and M. Awad, "Physical Asset Management for Critical Utilities— A Systematic Literature Review," *IEEE Access*, vol. 12, pp. 90644–90659, Jan. 2024, doi: 10.1109/access.2024.3421335.

[12] E. S. Lima, P. McMahon, and A. P. C. S. Costa, "Establishing the relationship between asset management and business performance," *International Journal of Production Economics*, vol. 232, p. 107937, Sep. 2020, doi: 10.1016/j.ijpe.2020.107937.

[13] H. Adshirinpour, M. M. Movahhedi, H. Divsalar, and S. Sohrabi, "Physical Asset Management in Equipment-Oriented Industries using the Equipment Life Cycle Management Approach," *Tehnički Glasnik*, vol. 15, no. 3, pp. 323–329, Sep. 2021, doi: 10.31803/tg-20200929105902.

[14] D. Maletič, N. M. De Almeida, B. Gomišček, and M. Maletič, "Understanding motives for and barriers to implementing asset management system: an empirical study for engineered

physical assets," *Production Planning & Control*, vol. 34, no. 15, pp. 1497–1512, Feb. 2022, doi: 10.1080/09537287.2022.2026672.
[15] S. Petchrompo and A. K. Parlikad, "A review of asset management literature on multi-asset systems," *Reliability Engineering & System Safety*, vol. 181, pp. 181–201, Sep. 2018, doi: 10.1016/j.ress.2018.09.009.
[16] M. Payette and G. Abdul-Nour, "Asset Management, Reliability and Prognostics modeling techniques," *Sustainability*, vol. 15, no. 9, p. 7493, May 2023, doi: 10.3390/su15097493.
[17] A. Giesting, "What is the Asset Life Cycle? [Life Cycle Stage Diagram] - FMX," FMX, Jun. 06, 2024. https://www.gofmx.com/blog/asset-life-cycle-management/.
[18] A. C. Márquez, M. Macchi, and A. K. Parlikad, Value based and intelligent asset management: Mastering the Asset Management Transformation in Industrial Plants and Infrastructures. Springer, 2019.
[19] A. C. Marquez, J. F. G. Fernandez, P. M.-G. Fernández, and A. G. Lopez, "Maintenance Management through Intelligent Asset Management Platforms (IAMP). Emerging Factors, Key Impact Areas and Data Models," *Energies*, vol. 13, no. 15, p. 3762, Jul. 2020, doi: 10.3390/en13153762.
[20] M. Parent and B. Cusack, "Cybersecurity in 2016: People, technology, and processes," *Business Horizons*, vol. 59, no. 6, pp. 567–569, Sep. 2016, doi: 10.1016/j.bushor.2016.08.005.
[21] ISO 55000:2024. "Asset Management - Vocabulary, Overview and principles," ISO (the International Organization for Standardization), ISO 55000:2024, Jun. 2024. [Online]. Available: https://www.iso.org/standard/83053.html#lifecycle.
[22] I. Alsyouf, M. Alsuwaidi, S. Hamdan, and M. Shamsuzzaman, "Impact of ISO 55000 on organisational performance: evidence from certified UAE firms," *Total Quality Management & Business Excellence*, vol. 32, no. 1–2, pp. 134–152, Oct. 2018, doi: 10.1080/14783363.2018.1537750.
[23] ISO 55001:2024. "Asset Management — Asset management System — Requirements," ISO (the International Organization for Standardization), ISO 55001:2024, Jul. 2024. [Online]. Available: https://www.iso.org/standard/83054.html.
[24] ISO 55002:2018. "Asset Management — Management systems — Guidelines for the application of ISO 55001," ISO (the International Organization for Standardization), ISO 55002:2018, Nov. 2018. [Online]. Available: https://www.iso.org/standard/70402.html.
[25] ISO 55012:2024. "Asset Management - guidance on people involvement and competence," ISO (the International Organization for Standardization), ISO 55012:2024, Jul. 2024. [Online]. Available: https://www.iso.org/standard/82454.html.
[26] ISO 55013:2024. "Asset Management - Guidance on the management of data assets," ISO (the International Organization for Standardization), ISO 55013:2024, Jul. 2024. [Online]. Available: https://www.iso.org/standard/82455.html.
[27] O. O. Aremu, A. S. Palau, A. K. Parlikad, D. Hyland-Wood, and P. R. McAree, "Structuring data for intelligent predictive maintenance in asset management," *IFAC-PapersOnLine*, vol. 51, no. 11, pp. 514–519, Jan. 2018, doi: 10.1016/j.ifacol.2018.08.370.
[28] EN 13306:2017. "Maintenance - Maintenance Terminology," CEN - European Committee for Standardization, EN 13306:2017, 2017.
[29] O. Candell, R. Karim, and P. Söderholm, "eMaintenance—Information logistics for maintenance support," *Robotics and Computer-Integrated Manufacturing*, vol. 25, no. 6, pp. 937–944, May 2009, doi: 10.1016/j.rcim.2009.04.005.

[30] R. F. Da Silva, A. H. De Andrade Melani, M. A. De Carvalho Michalski, G. F. M. De Souza, and S. I. Nabeta, “Risk management of physical assets supported by maintenance performance indicators,” *Sustainability*, vol. 16, no. 14, p. 6132, Jul. 2024, doi: 10.3390/su16146132.
[31] EN 15341:2009. “Maintenance - Key performance indicators,” CEN - European Committee for Standardization, EN 15341:2009, 2009.
[32] F. Z. Berrabah, C. Belkacemic, and L. Zemmouchi-Ghomari, “Essential and new maintenance KPIs explained,” International Journal of Education and Management Engineering, vol. 12, no. 6, pp. 11–20, Dec. 2022, doi: 10.5815/ijeme.2022.06.02.
[33] G. Gupta, H. Ghasemian, and A. A. Janvekar, “A novel failure mode effect and criticality analysis (FMECA) using fuzzy rule-based method: A case study of industrial centrifugal pump,” *Engineering Failure Analysis*, vol. 123, p. 105305, Feb. 2021, doi: 10.1016/j.engfailanal.2021.105305.
[34] A. Sharma and G. Gupta, “Comparative analysis of conventional and fuzzy FMECA approach for criticality analysis of a vertical roller mill,” *International Journal of Systems Assurance Engineering and Management*, vol. 14, no. 4, pp. 1395–1420, May 2023, doi: 10.1007/s13198-023-01944-x.
[35] O. I. De Normalisation and C. É. Internationale, “Failure Modes and Effects Analysis (FMEA and FMECA),” IEC 60812:2018, Jan. 2018.
[36] B. Mncwango and Z. L. Mdunge, “Unraveling the root causes of low overall equipment effectiveness in the kit packing department: A Define–Measure–Analyze–Improve–Control approach,” *Processes*, vol. 13, no. 3, p. 757, Mar. 2025, doi: 10.3390/pr13030757.
[37] W. Biały and J. Ružbarský, “Breakdown cause and effect Analysis. case study,” *Management Systems in Production Engineering*, vol. 26, no. 2, pp. 83–87, May 2018, doi: 10.1515/mspe-2018-0013.
[38] J. E. De Almeida Pais, H. D. N. Raposo, J. T. Farinha, A. J. M. Cardoso, and P. A. Marques, “Optimizing the Life Cycle of Physical Assets through an Integrated Life Cycle Assessment Method,” Energies, vol. 14, no. 19, p. 6128, Sep. 2021, doi: 10.3390/en14196128.
[39] K.-J. Wang, S. S. A. Basuki, and N. Kurniati, “A life-cycle asset management model by response surface method based optimization,” *International Journal of Production Economics*, vol. 263, p. 108957, Jun. 2023, doi: 10.1016/j.ijpe.2023.108957.
[40] D. Maletič, M. Maletič, B. Al-Najjar, and B. Gomišček, “Development of a model linking physical asset management to sustainability Performance: an Empirical research,” *Sustainability*, vol. 10, no. 12, p. 4759, Dec. 2018, doi: 10.3390/su10124759.
[41] F. Tao, Y. Wang, Y. Zuo, H. Yang, and M. Zhang, “Internet of Things in product life-cycle energy management,” *Journal of Industrial Information Integration*, vol. 1, pp. 26–39, Mar. 2016, doi: 10.1016/j.jii.2016.03.001.
[42] M. A. Camilleri, “The rationale for ISO 14001 certification: A systematic review and a cost–benefit analysis,” *Corporate Social Responsibility and Environmental Management*, vol. 29, no. 4, pp. 1067–1083, Feb. 2022, doi: 10.1002/csr.2254.
[43] ISO 14001:2015. “Environmental Management Systems - Requirements with guidance for use,” ISO (the International Organization for Standardization), ISO 14001:2015, 2015. [Online]. Available: https://www.iso.org/standard/60857.html
[44] A. Ahmed and S. Mathrani, “Critical success factors for a combined lean and ISO 14001 implementation in the manufacturing industry: a systematic literature review,” *The TQM Journal*, vol. 36, no. 7, pp. 2071–2106, Jul. 2023, doi: 10.1108/tqm-12-2022-0347.

[45] Y.-J. Park and S. Hur, “Improvement of Productivity through the Reduction of Unexpected Equipment Faults in Die Attach Equipment,” *Processes*, vol. 8, no. 4, p. 394, Mar. 2020, doi: 10.3390/pr8040394.
[46] S. Weerasekara, Z. Lu, B. Ozek, J. Isaacs, and S. Kamarthi, “Trends in Adopting Industry 4.0 for Asset Life Cycle Management for Sustainability: A Keyword Co-Occurrence Network Review and Analysis,” *Sustainability*, vol. 14, no. 19, p. 12233, Sep. 2022, doi: 10.3390/su141912233.
[47] D. Cagáňová, M. Balog, L. Knapčíková, J. Soviar, and S. Mezarcıöz, *Smart Technology trends in industrial and business management*. Springer, 2019.
[48] M. Soori, B. Arezoo, and R. Dastres, “Internet of things for smart factories in industry 4.0, a review,” *Internet of Things and Cyber-Physical Systems*, vol. 3, pp. 192–204, Jan. 2023, doi: 10.1016/j.iotcps.2023.04.006.
[49] B. D. Sarkar, V. Shardeo, A. Dwivedi, and D. Pamucar, “Digital transition from industry 4.0 to industry 5.0 in smart manufacturing: A framework for sustainable future,” *Technology in Society*, vol. 78, p. 102649, Jun. 2024, doi: 10.1016/j.techsoc.2024.102649.
[50] M. Piccarozzi, L. Silvestri, C. Silvestri, and A. Ruggieri, “Roadmap to Industry 5.0: Enabling technologies, challenges, and opportunities towards a holistic definition in management studies,” *Technological Forecasting and Social Change*, vol. 205, p. 123467, Jun. 2024, doi: 10.1016/j.techfore.2024.123467.
[51] R. Rame, P. Purwanto, and S. Sudarno, “Industry 5.0 and sustainability: An overview of emerging trends and challenges for a green future,” *Innovation and Green Development*, vol. 3, no. 4, p. 100173, Aug. 2024, doi: 10.1016/j.igd.2024.100173.
[52] F. A. De Lima, S. Seuring, and P. C. Sauer, “A systematic literature review exploring uncertainty management and sustainability outcomes in circular supply chains,” *International Journal of Production Research*, vol. 60, no. 19, pp. 6013–6046, Sep. 2021, doi: 10.1080/00207543.2021.1976859.
[53] D. Romero and J. Stahre, “Towards the Resilient Operator 5.0: The Future of work in smart Resilient Manufacturing systems,” *Procedia CIRP*, vol. 104, pp. 1089–1094, Jan. 2021, doi: 10.1016/j.procir.2021.11.183.
[54] L. Li and L. Duan, “Human centric innovation at the heart of industry 5.0 – exploring research challenges and opportunities,” *International Journal of Production Research*, pp. 1–33, Mar. 2025, doi: 10.1080/00207543.2025.2462657.
[55] J. Pizoń and A. Gola, “Human–Machine Relationship—Perspective and Future Roadmap for Industry 5.0 Solutions,” *Machines*, vol. 11, no. 2, p. 203, Feb. 2023, doi: 10.3390/machines11020203.
[56] C. Franciosi, A. Voisin, S. Miranda, S. Riemma, and B. Iung, “Measuring maintenance impacts on sustainability of manufacturing industries: from a systematic literature review to a framework proposal,” *Journal of Cleaner Production*, vol. 260, p. 121065, Mar. 2020, doi: 10.1016/j.jclepro.2020.121065.
[57] J. Bokrantz, A. Skoogh, C. Berlin, and J. Stahre, “Smart maintenance: instrument development, content validation and an empirical pilot,” *International Journal of Operations & Production Management*, vol. 40, no. 4, pp. 481–506, May 2020, doi: 10.1108/ijopm-11-2019-0746.
[58] J. Bokrantz, A. Skoogh, C. Berlin, T. Wuest, and J. Stahre, “Smart Maintenance: a research agenda for industrial maintenance management,” *International Journal of Production Economics*, vol. 224, p. 107547, Nov. 2019, doi: 10.1016/j.ijpe.2019.107547.

[59] J. Bokrantz, A. Skoogh, C. Berlin, T. Wuest, and J. Stahre, “Smart Maintenance: an empirically grounded conceptualization,” *International Journal of Production Economics*, vol. 223, p. 107534, Oct. 2019, doi: 10.1016/j.ijpe.2019.107534.

[60] S. Kolasani, “Unleashing Exponential Intelligence: Transforming businesses through advanced technologies,” *International Journal of Sustainable Development Through AI, ML and IoT*, vol. 3, no. 1, 2024, [Online]. Available: https://ijsdai.com/index.php/IJSDAI/index.

[61] O. Bongomin *et al.*, “Digital Twin technology advancing Industry 4.0 and Industry 5.0 across Sectors,” *Results in Engineering*, p. 105583, Jun. 2025, doi: 10.1016/j.rineng.2025.105583.

[62] J. Leng *et al.*, “Unlocking the power of industrial artificial intelligence towards Industry 5.0: Insights, pathways, and challenges,” *Journal of Manufacturing Systems*, vol. 73, pp. 349–363, Feb. 2024, doi: 10.1016/j.jmsy.2024.02.010.

[63] A. Polenghi, F. Acerbi, I. Roda, M. Macchi, and M. Taisch, “Enterprise information systems interoperability for asset lifecycle management to enhance circular manufacturing,” *IFAC-PapersOnLine*, vol. 54, no. 1, pp. 361–366, Jan. 2021, doi: 10.1016/j.ifacol.2021.08.162.

[64] C. Peña *et al.*, “Using life cycle assessment to achieve a circular economy,” *The International Journal of Life Cycle Assessment*, vol. 26, no. 2, pp. 215–220, Jan. 2021, doi: 10.1007/s11367-020-01856-z.

[65] A. F. D. V. Rodrigues, H. Delboni Jr, M. S. Powell, and L. M. Tavares, “Comparing strategies for grinding itabirite iron ores in autogenous and semi-autogenous pilot-scale mills,” *Minerals Engineering*, vol. 163, p. 106780, Jan. 2021, doi: 10.1016/j.mineng.2021.106780.

[66] L. Ji, Y. Kuang, Y. Yue, Z. Wang, and L. Tao, “Preliminary optimisation study on integrating mining with gravity separation,” *Canadian Metallurgical Quarterly*, vol. 58, no. 2, pp. 123–131, Nov. 2018, doi: 10.1080/00084433.2018.1527819.

[67] C. Loudari *et al.*, “Predicting energy consumption of grinding mills in mining industry : A review,” *AIP Conference Proceedings*, vol. 2814, p. 040003, Jan. 2023, doi: 10.1063/5.0148768.

[68] O. Durán, P. Afonso, and V. Minatogawa, “Analysis of Long-Term Impact of Maintenance Policy on Maintenance Capacity using a Time-Driven Activity-Based Life-Cycle Costing,” Mathematics, vol. 8, no. 12, p. 2208, Dec. 2020, doi: 10.3390/math8122208.

[69] F. Corman, S. Kraijema, M. Godjevac, and G. Lodewijks, “Optimizing preventive maintenance policy: A data-driven application for a light rail braking system,” Proceedings of the Institution of Mechanical Engineers Part O Journal of Risk and Reliability, vol. 231, no. 5, pp. 534–545, Jun. 2017, doi: 10.1177/1748006x17712662.

ATTACHMENTS

Annex A: Additional results of the case study

Lost Production for each failure per month.

Table A.1 – Production lost per month for both mills.

Month	Lost Production (tons)									
	Start-up problems		Leakage		Lubrication failure		Hydrostatic bearing		Automation failure	
	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
Jan	75.91	1041.09	0	0	683.22	1182.08	2787.10	867.58	15399.54	19954.34
Feb	151.83	32.53	7070.78	10497.72	6430.94	10985.73	20084.47	0	5140.41	0
Mar	260.27	140.98	0	1236.30	0	0	0	0	0	0
Apr	227.74	1539.95	0	8296.23	9185.50	0	55503.43	32.53	0	0
May	0	0	553.08	0	0	43.38	0	0	0	13393.26
Jun	271.12	0	1962.89	0	0	5932.07	7168.38	0	0	0
Jul	21.69	195.20	0	0	0	20724.31	0	0	0	1268.84
Aug	390.41	2299.09	39746	0	21244.86	2884.70	0	0	2819.63	0
Sep	130.14	43.38	0	1073.63	0	0	5932.08	0	0	32.53
Oct	292.81	336.19	0	0	0	249.43	4283.67	0	3014.84	0
Nov	21.69	65.07	0	3708.90	1474.88	1247.15	0	0	0	0
Dec	54.22	227.74	0	1539.95	97.60	0	0	0	802.51	0

Lost production per month and year for mill P1.

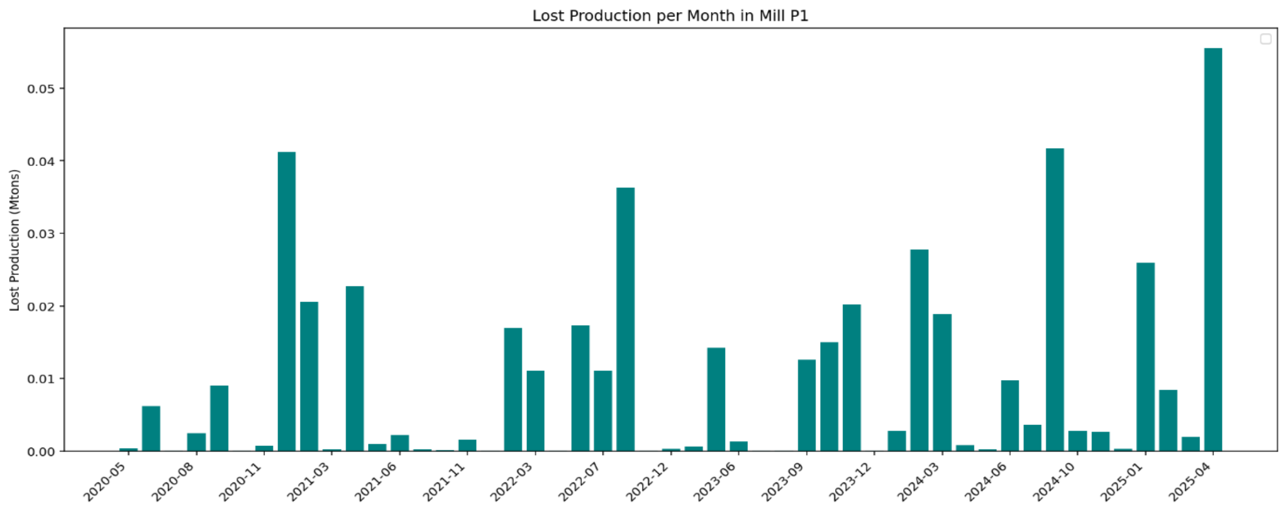

Figure A.1 – Production Lost per month and year for mill P1.

Lost production per month and year for mill P2.

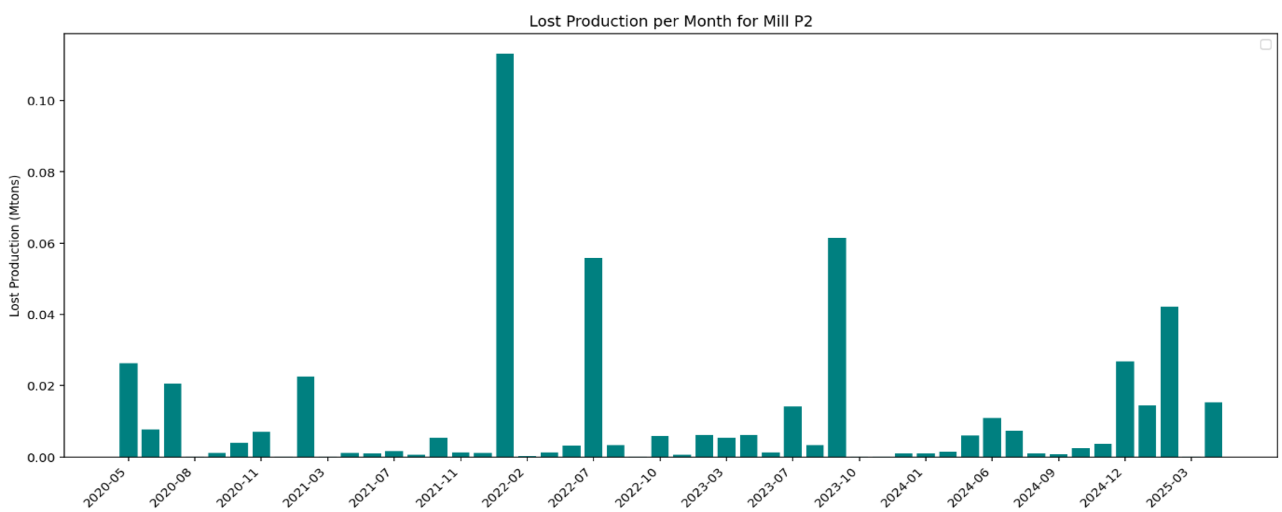

Figure A.2 – Production Lost per month and year for mill P2.

Severity was calculated by dividing the downtime of each component by the total downtime for the corresponding failure type (e.g., the downtime due to Leakage in the "Feed chute" divided by the total downtime for all Leakage failures). The resulting ratio (e.g., 0.77) was converted to a percentage and then mapped to a severity score on the scale from 1 to 10.

Table A.2 – Correspondence between severity scale and relative percentage

Severity (S)		
Value	**Level**	**Percentage**
1	None	0-0.5%
2	Very minor	0.5-1%
3	Minor	1-2%
4	Very Low	2-4%
5	Low	4-7%
6	Moderate	7-10%
7	High	10-15%
8	Very high	15-20%
9	Hazardous with warning	20-30%
10	Hazardous without warning	>30%

Occurrence was calculated by dividing the number of stoppages for each component by the total number of stoppages for the corresponding failure type (e.g., the number of Leakage failure in the "Feed chute" divided by the total number of Leakage failures). The resulting ratio was converted to a percentage and then mapped to an occurrence scale from 1 to 10.

Table A.3 – Correspondence between occurrence scale and relative percentage

Occurrence (O)		
Value	**Frequency**	**Percentage**
1	Unlikely (Preventive control)	0-0.01%
2	Very remote	0.01-0.09%
3	Remote	0.1-0.9%
4	Very low	1-2%
5	Low	3-5%
6	Moderate	6-10%
7	Moderately high	11-20%
8	High	21-30%
9	Very high	31-50%
10	Extremely certain	>50%

Annex B: Dashboard

Dashboard from Power Bi, with visualization of failures frequency, downtime by failure, downtime by month and year, total uptime and world cloud graph from comments in the company's data for both mills.

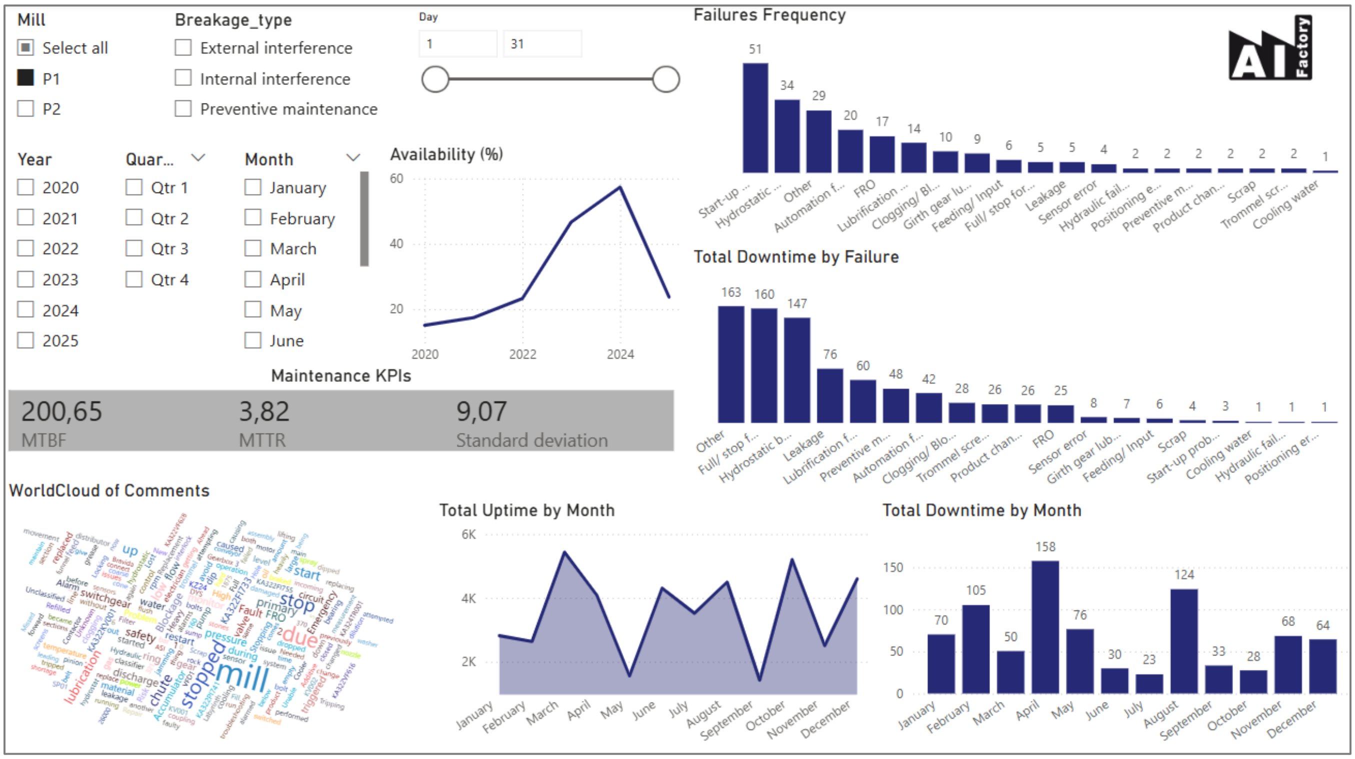

Figure B.3 - Power Bi dashboard.

Annex C: Weibull and Pareto Analysis

Analysis for mill P1 from the case study, Weibull distribution (see Figure C.4), Reliability function related with Weibull (see Figure C.5) and Pareto Principles (see Figure C.6).

Weibull Probability Plot

The Weibull model is a probabilistic model used to describe the time until failure of a component or system. It's widely used in reliability engineering, survival analysis, and risk assessment.

The Weibull distribution is defined by two parameters:

1. Shape parameter (β):

- Determines the failure rate behaviour over time.
- If $\beta < 1 \rightarrow$ Decreasing failure rate (infant mortality)
- If $\beta = 1 \rightarrow$ Constant failure rate (random failures)
- If $\beta > 1 \rightarrow$ Increasing failure rate (wear-out failures)

2. Scale parameter (η):

- It scales the distribution on the time axis.
- It's the time by which 63.2% of components have failed.

Weibull probability density function:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}},\ t \geq 0 \qquad \text{(C.1)}$$

The Equation (C.1 is the Reliability Function and the Hazard Function together.

The Hazard Function *h(t)* also known as the failure rate, it tells the instantaneous rate of failure at time t. the formula shows how failure risk changes over time, helps in identifying early-life failures, random failures or wear-out behaviour.

$$h(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \qquad \text{(C.2)}$$

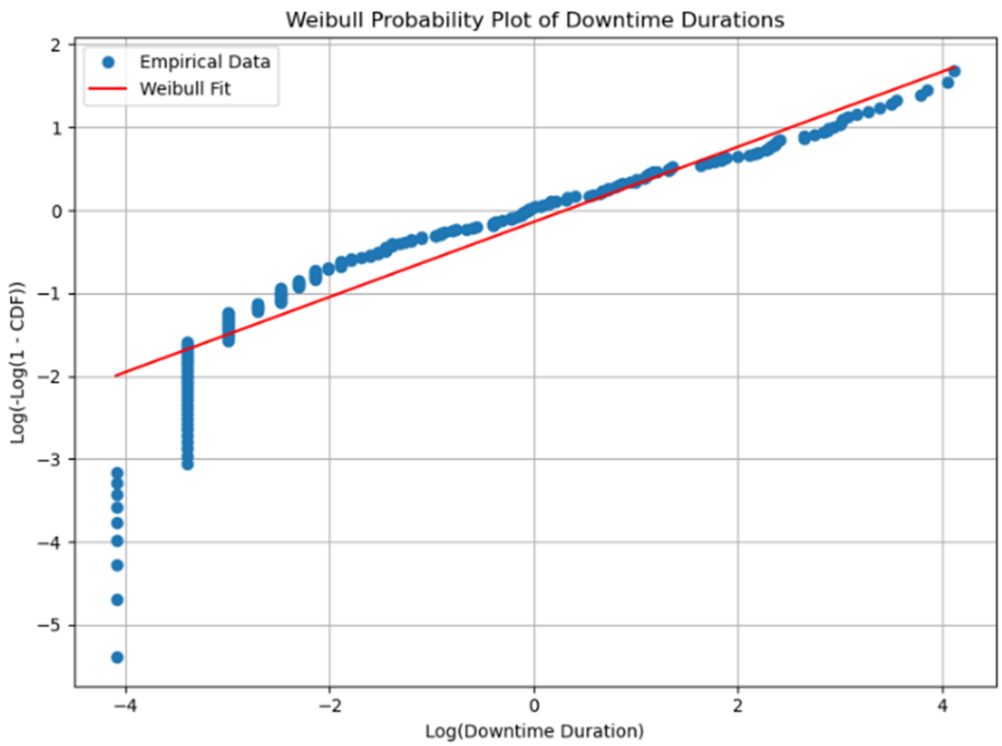

Figure C.4 - Weibull Distribution of downtime.

Legend:

- The blue dots represent the empirical data.
- The red line is the fitted Weibull distribution.

Reliability Function R(*t*)

The reliability function in the Weibull distribution describes the probability that a system or component is still functioning up to a certain time *t*, see (C.3. At *t*=0, the reliability is 100%, as *t* increases the R(t) decreases.

$$R(t) = e^{-\left({t}/{\eta}\right)^{\beta}} \quad \text{(C.3)}$$

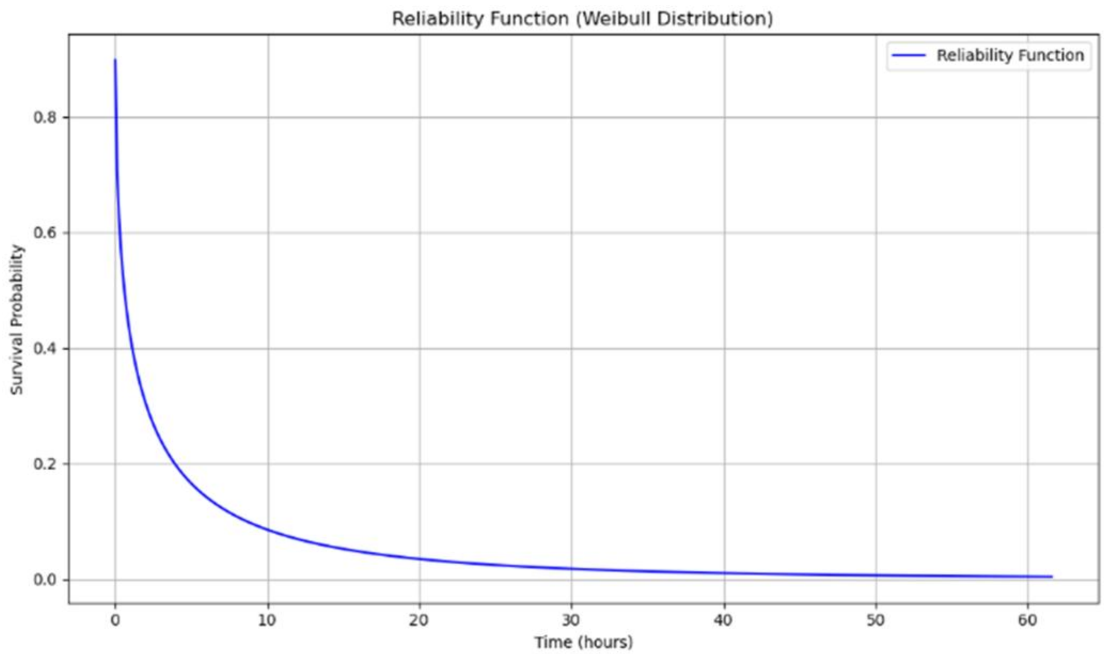

Figure C.5 - Reliability Function from Weibull distribution.

Legend:

- The y-axis represents the probability that the system survives (i.e., does not fail) up to a given time.
- The x-axis is time in hours.
- The curve shows a rapid decline, consistent with the shape parameter < 1, indicating a high likelihood of early failures.

Pareto Analysis: Downtime by Stop Cause

The Pareto Principle, also known as the 80/20 rule, states that roughly 80% of the effects come from 20% of the causes. This principle is applied in business, economics, and productivity.

From the case study, the top few causes (likely "Start-up problems", "Hydrostatic bearing", and "Other") contribute to over 80% of the total downtime. Focusing on these can yield the greatest improvements in reliability and uptime.

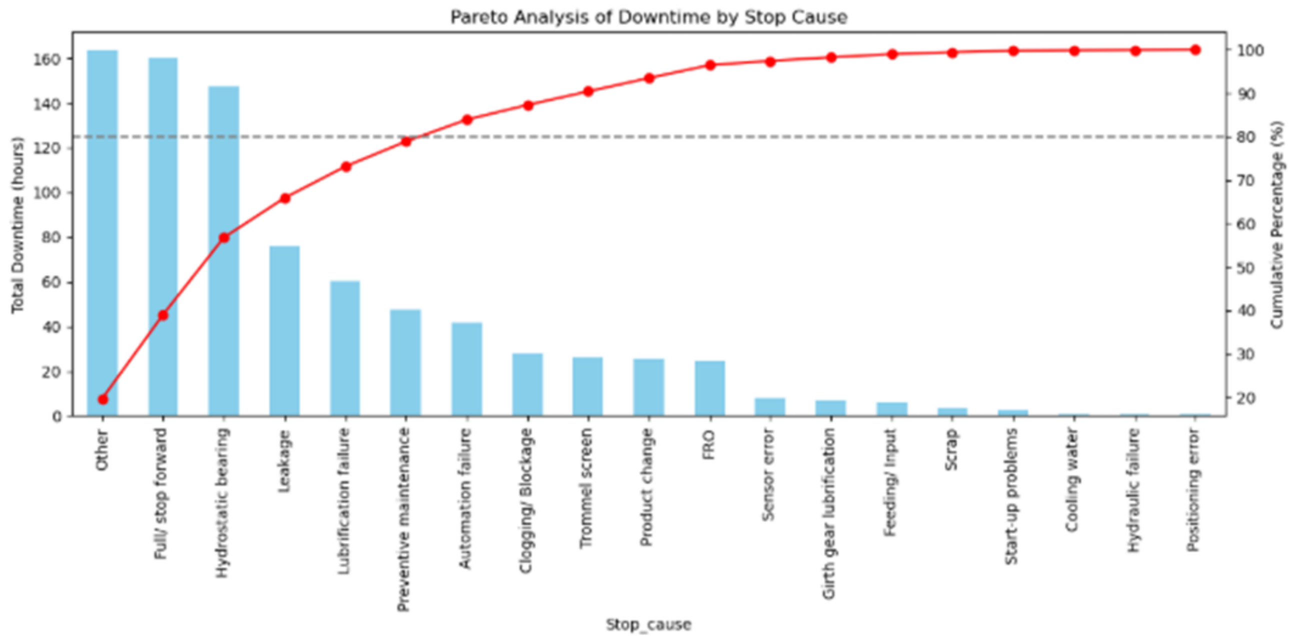

Figure C.6 - Pareto Analysis from downtime by failure.

Legend:

- Blue bars: Total downtime (in hours) for each stop cause.
- Red line: Cumulative percentage of total downtime.
- The dashed line at 80% helps identify the "vital few" causes contributing most to the downtime.

Annex D: Appended Paper

Intelligent Asset Management: Bridging Operational Efficiency and Environmental Sustainability[13]

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ABSTRACT

The transition to Industry 5.0 has amplified the importance of advanced strategies for managing physical assets while addressing operational efficiency, sustainability, and human-centricity. This study conducts a systematic literature review to assess how technological innovations, such as Artificial Intelligence (AI), are transforming physical assets to improve their performance. While these technologies contribute to predictive maintenance and resource optimisation, significant gaps are observed in aligning Intelligent Asset Management (IAM) frameworks with operational strategies and environmental objectives. This paper aims to identify these existing limitations and underexplored areas, in the current literature, such as the need for frameworks that balance technological advancements with sustainability and human-centric principles. By identifying these gaps, the article seeks to provide a foundation for future research directions that can bridge innovation and practical application, fostering resilience, efficiency, and sustainability in the era of Industry 5.0.

Keywords

Intelligent Asset Management; Physical Assets; Operational Efficiency; Environmental Sustainability; Industry 5.0

1. Introduction

The management of physical assets has evolved from a basic operational necessity into a critical strategic function for modern organizations. Beyond their tangible value, physical assets such as facilities, machinery and equipment play a pivotal role in fostering sustainability and driving operational excellence. These assets are essential for achieving efficiency, maintaining profitability and meeting the growing demands of environmental management in an increasingly competitive global landscape. The increasing importance of technological integration and the need for sustainable operations in asset management reflect the broader shifts in industry towards more efficient, human-centric, and environmentally responsible practices [1], [2].

Traditionally, Physical Asset Management (PAM) was limited to maintenance, logistics or engineering. However, the increasing complexity of technical systems and the uncertainties faced by organizations have demonstrated the need for a more structured, integrative and strategic approach. In recent years, PAM has expanded significantly, driven by technological advancements, environmental concerns and economic pressures. Intelligent Asset Management (IAM) integrates technological innovation, strategic planning, and environmental responsibility to maximize asset value and contribute to a resilient and sustainable future [3].

The advent of Industry 5.0 introduces a new dimension to asset management by emphasizing collaboration between humans and advanced technologies, such as AI, Internet of Things (IoT) sensors and robotics. Unlike Industry 4.0, which focused on automation and digitalisation, Industry 5.0 highlights the need for human-centricity, sustainability, and resilience. Industry 5.0 underscores the necessity of integrating human expertise with these advanced technologies to enable more adaptive and flexible decision-making processes [4]. For example, the integration of IoT sensors and AI-driven analytics can provide real-time insights into asset health, allowing organisations to perform predictive maintenance and minimize downtime [5]. Furthermore, Industry 5.0, advocates a balance between technological advancements and ecological responsibility, challenging organisations to adopt IAM structures that not only improve operational efficiency but also align with broader sustainability goals. By incorporating human collaboration into intelligent systems, it creates opportunities for industries to develop innovative solutions tailored to specific operational, environmental, and social challenges [6].

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