Chair of Economic- and Business Management

Master's Thesis

Development of an Asset Management framework for criticality evaluation and retrofit/replacement decisions

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January 2023

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Scope of the Master's thesis

Ms. Mahshid Ahmadpoursamani is given the topic

Development of an Asset Management framework for criticality evaluation and retrofit/replacement decisions

to work on in a Master's thesis.

In the first section of the Master's thesis, the theoretical foundations for dealing with the described topic are to be worked out. For this purpose, the basis for the introduction of an asset management framework, in particular the necessary interfaces to other management systems, is to be discussed. An essential part of the thesis is the development of possible key performance indicators which can be used for the evaluation of criticality, retrofitting or asset replacement. In order to work on this topic, knowledge of asset management and approaches for developing an asset management framework are to be gained from relevant literature.

The focus of the practical part is the application of the developed asset management system at a production site of an asset-intensive company. The asset management system must be applicable to the existing requirements of the company and allow decisions to be made on retrofitting, replacement or the criticality of the assets on the basis of the data collected so far. In the course of this thesis, the knowledge gained must be validated by applying in the form of a pilot project.

Leoben, June 2022

Univ.-Prof. Dr. Wolfgang Posch

AFFIDAVIT

I declare on oath that I wrote this thesis independently, did not use other than the specified sources and aids, and did not otherwise use any unauthorized aids.

I declare that I have read, understood, and complied with the guidelines of the senate of the Montanuniversität Leoben for "Good Scientific Practice".

Furthermore, I declare that the electronic and printed version of the submitted thesis are identical, both, formally and with regard to content.

Date 29.01.2023

Signature Author
Mahshid Ahmadpoursamani

Principle of equality

For reasons of readability, gender-specific formulations have not been used in this paper. It is explicitly stated that the masculine forms used for persons are to be understood for both genders.

Acknowledgement

The biggest thanks go to the BRP-Rotax central maintenance team, specifically Manuel Adam, Petar Vucur, Domink Mizelli, Michael Brandstätter and Martin Egger, who supported me throughout the entire work with their expertise and constant willingness to help. Thank you for the encouragement and positive energy that motivated me to do my best.

I would like to express my special thanks to my supervisor Dipl.-Ing. Stefan Philip Kernbauer for his professional and personal support for the success of this master’s thesis and his tremendous help and guidance to steer the work in the right direction.

Further thanks go to Univ.-Prof. Dipl.-Ing. Dr. mont. Wolfgang Posch for his trust and the approval of the master's thesis topic at the Chair of Economic- and Business Management.

My special gratitude goes to my family, especially my parents, who always and unconditionally supported me in all my endeavours.

Lastly, I would like to wish all women around the world, especially the brave women of Iran and Afghanistan, the opportunity that I could have, namely the right to live a free life as they want.

Abstract

The effective management of physical assets is of paramount importance for asset-intensive organizations as the assets contribute significantly to the organization’s profitability and financial performance. Historically, asset monitoring has been approached through the lens of maintenance management, but it is important to recognize that maintenance is just one stage of an asset's lifecycle stages. This highlights the need for a more comprehensive approach, more precisely an Asset Management System (AMS), that seeks to maximize the value by monitoring assets throughout their entire lifecycle, from concept to disposal. The AMS comprises of the other management systems principles and provides a framework, assisting the decision-makers to assess the criticality of assets and make informed decisions regarding assets’ timely improvement or replacement.

The aim of this master's thesis is therefore to develop an AMS decision-making framework that includes the relevant Key Performance Indicators (KPI) with respect to the AMS interfaces to the other management systems. This framework serves to assist managers in evaluating the criticality of assets, determining the appropriate course of action to maintain, enhance or replace the assets, and aligning these decisions with the overall strategic goals of the organization. Hence, the theoretical part of this study delves into the core concepts of the AMS, its interfaces with other management systems, KPIs and KPIs assessment techniques, as well as the assets criticality assessment approaches.

The theoretical part forms the basis for the application of the proposed AMS framework in a practical case study conducted at the company BRP-Rotax. Since the AMS framework must be adopted based on the company’s requirements and its available data, the current situation of the company as well as its current AMS are first assessed using expert interviews and workshops. The results serve as the basis for the KPIs determination and the framework implementation.

The result of this work validates the practical applicability of the developed AMS framework, and simultaneously presents recommendations for enhancing the developed AMS in order to bridge the gap between the current state at the company and the desired target state.

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Abbreviation list

AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
AMS	Asset Management System
BSC	Balanced Scorecard
BU	Business Unit
CAPEX	Capital Expenditure
CCF	Company Carbon Footprint
CCK	Crankshaft and Camshaft department
CCS	Work Specific Components department
CCT	Turbo Systems and Connecting Rods department
CCZ	Cylinder Head and Casing department
CM	Central Maintenance
CAGR	Compounded Annual Growth Rate
C_p	Process capability
C_{pk}	Process performance
CPS	Cyber-Physical Systems
et al.	et alteri or et alii = and others
e.g.	exempli gratia
EAC	Equivalent Annual Cost
Ed.	Editor
EnPIs	Energy performance indicators
etc.	et cetera
FMEA	Failure Modes and Effects Analysis
HSE	Health, Safety and Environment
i.e.	id est
incl.	including
IoT	Internet of Things
IRR	Internal Rate of Return
IT	Information Technology
JIPM	Japan Institute of Plant Maintenance
KFS	Key Figure Systems
KPI	Key Performance Indicator
LCA	Life Cycle Analysis
LCC	Life Cycle Costing

LSA	Logistic Support Analysis
LSL	Lower Specification Limitation
MDCM	Multiple Criteria Decision Making
MOC	Manufacturing Operation Cockpit
MTBF	Mean Time Between Failure
MTTR	Mean Time to Repair
NPV	Net Present Value
OEE	Overall Equipment Efficiency
OPEX	Operating Expenses
O&M	Operations and maintenance
p.	following page
pp.	following pages
PAM	Physical Asset Management
PC	Personal computer
PLC	Programmable Logic Controller
QMS	Quality Management System
RAV	Replacement Asset Value
ROI	Return on Investment
RCM	Reliability Centered Maintenance
RFID	Radio Frequency Identification
SAP	Systems Applications and Products in Data Processing, software
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TPM	Total Productive Maintenance
USL	Upper Specification Limitation
vs.	versus

1 Introduction

As an introduction to the thesis, the first chapter describes the initial situation and the problem. Moreover, the objective and research questions of the study, as well as the methodological approach will be discussed. Lastly, this chapter concludes by describing the work's structure.

1.1 Initial Situation and Problem

With company's rapidly changing environment, globalization of the market, resources scarcity and the need to obtain significant competitive advantages in the international context in the last years, enormous pressure has been imposed on particularly capital-intensive industries. Therefore, it has become crucial for organizations to constantly evaluate and improve their performance by considering the best applicable practices to manage their assets more effectively.[1]

In the traditional view, maintenance was typically considered as a cost center. The transformation from reactive maintenance to proactive maintenance has made it a competitive factor that contributes significantly to an organization's profitability and sustainability.[2] Nevertheless, maintenance is only one phase of the asset's lifecycle, as it is not the only concern companies should focus on. Creating value requires a comprehensive approach and to this end, the implementation of an Asset Management System (AMS) to manage assets throughout their entire lifecycle – from asset planning and acquisition to its decommissioning/disposal. „Asset management supports the realization of value while balancing financial, environmental and social costs, risk, quality of service and performance related to assets."[3]

Different departments of an organization may seek different objectives regarding the value assets provide to them; for instance, finance might seek improved Return on Investment (ROI) through asset performance, while maintenance views assets as reliable machines.[4] Successful asset management ensures realizing all these goals and more, along with enhancing the organization's sustainable development. Yet, asset management requires the active involvement of all departments and individuals and their cooperation with each other to support the organization.[5] The publication of the ISO 55000 series of asset management has led companies to implement asset management to enable all parts of an organization to speak the same language and align their management structure with asset management aiming at competitiveness and excellence.[6]

[1] Refer to Ibifuro, I.; David, B. (2017), p. 2
[2] Refer to Henderson, K. et al. (2014), p. 448
[3] ISO 55000: 2014-01, pp. 1
[4] Refer to IBM Global Business Services (2007), p. 6
[5] Refer to Institute of Asset Management (2015), p. 7
[6] Refer to Favarão da Silva, R.; Martha de Souza, G. F. (2020), p. 290

1.2 Objective and research questions

The present work aims to implement and develop an asset management evaluation system at BRP-Rotax with about 2000 production assets. The existing physical asset management system at BRP-Rotax does not provide reliable information on the criticality of the assets. For this reason, a fundamentally new physical asset management system is being sought.

Achieving this goal requires a developed AMS framework regarding its interfaces with other management systems, that is consistent with the organization's desired goals. The developed AMS must enable the organization to assess the criticality of its assets and thus to make decisions based on the assets condition. For this purpose, we need to define Key Performance Indicators (KPIs) to determine the assets' criticality. The defined KPIs serve the evaluation system and lead to KPI-based action plans for critical assets respectively the entire plant. Hence, this study aims to answer the following research questions:

1. What are the prerequisites for the AMS successful implementation?
   a. What are the AMS interfaces?
2. What are the asset management KPIs regarding its interfaces?
3. How to develop an asset management evaluation system for performance assessment and improvement?
   a. How to evaluate assets' criticality using assessment techniques?
   b. How to determine appropriate actions for critical assets and realize them?

1.3 Methodical approach

To answer the research questions and to develop an AMS applicable for the practical part, the study begins with the asset management fundamentals and the associated definitions. Then, the integration of AMS with other management systems such as financial management and risk management is discussed. To answer question 2, this thesis covers the basics regarding KPIs, particularly production and maintenance KPIs. Based on defined KPIs and scientific benchmarking, an asset evaluation system consisting of two phases is proposed.

The work ends with the practical part, which is to be built on theoretical foundations. First, the actual situation of the company as well as the internal requirements are determined. Based on that, the necessary KPIs must be determined in workshops, which will be used in the evaluation system. The results serve as the basis for the establishment of an AMS for the company. The development of the AMS ends with its implementation in the company by applying the system on three selected machines.

1.4 Work structure

This master thesis is divided into the scientific principles incl. introduction, fundamentals of Physical Asset Management (PAM) and its interfaces, fundamentals of KPIs, asset management evaluation system, practical case study, and summary and outlook.

The first chapter serves as an introduction to the topic under discussion. In addition to the initial situation, research questions as well as the methodological approach are presented in this chapter. The chapter ends with a description of the resulting structure of the work.

Chapters 2 and 3 describe the theoretical foundations that are considered relevant for answering the first research question. At the beginning of the theory part, these chapters provide fundamentals to the topics PAM and AMS, narrowing down to focus more specifically on the physical asset lifecycle phases and AMS interfaces with other management systems. Maintenance management has the greatest impact on the asset lifecycle. Therefore, the basics of maintenance management will be explained in more detail. Chapter 3 concludes with the prerequisites for the successful implementation of the AMS.

Chapter 4 deals with the tasks of KPIs, KPI systems and KPI assessment approaches. This chapter starts with the definition of KPIs. Then the KPIs of maintenance management are presented in relation to other AMS interfaces. Another focus of the fourth chapter is on KPI systems like the “Maintenance Balanced Scorecard”. Furthermore, the KPI assessment techniques, particularly Multiple Criteria Decision Making (MCDM) methods, are discussed in this chapter. This chapter ends by introducing one of the most popular MCDM method, the Analytic Hierarchy Process (AHP) method.

Chapter 5 elaborates on the asset management evaluation system. To define an asset management decision-making framework, which is the ultimate goal of this study, risk-based asset evaluation systems are introduced in this chapter based on scientific benchmarking. To define factors, which assist the decision-making process and lead to measures, i.e. repair, retrofit, maintenance strategy optimization, or replacement of the observed asset based on its criticality, Section 5.3.1 presents all the common factors from the literature review worth considering in the defined framework. The proposed framework is then developed by combining the appropriate information gathered from the above factors and the other chapters’ study areas like the defined KPIs in Chapter 4 into a single, structured framework that leads to KPI-driven action plans.

Chapter 6 contains the practical part of this thesis by company introduction and task definition at the beginning. The current and target situation of asset management at BRP-Rotax are assessed and determined. In the next step, the required KPIs for the decision-making framework development are selected based on their availability and accuracy in the company. The framework is developed, and the action plans are defined. Finally, the proposed framework is validated through application on three selected machines. The work concludes with a summary and outlines the areas that need to be improved in the company as well as the next steps in implementing the AMS framework.

2 Fundamentals of Physical Asset Management

As discussed in the first chapter and regarding all factors affecting an organizations' performance and competitiveness, the necessity for effective and efficient Physical Asset Management (PAM) implementation to obtain a lifecycle-oriented approach has steadily increased. To this end, this chapter discusses the fundamentals of PAM, incl. asset definition, asset lifecycle phases, and the required AMS. Consequently, the interfaces of the AMS with other supporting and involved management systems will be reviewed in the subsequent chapter. The ISO 55000 series standard and the Institute of Asset Management (IAM) guidelines form the basis for the framework and definitions in this chapter. It should be noted that the term asset in the context of this study refers to physical assets such as equipment, machinery, and vehicles.

2.1 Physical Asset Management (PAM)

„An asset is an item, thing, or entity that has potential or actual value to an organization. The value will vary between different organizations and their stakeholders and can be tangible or intangible, financial or non-financial."[7]

To manage assets and monitor their performance, minimize all asset-related costs and risks, and utilize them for a more extended period, PAM has the task of managing and evaluating all asset-related activities at all stages of the asset lifecycle. In addition, PAM provides necessary support systems and resources, such as qualified personnel or technical support, to achieve business objectives. There are a variety of definitions and terms in the literature to define PAM. However, they all refer to the same concept: PAM is a set of activities to create and obtain maximum value by physical assets through a lifecycle management approach. Asset management is not a new topic. Although with the Industry 4.0 revolution and the maturity of organizations along with the recognition of asset management as a broader view than just an extension of asset maintenance or equipment management, the traditional view of PAM as a necessary evil has shifted to a systematic view of the entire lifecycle, as shown in Figure 1.[8]

The publication of the ISO 5500X: 2014 standards (ISO 55000, ISO 55001, ISO 55002), aiming to provide a standardized framework for the successful implementation of the AMS within the organization, was the motive force encouraging more companies to implement AMS in their organizations and allocate resources and effort to that. Referring to clause 2.4.2 of ISO 55000, asset management is built on four fundamentals, as illustrated in Figure 2: Value, Alignment, Leadership, and Assurance.[9]

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[7] ISO 55000: 2014-01, p. 2
[8] Refer to IBM Global Business Services (2007), p. 7
[9] Refer to Institute of Asset Management (2015), p. 11

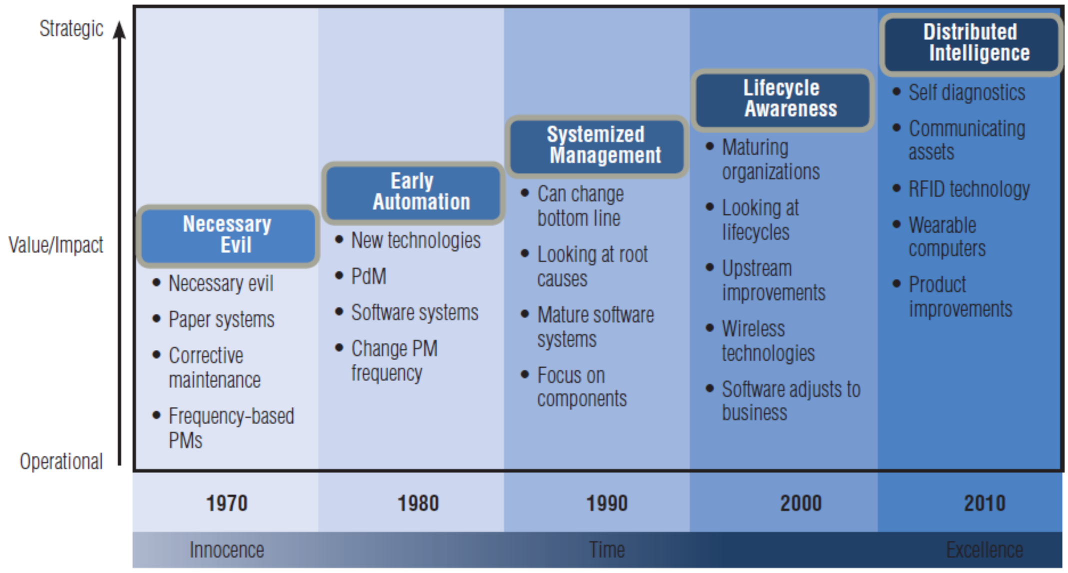

Figure 1 - Evolution of Asset Management and Corporate Thinking[10]

Asset Management seeks to plan and manage physical assets' acquisition, deployment, maintenance, and retirement to maximize economic return (value target) while considering human-, environmental-, and sustainability requirements at all the above stages.[11] Therefore, Section 2.2 deals with the asset lifecycle phases in more detail.

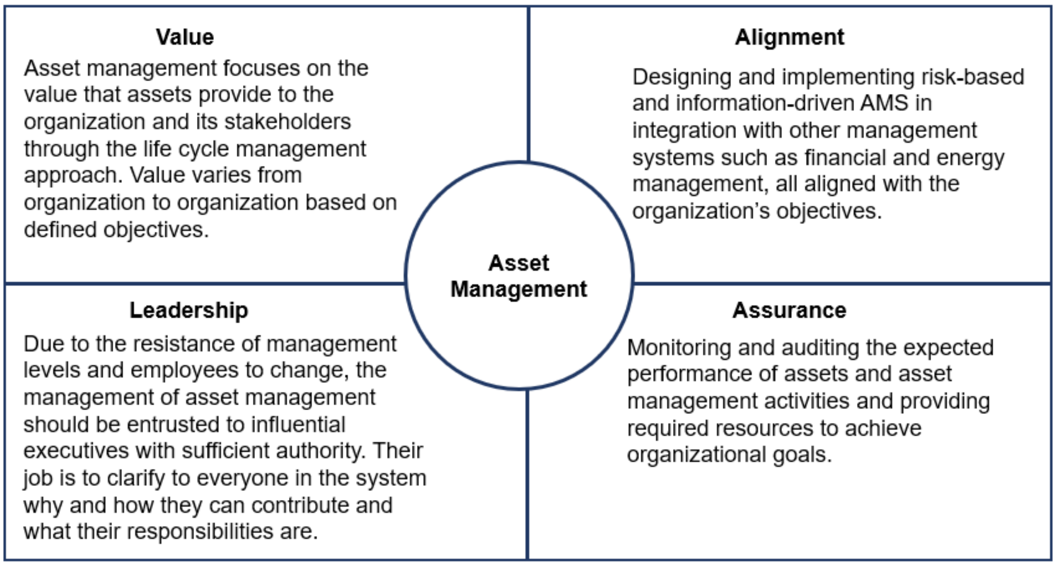

Figure 2: Asset Management fundamentals[12]

2.2 Asset lifecycle phases

Achieving world-class performance and minimizing all costs associated with assets requires implementing a lifecycle-oriented asset management approach. The lifecycle of

[10] Source: IBM Global Business Services (2007), p. 7
[11] Refer to Biedermann, H. (2008a), p. 5
[12] Source: Own representation refer to ISO 55000: 2014-01, pp. 11

a physical asset consists of the identification, design or acquisition, utilization and maintenance, modernization, and disposal of the asset, as illustrated in Figure 3.

PRÜß and NEBL (2006) divide the mentioned lifecycle stages into three phases as follows: investment phase, asset utilization and maintenance phase, and disinvestment phase.[13]

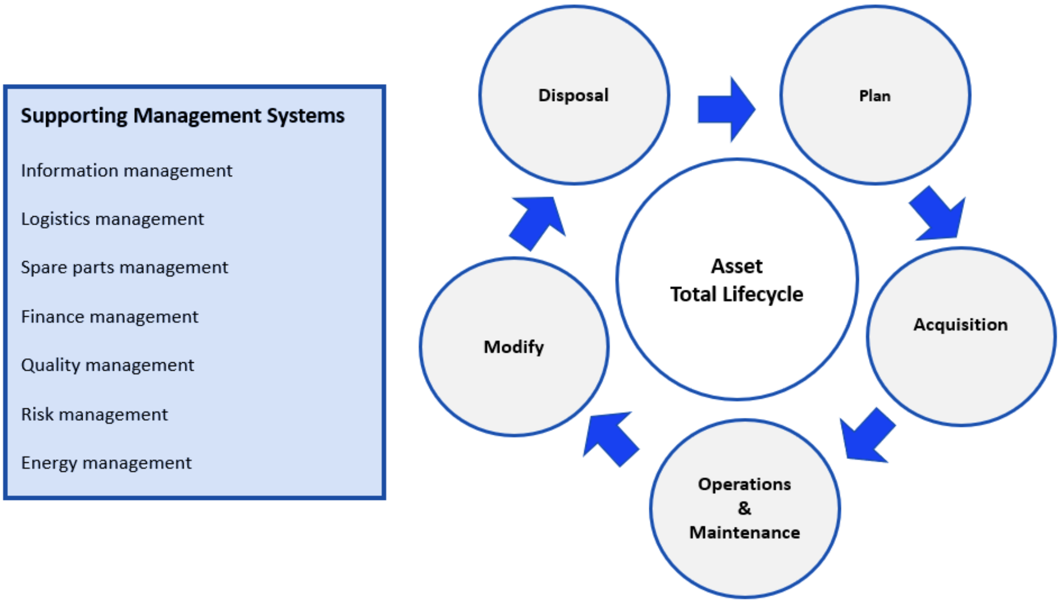

Figure 3: Asset lifecycle phases[14]

Investment:

The investment phase is mainly aimed at replacing obsolete asset or providing additional production capacity. At this stage, the organization, based on its requirements and the available budget, determines the desired asset and the deployment time at which the asset should be prepared, following that market analysis deciding whether to purchase or design the asset. Asset acquisition, layout arrangement, installation, and running of the acceptance tests to guarantee the asset's functionality are the other steps included in the investment phase.[15] Requirements for asset reliability and the level of mechanization and automation should be examined studiously within the planning stage. In this regard, "Reliability-Centered Procurement" highlights long-term reliability, sustainability, readily available logistical support, and asset commonality as the key factors that should be considered at this stage.[16]

This phase significantly impacts other stages of the asset lifetime and total costs arising over the asset lifecycle. As Figure 4 shows, the longer but reasonable development time and budget investment in terms of asset reliability and maintainability would lead to lower operating expenses (OPEX) and disposal costs as well as a longer asset lifetime.

Nevertheless, it should be considered that the budget is limited, and the balance between planning effort and planning time must be maintained so that neither under- nor over-planning happens, but to plan optimally. The goal is to find a compromise between

[13] Refer to Nebl, T.; Prüß, H. (2006), p.32
[14] Source: Own representation refer to El-Akruti, K.; Dwight, R. (2013), p. 404
[15] Refer to Biedermann, H. (2021), lecture.
[16] Refer to Hastings, N. A. J. (2010), p. 181

investment and future operations and maintenance costs (O&M) to acquire the asset that meets the technical requirements and causes minimum costs over its entire lifecycle.[17] Financial management significantly impacts the decisions made in this phase, trying to find the optimal time to replace the asset, which will be discussed later in Chapter 5.

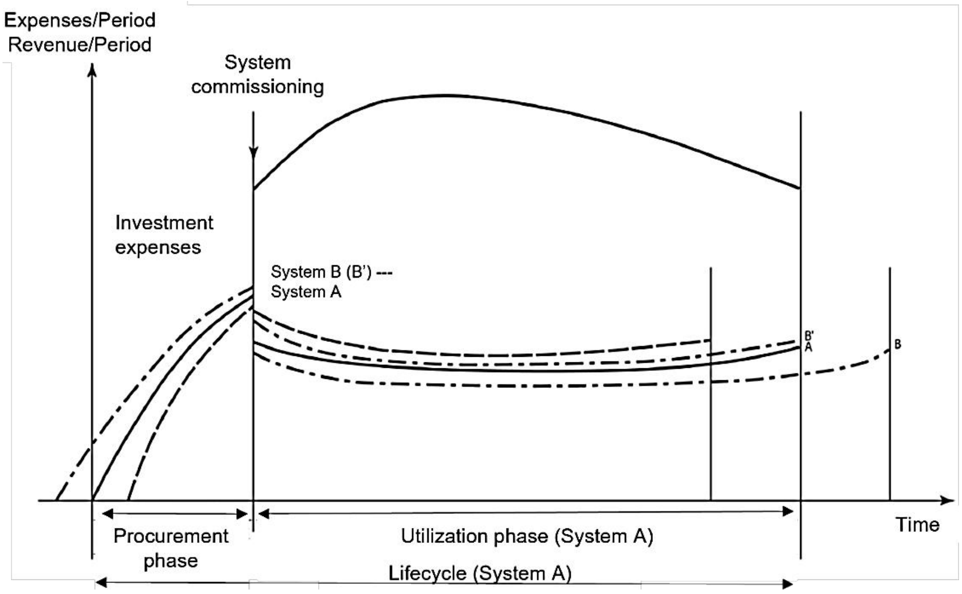

Figure 4: Asset lifecycle costs[18]

Operations and maintenance (O&M):

The asset O&M phase is the phase in which asset performance creates the most value; O&M causes about 65-80% of the asset total lifecycle costs.[19] This stage includes capacity planning, asset performance evaluation, asset maintenance (inspection, maintenance, repair), and asset refurbishment and modernization when required.[20] Maintenance plays a prominent role among all other lifecycle stages since effective maintenance increases product quality, asset availability, asset economic life, and most importantly, the organization's profitability by reducing costs, risks, and downtimes.[21]

Disinvestment:

All physical assets wear and tear over time, resulting in asset disposal. The following factors could influence the asset's operational life termination, thus leading to decommissioning and disposal:[22]

- Technical factors such as reduced reliability and increased risk of failure
- Commercial reasons such as asset obsolescence due to technological advances
- Regulatory reasons such as climate law requirements
- Threats and risks the asset can pose to the environment, health, and safety

Assets and their components might be resold, recycled, or scrapped at this stage.

[17] Refer to Biedermann, H. (2008b), p. 15
[18] Source: Biedermann, H. (2008a), p. 17 (slightly modified)
[19] Refer to The Global Forum on Maintenance and Asset Management (GFMAM) (2021), p. 8
[20] Refer to Nebl, T.; Prüß, H. (2006), p. 32
[21] Refer to Maletič, D. et al. (2020), p. 33
[22] Refer to Hastings, N. A. J. (2010), pp. 211

The maintenance framework document published by the Global Forum on Maintenance and Asset Management provides a broad overview of asset lifecycle phases and all relevant standards in this area.[23] Lifecycle Costing (LCC) as a “cradle to grave” cost analysis approach estimates the costs arising over the asset lifecycle phases, which will be discussed in Chapter 6. An AMS should be developed and used by the organization to manage, coordinate, and control asset management activities, incl. asset-related risks and costs throughout the asset lifecycle. In this regard, Section 2.3 introduces the Asset Management System.

2.3 Asset Management System (AMS)

„The organization shall establish, implement, maintain and continually improve an asset management system, incl. the processes needed and their interactions, in accordance with the requirements of this International Standard.”[24]

AMS consists of strategies, plans, and programs to ensure the establishment of asset management strategies and the processes required to achieve its objectives by coordinating the contributions and interactions between organizational units.[25] Though, it should be noted that by implementing the ISO 55000 series of standards, the organization will acquire the minimum standard for an effective AMS, but not the detailed guide on which activities are to be done or on AMS implementation way. Managing aspects such as changing organizational culture, leadership, and motivating employees require arrangements outside the AMS that the organization must implement.[26]

AMS is aligned with the organizational and other management systems strategies, as these management systems should not be viewed individually but in harmony with the objectives of the other systems. Consequently, a new AMS does not need to be defined from the ground up, but rather built up and developed based on other management systems principles. AMS translates the objectives of other management systems, such as the energy management system, into associated KPIs to evaluate and improve asset management performance based on the target KPIs, and to ensure maximum value realization.

In light of the discussion above, Chapter 3 shall elaborate on the interfaces of the AMS with other management systems.

[23] The Global Forum on Maintenance and Asset Management (GFMAM) (2021)
[24] ISO 55001: 2014-01, p. 2
[25] Refer to ISO 55000: 2014-01, pp. 4
[26] Refer to Institute of Asset Management (2015), p. 26

3 Asset management system interfaces

Following the guidelines of international standards is a fundamental step toward successfully implementing the AMS, which means numerous requirements must be met. AMS does not seek to replace other existing disciplines but to provide an integrated framework by incorporating other standards, such as those for quality management (ISO 9001:2015) and risk management (ISO 31000:2018), so that all management systems can work together more effectively.[27] An integrated AMS built on the principles of other management systems reduces the effort and cost of creating a new management system from scratch. In addition, the integrated approach enhances coordination and alignment between departments and the integration of their disciplines.[28] For this reason, the third chapter of this master's thesis covers the AMS interfaces with other management systems. In conclusion, the prerequisites for successfully implementing AMS will be discussed in Section 3.9.

3.1 Energy and Environmental Management

„Energy management is the proactive, organized, and systematic coordination of procurement, conversion, distribution, and use of energy to meet the requirements, taking into account environmental and economic objectives."[29]

One of the main concerns of the AMS is the sustainable development of an organization, defined as „development that meets the needs of the present without compromising the ability of future generations to meet their own needs."[30] Energy is considered a critical factor linked to sustainable development.[31] Given the scarcity of fossil fuels, maintaining the capital stock (man-made capital and natural capital incl. renewable and non-renewable resources) particularly nonrenewable resources, is the primary concern in this respect.[32] Moreover, the increase in energy prices and the role of company carbon footprint (CCF)[33] in exacerbating the greenhouse effect, and thereby more stringent regulations concerning global warming, have pushed companies to take energy management and the importance of energy with greater seriousness. Competitive companies are the ones that take steps towards being eco-friendly and deal with energy management, considering the energy flow from energy purchase, energy conversion, distribution, and energy consumption to energy release or recycling.[34] Hence, energy management should be incorporated into the following organizational areas:

[27] Refer to Sangreman Lima, E. et al. (2018), p. 3094
[28] Refer to ISO 55000: 2014-01, p. 9
[29] Guideline 4602 of the German Association of Engineers, quoted by Kals, J. (2015), p. 5
[30] Refer to Kals, J. (2015), p. 15
[31] Refer to Posch, W. (2011), p. 107
[32] Refer to Reichert, R.H. (2004) quoted by Posch, W. (2011), p. 108
[33] Refer to Kals, J. (2015), p. 19
[34] Refer to Posch, W. (2011), pp. 1369

Organizational structure: Managers should formulate a long-term strategy that considers climate change regulations, investments to minimize the CCFs, technology selection, short and long-term profitability, and economic asset replacement decisions. Moreover, they need to define energy performance indicators (EnPIs), namely energy applied per asset, carbon emissions and energy efficiency. In this regard, Lifecycle Analysis (LCA) defined by ISO 14040 evaluates the environmental impacts of the asset throughout its lifecycle.[35] Equation 1 represents the energy efficiency calculation:

$$Energy\ efficiency = \frac{Useful\ energy}{Energy\ input}$$

Equation 1: Energy efficiency[36]

Process organization: It encloses energy-related processes, workflow management, quality management, and environmental management integration to fulfil energy necessities.[37] In addition, the security of supplied energy and maintaining the energy quality should be considered in terms of sustainable development of the company's energy system. The unstable energy supply leads to supply-related shutdowns incl. asset shutdowns, loss of production and time to restore the asset, or even the destruction of electronic components of the asset due to voltage spikes and other possible losses.[38]

Project organization/change management: Here, the emphasis is on alignment and interaction between departments within an organization.[39] Several studies in the literature considered environmental and energy aspects regarding asset maintenance approach and replacement decisions. For instance, ABDI and TAGHIPOUR (2019) proposed a deterministic Repair/Replace model considering both environmental and economic factors in the lifecycle stages of the asset regarded to be replaced and the one planned to be acquired.[40] Besides all the costs involved in the replacement decision, primary energy use, GHG emissions, acidification potential, and other environmental factors are considered in calculating the total cost of repair and replacement, as well as emissions generated by each asset through its lifecycle phases.

3.2 Financial management

The financial and cost data is essential in making sound asset-related decisions, so the integration of the financial management system with AMS is indispensable. Asset management realizes value creation and performance improvements in financial management by improving ROI, supporting asset investment decisions, and reducing costs over the asset lifecycle.[41] Moreover, the constant information flow between these systems helps to obtain more accurate funding requirements estimations. For this

[35] Refer to Kals, J. (2015), pp. 37
[36] Kals, J. (2015), p. 28
[37] Refer to Kals, J. (2015), p. 85
[38] Refer to Posch, W. (2011), p.116
[39] Refer to Kals, J. (2015), p. 86
[40] Abdi, A.; Taghipour, S. (2019)
[41] Refer to ISO 55000: 2014-01, p. 2

reason, asset managers must be familiar with accounting language, financial principles, and analysis to assess data accuracy and make sound decisions.[42]

Accounting terminology classifies assets into fixed assets and current assets. Fixed assets refer to physical items with a long-term value, like spare parts kept in the warehouse for longer than one year, buildings, and machinery. Faster moving assets such as inventory (materials, work in process, finished goods, consumables) that are held/used in a shorter period are regarded as current assets. Regarding capital planning and budgeting, the term CAPEX (Capital Expenditure) refers to the budget allocated for planning and acquiring the asset, like asset development planning, and OPEX refers to the O&M budget, like outsourcing costs and spare parts procurement.[43] In this context, LCC, as a method that considers all costs arising over the asset lifecycle and assists the asset replacement decision-making process, is discussed in Chapter 5.

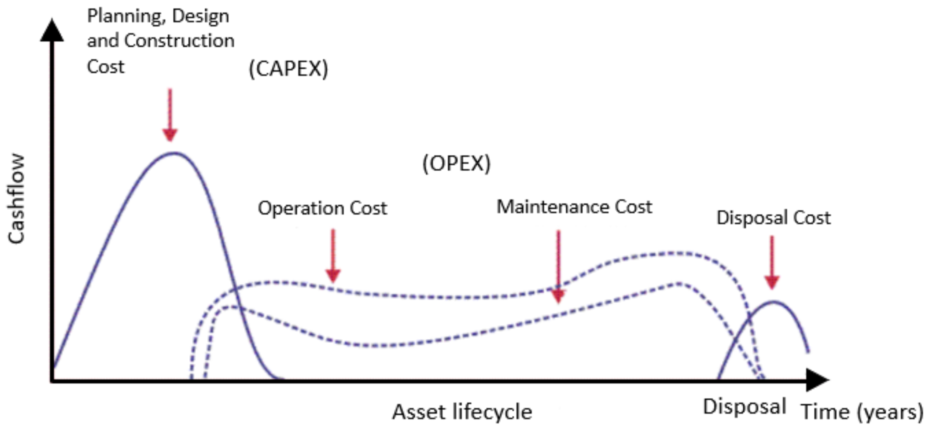

Figure 5: Asset lifecycle costs[44]

As Figure 5 shows, financial aspects are at the core of asset-related decisions, which highlights the importance of asset managers' involvement in the CAPEX and OPEX planning process and the AMS contribution to the organization's well-being and profitability.[45] Section 5.3.1 covers this topic in more detail. Consequently, integrating the financial and asset management systems, incl. their principles, provides both systems benefits and improvement in funding plans and asset operation.

3.3 Information management

An integrated information management system is required to make effective decisions and monitor assets and ongoing operations properly. Information management needs to collect accurate asset data, such as data regarding the asset's technical condition, its location, and failure history throughout the asset lifecycle. By classifying and analyzing this data, the system provides information that enables management systems such as maintenance management to predict asset failure behaviour, estimate the required O&M

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[42] Refer to Hastings, N. A. J. (2010), p. 104
[43] Refer to Hastings, N. A. J. (2010), pp. 3
[44] Source: The Global Forum on Maintenance and Asset Management (GFMAM) (2021), p. 9
[45] Refer to Hastings, N. A. J. (2010), p. 93

budget for the next fiscal year, plan spare parts requirements, manage reports, etc.[46] Most importantly, data itself is one of the most critical assets of an organization, as it is costly for the organization to collect and maintain data. Moreover, the efficient collection and management of data can bring tremendous value to the organization.

Data capturing technologies like Radio Frequency Identification (RFIDs), barcodes, and sensors are some of the known ones for capturing asset data. Consequently, considering a challenge for organizations to handle the significant mass of information generated over the asset lifecycle, providing an efficient model such as enterprise asset management software for managing data and asset information is crucial.[47]

3.4 Quality management

ISO 9000 defines quality as the „degree to which a set of inherent characteristics fulfils requirements"[48], where inherent characteristics refer to the existing features of a product, process, or system to realize values defined by the organization and related stakeholders. Therefore, the Quality Management System (QMS) includes the coordination and monitoring of quality-related activities with a focus on achieving customer satisfaction and the satisfaction of other interested parties through quality as well as environmental, health, safety, and financial objectives.[49]

Quality management stands for the lowest possible scrap rate at maximum asset utilization within the context of the production process and strives for improvements through mastering the processes. The ultimate goal is minimum defects and interruptions in the production process, higher asset availability, reduced required labor for troubleshooting and thus improved ROI.[50] In this regard, Total Productive Maintenance (TPM), as one of the best-known approaches, paves the way toward performance advancements of the QMS and will be discussed in Section 3.7.2.

3.5 Logistics management

People, services, and resources are the supporting factors of a physical asset throughout its entire lifetime, from planning and budgeting the asset acquisition to its disposal. The iceberg diagram shown in Figure 6 represents the risks of poor management that consider only the acquisition costs and overlooks the "downstream" costs and activities related to logistics and asset lifecycle. Logistics management flows into all phases of the asset lifecycle, incl. logistic support in the planning and acquisition phase, selection of creditworthy suppliers in terms of technical and logistic support, spare parts procurement, and, in a nutshell, through-life support.[51]

[46] Refer to Ouertani, M. et al. (2008), p. 26
[47] Refer to Ouertani, M. et al. (2008), p. 32
[48] BS EN ISO 9000: 2005-09, p. 7
[49] Refer to BS EN ISO 9000: 2005-09, p. 6
[50] Kurt, M. (2005), pp. 164
[51] Refer to Hastings, N. A. J. (2010), p. 180

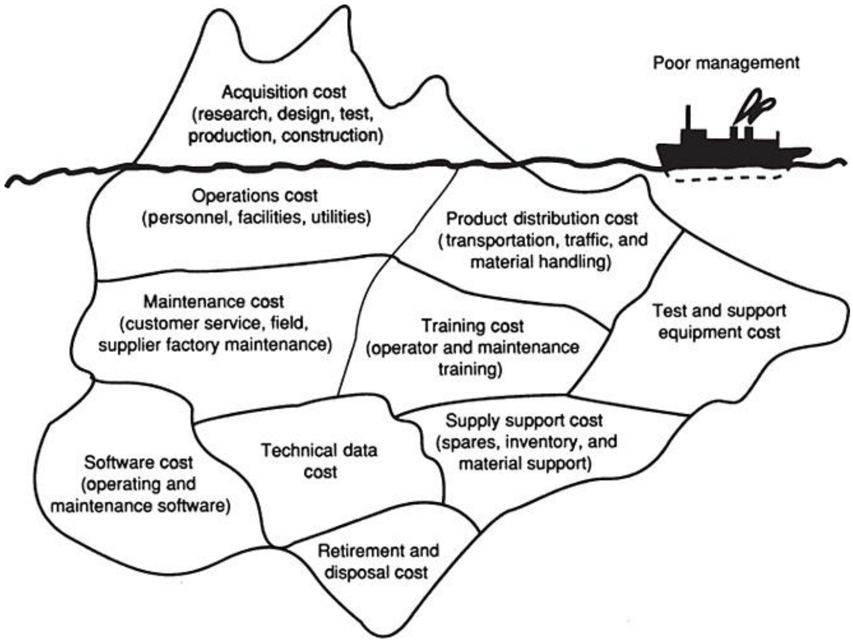

Figure 6: Iceberg diagram- Total cost visibility[52]

Reliability Centered Procurement assists in the equipment selection process at the procurement stage by considering the equipment's long-term reliability, sustainability, and available logistical support and weights the equipment based on that.[53] Moreover, the logistic support analysis (LSA) determines what support resources and services should be provided for the asset, how they should be provided, and at what location. Logistic support includes data analysis on the asset, the logistics of operational support, incl. the provision, transportation, and storage of consumables, as well as policy decisions on whether to repair or replace, considering the support contract signed between the company and supplier. In addition, it includes the level of repair analysis, which determines and provides the requirements for maintenance, repair, and overhaul activities, incl. the necessary facilities, and spare parts. Repair analysis determines whether the repair should be performed in the user's area or in-house but at a specific location or whether the asset should be outsourced and repaired by its manufacturer, supplier, or contractor. To this end, Integrated Logistic Support ensures the implementation of LSA.[54]

3.6 Spare parts management

Inventory management, particularly spare parts management, is essential to logistics and maintenance management. Spare parts management aims to ensure asset availability by providing required spare parts with high availability and accessibility while minimizing costs.[55] This involves planning, coordination, and monitoring spare parts-

52 Source: O'Reilly, https://www.oreilly.com/library/view/system-engineering-management/9781119047827/b02.xhtml, (retrieved: 20.07.2022)
53 Refer to Hastings, N. A. J. (2010), p. 181
54 Refer to Hastings, N. A. J. (2010), pp. 184
55 Refer to Hastings, N. A. J. (2010), p. 297

related procurement, stocking, and disposal activities. DIN 24420 defines spare parts as „parts, assemblies or complete products intended to replace damaged, worn or missing parts, assemblies or products."[56]

DIN 31051 groups spare parts into reserve parts, standard parts, and small parts. Reserve parts are the ones with high inventory value but a low quantity and are not used independently but assigned to one or more assets. Standard parts are mainly those with a medium demand that can be used in several maintenance objects and cannot be economically repaired or reused due to their design, such as relays and rolling bearings. Small parts are those with the highest inventory quantity, but low value and are generally usable, like screws.[57] Also, there is the type defined by the ISO 13306 as the insurance spare part, which is the „spare part which is not normally needed during the useful life of the item but whose unavailability would involve an unacceptable downtime due to its provisioning."[58]

As mentioned in Section 3.5, logistics management should support the provision of the right resources, in this context spare parts and in particular reserve parts. „A success-oriented provision of spare parts should therefore ensure that the asset parts required for the execution of maintenance measures are available in the required quality and quantity at the right time in the right place in the most economical way possible."[59]

ABC and XYZ analyses help to optimize spare parts inventory, reduce warehouse costs, and take up limited financial and human resources for spare parts that require intensified planning activities. Taking a brief look at one of these methods, Figure 7 shows the ABC analysis classifying spare parts into A (items with high demand value), B (items with medium demand value), and C (items with low demand value) parts based on their annual demand value, resulted from multiplying the annual demand by the item value.[60]

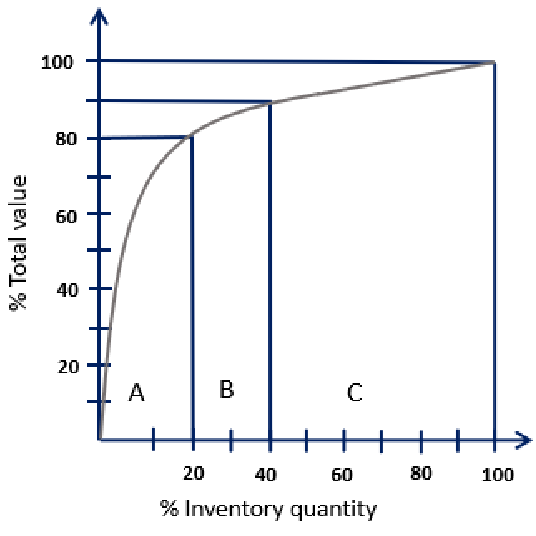

Figure 7: ABC distribution of total inventory[61]

[56] DIN 24420, Teil I/4-1 quoted by Biedermann, H. (2008b), p. 3
[57] Refer to Biedermann, H. (2008b), p. 3
[58] BS EN 13306: 2017-11, p. 14
[59] Biedermann, H. (2008b), p. 82
[60] Refer to Hastings, N. A. J. (2010), p. 312
[61] Source: Biedermann, H. (2008b), p. 83 (slightly modified)

As Figure 7 shows, A parts account for 20% of the inventory with about 70-80% of the total value, and B parts represent a further 10-15% of the total value with 30% of the inventory value. The remaining 10-15% of the total value points out the C parts, which usually account for 50% of the inventory.[62]

The supply of spare parts should be planned so that losses due to unnecessary warehousing and fixed capital costs, as well as the risk and costs of asset failure and operational downtime due to the unavailability of spare parts, are minimized.[63] The right strategy would be determined based on the spare part cost, asset criticality, the expected usage given the failure behaviour of the asset, storage costs, and delivery lead time. In-house spares inventory, original equipment manufacturer/vendor management inventory, shared spares inventory, and consignment inventory are some of the stocking strategies.[64]

3.7 Maintenance management

Maintenance is defined as the „combination of all technical, administrative and managerial actions during the lifecycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function."[65] Technical actions here refer to observations and analyses such as tests and inspections to assess the asset's condition and the required maintenance actions. Chapter 1 addressed the challenges organizations face that drive them to strengthen their competitiveness, incl. maintaining high productivity. As a result, there has been tremendous pressure on maintenance management to guarantee the maximum availability and reliability of the assets while minimizing costs, the occurrence of failures, and defective products to make the organization a "world-class one."[66] Maintenance, embedded in PAM, translates the organizational and PAM's objectives to maintenance strategies and actions by defining KPIs to measure, evaluate and improve maintenance performance.

In this context, KINZ (2021) determines maximizing the value-added contribution as the greatest goal of the so-called "agile, learning-oriented and value-added maintenance" gained by total cost optimization and the other abovementioned goals as factual, human and social as well as sustainability and environmental goals.[67] BS EN 13306 divides maintenance activities into 15 subcategories incl. repair, restoration, overhaul, compliance test, etc.; where DIN 31051 divides all these activities into four main tasks as follows:[68]

<u>Servicing/routine maintenance</u>: „Measures to delay the depletion of the existing wear and tear stock."

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[62] Refer to Biedermann, H. (2008b), p. 83
[63] Refer to Kurt, M. (2005), pp. 195
[64] Refer to The Global Forum on Maintenance and Asset Management (GFMAM) (2021), p. 26
[65] BS EN 13306: 2017-11, p. 8
[66] Refer to Favarão da Silva, R.; Martha de Souza, G. F. (2020), p. 288
[67] Refer to Biedermann, H.; Kinz, A. (2021), pp. 22
[68] Refer to DIN 31051: 2012-09, pp. 5

Inspection: Actions for the determination and assessment of the actual state of the asset incl. the causes of wear and deriving the necessary consequences for future use

Maintenance/restoration: Actions to restore the asset to working condition.

Improvement: Measures to increase the asset's reliability without changing its primary function.

Reliability, availability, and maintainability are KPIs, that capture the most important values and are defined as follows:

Reliability: The „ability of an item to perform a required function under given conditions for a given time interval"[69], which is closely linked to safety, economy and availability. In addition to asset reliability, people reliability, asset maintainability, and process reliability are the other core areas of operational reliability.[70] Mean time between failures (MTBF) is the most common measure of reliability and indicates the average time between two failure events, for the observed period as shown in Equation 2:

$$MTBF = \frac{Total\ operating\ time}{Number\ of\ failures}$$

Equation 2: MTBF calculation[71]

Reliability analysis examines failure causes and failure rate patterns. Burn-in, also known as early life failures, random failures, and wear-out failures, are the three most common failure patterns illustrated in a common graphical representation of failure rate known as the bathtub curve in Figure 8. Asset components can exhibit poor reliability during the burn-in and wear-out phases.[72]

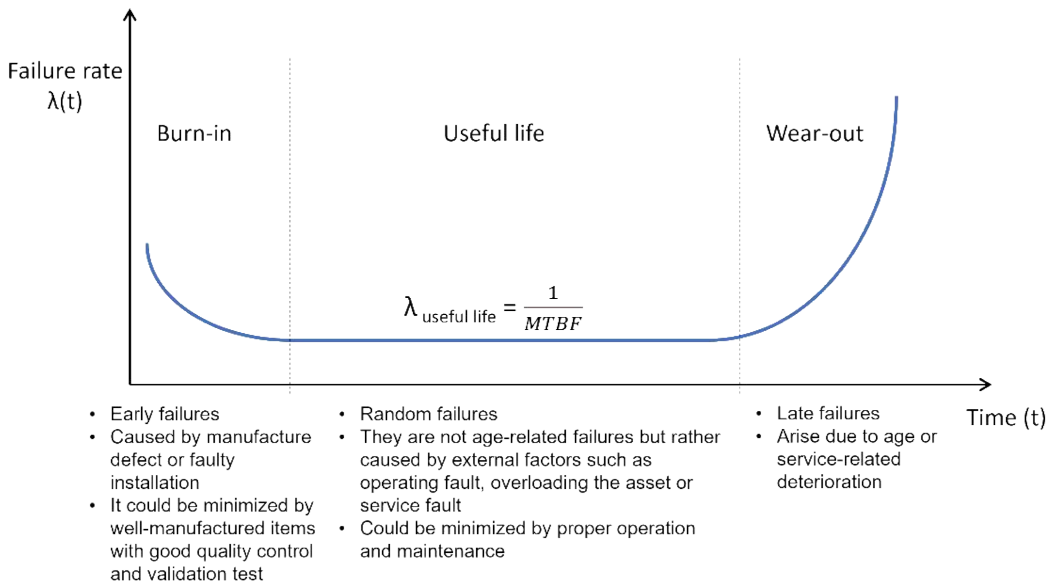

Figure 8: The bathtub curve - Failure rate versus time[73]

[69] BS EN 13306: 2017-11, p. 15
[70] Refer to Schuman, C. A.; Brent, A. C. (2005), p. 570
[71] Refer to BS EN 15341: 2019-08, p. 31
[72] Refer to Hastings, N. A. J. (2021), pp. 450
[73] Source: adapted from Biedermann, H. (2008b), p. 18 and Hastings, N. A. J. (2021), pp. 450

Maintainability: The „ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources."[74] Mean time to repair (MTTR) is one of the most common maintainability measures. MTTR represents the average repair time, which observes the time interval from when a failure occurs until the asset runs again. The interval includes also delays, testing before restarting the asset, etc. It should be noted that the downtime considered as the total repair time in Equation 3 refers to the time allocated for unplanned maintenance.

$$MTTR = \frac{Total\ time\ to\ repair}{Number\ of\ failures}$$

Equation 3: MTTR calculation[75]

Availability: The „ability of an item to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided"[76] Asset availability is calculated as shown in Equation 4:

$$Availability = \frac{MTBF}{MTBF + MTTR}$$

Equation 4: Availability calculation[77]

3.7.1 Role of maintenance management in asset lifecycle phases

Maintenance management contributes to all asset lifecycle phases, as the other stages contribute. In the acquisition phase, maintenance management determines the required reliability and availability of the asset and its components. In the O&M phase, it defines the maintenance strategies and the associated tasks. As the asset ages, maintenance management has the task of listing the obsolete components, checking for their availability, and comparing the future operating and maintenance costs of the old asset with those of the new asset plus the new asset's acquisition costs. Ultimately, maintenance management must estimate expected maintenance costs prior to disposal and, most importantly, provide accurate data to the asset management information system throughout all these phases.

The above points are only part of the maintenance management involvement within the AMS.[78] Maintenance management has evolved over time, from the first generation, i.e. corrective maintenance, also known as reactive maintenance, the "break-and-fix" approach, to the fourth and latest generation, i.e. proactive strategic maintenance, which considers risk and environmental factors and is consistent with asset management focusing on lifecycle value.[79]

[74] BS EN 13306: 2017-11, p. 17
[75] Refer to BS EN 15341: 2019-08, p. 36
[76] Refer to BS EN 13306: 2017-11, p. 17
[77] Hastings, N. A. J. (2021), p. 472
[78] Refer to BS EN 16646: 2014-12, pp. 23
[79] da Silva, R. F.; de Souza, G. F. M. (2021), p. 3

Maintenance Strategies

BIEDERMANN (2008) defines maintenance strategies as procedures that specify the required maintenance activities in terms of content, method, and scope to be performed in a specific time sequence based on optimization criteria for individual assets.[80] Maintenance strategies include four main categories as follows:

Reactive maintenance: Actions are performed first after asset failure to either repair and restore the asset to its normal operating condition or to replace the asset for which the decision has already been made based upon its condition.[81]

Preventive maintenance: Preventive maintenance is based on the identification of failure behaviour respectively failure time to prevent asset failure by replacing its components in a well-timed manner. Preventive maintenance and repairs are performed at regular intervals and can be carried out periodically, time-, operation- or performance-based.[82]

Predictive maintenance: With the transformation to industry 4.0 and the advent of the Internet of Things (IoT), digitalization, artificial intelligence (AI), Cyber-Physical Systems (CPS), and big data, predictive and prescriptive maintenance are the latest forms of maintenance as of today. Data and data accuracy are thus the critical factors enabling the implementation of these maintenance strategies. Predictive maintenance uses continuous, real-time monitoring of assets to analyze collected asset data, such as maintenance history and asset potential failure causes, to identify and predict failure patterns and prevent failures before they occur.[83] Visual inspection, vibration analysis, and thermal analysis are some of the techniques used to monitor the condition of the asset. Yet, random failures cannot be completed by either preventive or predictive maintenance.[84]

Prescriptive maintenance: Prescriptive maintenance takes the predictive maintenance a notch further as it not only predicts when equipment is likely to fail, but also provides different maintenance solutions considering the risk of each action. Prescriptive maintenance uses both historical and real-time data for analysis and recommends then the best action to take.[85]

Hence, effective maintenance contributes significantly to the performance improvement of asset management and other management systems, such as financial management. It enhances financial performance through effective maintenance budgeting, increased revenue, reduced downtime costs, and utilizing assets for a more extended period rather than premature replacement. On the other hand, the PAM supports maintenance by providing maintenance facilities, logistic support, training programs, qualified staff, and required information systems and facilitates communication between maintenance and other departments.[86] Consequently, besides determining the appropriate AMS for the organization, it is necessary to implement an effective and efficient maintenance management model selected from the best-defined models in the literature, such as

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[80] Refer to Biedermann, H. (2008a), p. 52
[81] Refer to The Global Forum on Maintenance and Asset Management (GFMAM) (2021), p. 19
[82] Refer to Biedermann, H.; Kinz, A. (2021), p. 55
[83] Refer to Poór, P. et al. (2019), p. 500
[84] Refer to Biedermann, H.; Kinz, A. (2021), p. 55
[85] Refer to Fox, H. et al. (2022), pp. 2
[86] Refer to BS EN 16646: 2014-12, p. 29

Reliability Centered Maintenance (RCM) and TPM, to improve the organization's performance and strengthen its competitive position. Section 3.7.2 deals with the TPM approach.

3.7.2 Total Productive Maintenance (TPM)

Japan Institute of Plant Maintenance (JIPM) defines TPM as follows: „TPM is designed to maximize equipment effectiveness (improving overall efficiency) by establishing a comprehensive productive maintenance system covering the entire life of equipment, spanning all equipment-related fields (planning, use, maintenance, …) and, with the participation of all employees from top management down to shop-floor workers, to promote productive maintenance through motivation management or voluntary small-group activities."[87]

Figure 9, proposed by the JIPM, shows the eight pillars of TPM, which are based on the workplace management system 5S. 5S refers to Sort, Set in order, Shine, Standardize and Sustain, since cleaning and organizing the workplace makes problems visible and leads to improvements.[88]

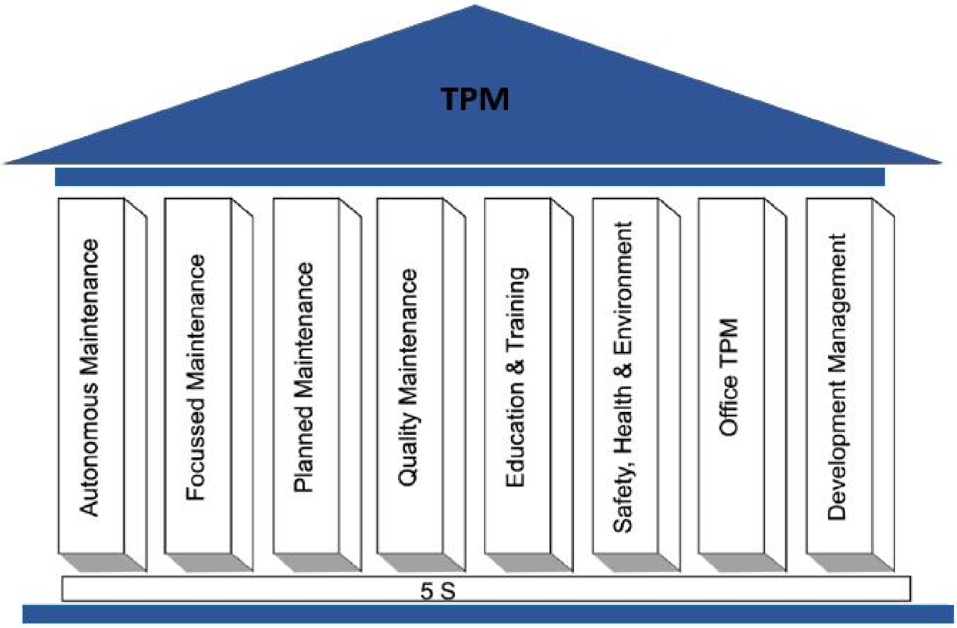

Figure 9: TPM pillars[89]

Autonomous Maintenance: This pillar represents the operators' involvement in maintenance tasks so that they take over basic daily tasks such as cleaning, lubricating and visual inspection to keep the equipment they work on in good working order. Thus, qualified maintenance personnel are relieved of minor tasks and can work more effectively on technical repairs.[90]

[87] Refer to Tsuchya (1992) in McKone, Cua et al. (1999) quoted by Schröder, W. (2010), p. 146
[88] Refer to Singh, R. et al. (2013), p. 593
[89] Source: Ahuja, I. P. S.; Khamba, J. S. (2008), p. 721
[90] Refer to Singh, R. et al. (2013), p. 595

Planned Maintenance: This pillar refers to the proactive maintenance approach that combines and implements the predictive, preventive, and corrective maintenance strategies for the equipment and its components so that optimal maintenance costs, zero equipment failure, and the highest possible equipment maintainability, availability, and reliability are achieved. The advantage of scheduled maintenance is that the necessary resources, such as spare parts, are allocated and available for executing the maintenance tasks.[91]

Focused Maintenance (Kaizen): Kaizen forms the basis of this pillar and aims to minimize and reduce losses to zero.[92] As a continuous improvement cycle, Kaizen pursues minor improvements by engaging all individuals and all levels of the organization; the Kaizen principle states that many minor improvements benefit the organization more than a few big ones.[93] The improvement of production system efficiency and its overall equipment efficiency (OEE) is one of the other main objectives of this pillar. As the core KPI of TPM, OEE strives to reduce six significant losses illustrated in Figure 10. 90% availability, 95% performance efficiency, and 99% quality rate are the TPM standards. 85% OEE is considered a benchmark performance.[94]

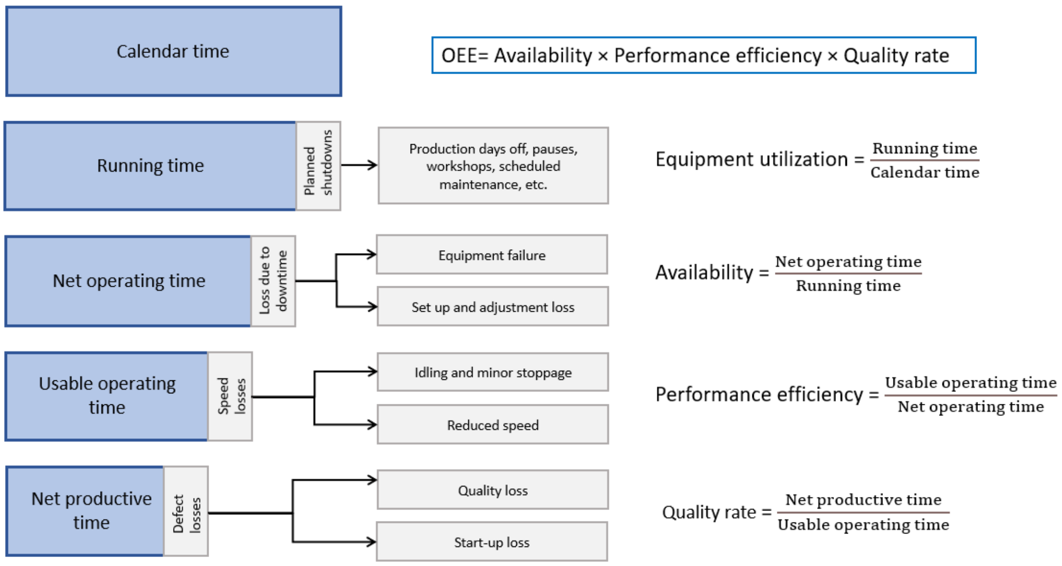

Figure 10: Calculation of OEE[95]

Quality Maintenance: This pillar focuses on customer satisfaction by achieving zero defects and emphasizes quality assurance rather than quality control. Tracking equipment problems and their causes, as well as monitoring operations and maintenance personnel and material conditions, help to mitigate defects.[96]

Education and Training: „Continuous improvement is possible only through continuous improvement in knowledge and skill of the people at different levels."[97] As mentioned

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[91] Refer to Singh, R. et al. (2013), p. 596
[92] Refer to Ahuja, I. P. S.; Khamba, J. S. (2008), p. 722
[93] Refer to Singh, R. et al. (2013), p. 596
[94] Refer to Ahuja, I. P. S.; Khamba, J. S. (2008), p. 724
[95] Source: Löschnauer, J. et al. (2006), p. 102 (slightly modified)
[96] Refer to Ahuja, I. P. S.; Khamba, J. S. (2008), p. 722
[97] Singh, R. et al. (2013), p. 598

earlier, human reliability impacts operational reliability. This pillar focuses on the knowledge and skills of employees, the assessment of their capabilities, and training programs to close the gap between the knowledge required for given tasks and the skills of operations and maintenance personnel and to align them with business objectives.[98]

Safety, Health, and Environment: This pillar aims to create a safe work environment and standard operating guidelines and to prevent accidents and incidents.

Development Management: Learning from the existing systems and applying this knowledge to new systems is at the core of this pillar, leading to improvements in maintenance tasks.[99]

Office TPM: This pillar follows the other four pillars, i.e. planned maintenance, quality maintenance, autonomous and focused maintenance, and focuses on improving the productivity and efficiency of administrative functions, automating procedures where possible, and reducing losses such as process, cost, and communication losses.[100]

The supporting TPM pillars address the ISO 55001 structure, AMS requirements, and its interfaces, like quality management. As a result, applying this approach as a lifecycle maintenance model for the PAM can facilitate organizational adjustment and alignment with the AMS framework. It is worth noting that resistance to change poses obstacles in implementing the AMS incl. TPM. Accordingly, the successful implementation of these approaches relies on the attitude and mindset of employees and managers.

3.8 Risk management

ISO 31000 defines risk as the impact of uncertainty on objectives, which can manifest in both opportunities and threats. Risk causes, potential events, risk consequences, and risk probability are the components that define risk. Risk consequence defined as the result of an event, expressed qualitatively or quantitatively, affects the organization's objectives, such as reduced asset availability due to a failure. Probability refers to the likelihood and the chance of that failure occurring.[101] Risk is calculated as shown in Equation 5.

$$Risk = Probability\ of\ filure \times failure\ Consequence$$

Equation 5: Risk calculation[102]

Following ISO 55001, an organization shall implement processes to identify, observe and manage asset-related risks and opportunities considering their behaviour change over time, document all the data, and ultimately make informed decisions to eliminate or reduce risk and exploit opportunities. For this reason, the risk management approach should be integrated within the AMS and its processes. In addition, AMS should ensure

98 Refer to Ahuja, I. P. S.; Khamba, J. S. (2008), p. 722
99 Refer to Ahuja, I. P. S.; Khamba, J. S. (2008), p. 722
100 Refer to Singh, R. et al. (2013), p. 598
101 Refer to ISO 31000: 2018-02, pp. 1
102 Refer to ISO 31000: 2018-02, pp. 1

that the asset management approach in managing risks is aligned with the organization's strategy for this matter.[103]

Consequently, it is critical for organizations to continuously assess their assets at all stages by performing risk analysis to determine assets' criticality and make decisions regarding uncertainties. Failure Modes and Effects Analysis (FMEA), risk level matrix, and AHP are some commonly used methods to evaluate assets respectively assets' components in terms of risk leading to the right strategy selection for the asset, namely the proper maintenance strategy. These methods will be discussed more in Chapter 5.

3.9 AMS successful implementation

As Figure 11 shows, AMS consists of three organizational levels: strategic, tactical, and operational, with feed-forward and feedback mechanisms.[104]

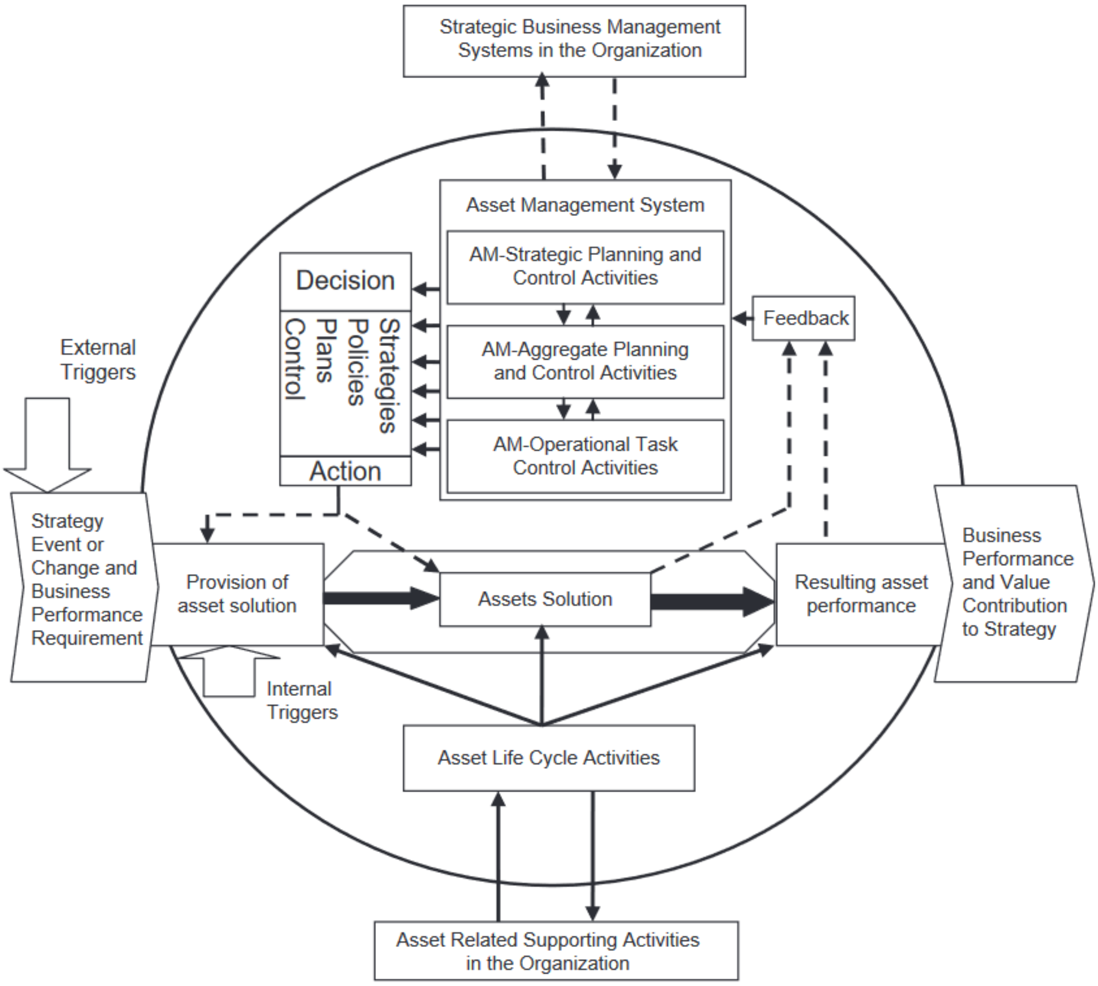

Figure 11: The AM system functional model[105]

[103] Refer to ISO 55001: 2014-01, pp. 2
[104] Refer to El-Akruti, K.; Dwight, R. (2013), p. 406
[105] Source: El-Akruti, K.; Dwight, R. (2013), p. 409

The necessity for an AMS to set asset management policy and processes to realize both asset management and the organization's goals indicates the importance of its integration with other management systems and the task of directing, coordinating, and controlling the asset-related activities and relationships along and between hierarchical levels of the organization and across asset lifecycle stages.[106] This requires, in the first place, an adequate flow of information between all management systems and all stakeholders inside and outside the organization so that everyone is aware of the importance of providing and sharing accurate information and also of their role in asset management decision-making and thus of the value they deliver to the system.[107]

A successful AMS on this matter defines the objectives of all involved parties into qualitative and quantitative KPIs to assess and improve performance in alignment with the AMS and the organization's goals and to ensure meeting the desired result. AMS provides many benefits to itself, top management, and other functional units. Improvements in organizational knowledge, employees' performance, communication, the interaction between management systems, sustainable decision-making approach, and asset lifecycle planning are some of the advantages of AMS. Therefore, the AMS plays a significant role in the organization's strategy development and implementation.[108] Chapter 5 discusses the implementation of the AMS framework in more detail. With respect to the AMS interfaces listed in this chapter and to assess their performance, Chapter 4 shall elaborate on the fundamentals of KPIs and associated analyses.

[106] Refer to El-Akruti, K.; Dwight, R. (2013), p. 400
[107] Refer to ISO 55000: 2014-01, p. 6
[108] Refer to ISO 55000: 2014-01, p. 6

4 Fundamentals of Key Performance Indicators (KPIs)

Chapter 4 of this master's thesis covers the basics of KPIs and KPI assessment methods. Sections 4.1 and 4.2 deal with the definition of KPIs and their task in planning and control systems. Subsequently, KPIs are presented in the context of maintenance management regarding asset management, which should also be applicable for the purpose of asset criticality evaluation. Moreover, to compare different KPIs and their importance against each other with respect to their superordinate objectives, KPIs assessment methods and the most popular Multi-Criteria Decision-Making method (MCDM), i.e. the AHP method, are discussed in Section 4.4.

4.1 KPIs definition

Every organization needs to know how it performs and where its strengths, weaknesses, opportunities, and threats (SWOT) lie, to manage and improve its performance and avert business risks and turn them into opportunities. KPIs measure the organization's performance and indicate how effectively each management system contributes toward achieving the organization's values and goals. For this reason, every organization needs to define a framework consisting of the business objectives, i.e. the KPIs to be measured and the methods to measure them.

Available, measurable, and accurate data is essential in this context to obtain meaningful and informative results. The next step involves planning and building an appropriate measurement system for the defined KPIs and developing formulas for the defined KPIs. The following step includes the implementation and management of the system. The calculated measures reflect organizational performance and areas for improvement. Lastly, the measurement system must be continuously evaluated and updated to ensure that the defined KPIs are relevant, and that the system provides purposeful information.[109]

Key figures are deliberately condensed measures into ratios and absolute figures to report in a concentrated form on a numerically ascertainable fact. Key figures deliver quantitative information about the business, technical or organizational circumstances.[110] In this connection, GABLER (2022) defines KPIs as „key figures that refer to the success, performance or utilization of the business, its individual organizational units or a machine."[111] KPIs are mainly quantitative information in the form of numbers calculated using formulas, but they can also result from qualitative assessments and questionnaires. Translating an organization's goals into measurable and evaluative

[109] Refer to Saari, E. (2019), p. 18
[110] Refer to Weber, J. (1999) quoted by Gladen, W. (2014), p. 9
[111] Springer Gabler, https://wirtschaftslexikon.gabler.de/definition/key-performance-indicator-kpi-52670 (Retrieved: 02.08.2022)

factors is the purpose of defining KPIs. By comparing the assessed KPIs with benchmarks or defined target values, management areas define plans and strategies for improvement. It should be noted, that the review and redefining of KPIs, if needed, as well as performance evaluation and improvement, should be conducted as a continuous process as they as well as business objectives change over time.[112] To understand KPIs task better, Section 4.2 deals with the role of KPIs in planning and control systems.

4.2 KPIs task in planning and control systems

KPIs provide management information for the management process that includes three phases, namely planning, realization, and control. These three phases form the control loop of the planning and control system, as illustrated in Figure 12. Control is an essential element of this loop since it improves the system. KPIs as guidance information contribute to the task concretization in all three phases and assist in documenting the planning results and the target- and actual-achievement levels. Moreover, they facilitate communication through the management process phases.[113]

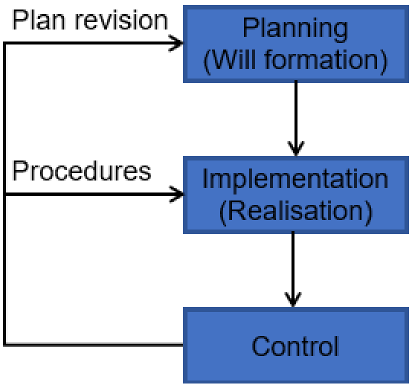

Figure 12: Control loop of the planning and control system[114]

In the **planning phase**, KPIs have a stimulating function in analyzing specific problems on a case-by-case basis by providing initial information and localizing planning problems. The Balanced Scorecard (BSC) is an example of a KPI system and the conceptual use of KPIs in the decision-making process that influences the thought processes and actions of managers and employees by providing a common language through a simple internal business model. KPIs operationalize the actual and target goals and thus make them adaptable and predeterminable. KPI systems as simulation models help to make decisions in the planning phase by comparing alternative actions and estimating their effects.[115]

The enforcement phase implements the goals defined in the planning phase, so coordination between the responsible parties is necessary. In this sense, KPIs fulfill a factual and personnel coordination task within the framework of hierarchical coordination, horizontally between organizational units and participants of one

[112] Refer to BS EN 15341: 2019-08, p. 8
[113] Refer to Gladen, W. (2014), p. 26
[114] Source: Gladen, W. (2014), p. 26 (slightly modified)
[115] Refer to Gladen, W. (2014), pp. 26

management level and vertically between different management levels. The goals defined in the planning phase are broken down into more detailed operational sub-goals for the various management levels and converted into area specific KPIs. A balanced relation between ends and means links the different management systems to align their objectives with the organization's ultimate goals. In addition, the organizational units tasked with implementing the targets need tailored information, such as instructions, to which they can align their decisions and actions. Thus, KPIs have the communication task to convey specific tasks briefly and concisely.[116]

The management systems' target deviations and performance will be evaluated in the **control phase** by comparing them with the target values as measurement criteria. In this phase, GLADEN (2014) speaks of the learning and motivation functions, whereby in the learning function, the divisions and employees carry out a self-monitoring process to evaluate deviations and the decisions made and to improve them. On the other hand, in the motivational function, the superior authority of a department will perform the controlling task. Here, there is a risk that the department heads may pursue their own interests rather than those of the organization in the controlling process and report the intended deviations. Thus, control results credibility should be ensured; the results in this function are also associated with incentives such as reward or punishment.[117]

4.3 Production and maintenance KPIs in line with PAM

Maintenance standard BS EN 15341 classifies maintenance KPIs within the PAM into the following groups:[118]

- Maintenance within physical asset management
- Maintenance subfunctions
    - Health – Safety, Environment
    - Maintenance Management
    - People Competence
    - Maintenance Engineering
    - Organization and Support
    - Administration and Supply
- Information, Communication, and Technology

In the literature, there is a wide range of KPIs. KPIs defined in Table 1 are selected regarding PAM's interfaces, the next chapter's objective, and the scope of the practical part. Both quantitative and qualitative KPIs are listed in this table, although a distinction between them is necessary, which will be discussed in Chapter 5 by Section 5.2.3.

116 Refer to Gladen, W. (2014), pp. 28
117 Refer to Gladen, W. (2014), pp. 29
118 Refer to BS EN 15341: 2019-08, p. 11

Table 1: Maintenance KPIs within Asset Management[119,120,121]

KPI	Description	Formula
Asset age	The asset's age is measured in years since commissioning and provides information about the degree of wear of the asset.	$\frac{Actual\ cumulative\ operational\ life}{Expected\ cumulative\ operational\ life} \times 100$
The economic life of the asset	The economic life analysis is based on the equivalent annual cost (EAC) and is determined by comparing the EAC values over the asset lifecycle.	The age at which the total cost of the asset over its lifecycle is the lowest. This is obtained by comparing the equivalent annual costs over the asset's lifecycle.
Downtime degree	It is very suitable for the evaluation of the asset's failure behavior.	$\frac{Asset\ downtime\ (unplanned)}{Asset\ operating\ time}$
Scrap rate	It compares the number of scrap parts with the total production quantity of a period.	$\frac{Number\ of\ scrap\ parts}{Total\ production\ volume} \times 100$
Output relevancy	Is the asset rigidly interlinked with upstream and downstream assets? How many parallel assets carry out the same process step? This KPI considers both redundancy and chaining degree.	This KPI is to be evaluated subjectively by experts.
MTTR	Time interval includes since the failure occurs until the asset is fully functional again.	$\frac{Total\ time\ to\ restoration}{Number\ of\ failures}$
MTBF	MTBF refers to the operating time between two consecutive failures. It is suitable for the planning of spare parts stocks.	$\frac{Total\ operating\ time}{Number\ of\ failures}$
Asset availability	it shows the percentage of shutdowns to the running time of the asset.	$\frac{MTBF}{MTBF + MTTR}$
OEE	OEE is the core KPI of the TPM approach.	$Availability \times Performance\ level \times Quality$
Maintenance intensity	This KPI is suitable for repair/replace decisions.	$\frac{Annual\ maintenance\ costs}{Asset\ replacement\ value} \times 100$
Prevention level	The degree of prevention reflects the percentage of preventive maintenance measures.	$\frac{Costs\ for\ planned\ maintenace}{Total\ maintenance\ costs} \times 100$
Spare parts availability	This KPI plays a significant role in the repair/replace decision.	It will be determined by market analysis.
Spare parts intensity	This KPI is suitable for repair/replace decisions; when spare parts replacement costs are way more than asset replacement value, maybe it is the time to replace the asset.	$\frac{Replacement\ value\ of\ spare\ parts}{Asset\ replacement\ value} \times 100$
Outsourcing rate	This KPI provides information on the percentage of outsourced services used for maintenance activities.	$\frac{Costs\ of\ external\ maintenance\ services}{Total\ maintenace\ costs} \times 100$

119 Refer to Kinz, A. et al. (2017)
120 Refer to Kurt, M. (2005)
121 Refer to BS EN 15341: 2019-08

Continuation to Table 1: Maintenance KPIs within Asset Management

Frequency of failures causing injuries to people	Does the asset have special impact on the employee's safety in the event of an incident?	$\frac{Number\ of\ failures\ causing\ injuries}{Actual\ working\ time}$
Frequency of item failures causing damage to the environment	Does the asset have special impact on the employee's safety in the event of an incident?	$\frac{Number\ of\ failures\ causing\ damage\ to\ enviroment}{Total\ number\ of\ failures}$
Maintenance actions to improve energy conservation (N°/year)	This KPI considers improvements concerning energy management.	$\frac{Number\ of\ maintenance\ actions\ implemented\ to\ improve\ energy\ conservation}{Year}$

In order to consider all KPIs together, measure the relationships between them, and, most importantly, measure the organization's performance based on these KPIs to provide meaningful business information, performance measurement systems built from KPIs are required.[122] Therefore, Section 4.4 discusses key figure systems in more detail.

4.4 Key figure systems and KPIs assessment

The analysis is distinguished by the fact that a complex issue is broken down into its individual components as far as possible. This simplifies the issue, as partial results can be obtained by evaluating that issue's components. An overall conclusion is then drawn from the aggregation of these partial results.[123]

Key figure systems (KFS) mostly have a hierarchical structure to meet the following requirements better:[124]

- Objectivity and consistency: Systematic structure to prevent subjective arbitrariness of interpretations and the possibility of contradictory statements.
- Simplicity and clarity: One of the tasks of key figures is to reduce complexity. Therefore, it is advantageous not to define numerous key figures in a KFS, but rather a limited number with a sensible sequence to maintain simplicity and transparency.
- Aggregation of information: The hierarchical structure of the KFS allows key figures to be divided into upper and lower levels so that only a few key figures are defined at the upper levels, especially at the management levels, and to fall back on detailed figures only when necessary.
- Multi-causal analysis: Decomposing superordinate key figures into their sublevels enables multi-causal analysis of key figures.
- Indicator function and system openness to realize it: One must disregard the uniqueness of a single-line system, so that at the levels of the hierarchy there is

[122] Refer to Gladen, W. (2014), p. 86
[123] Refer to Lachnit (1976) quoted by Gladen, W. (2014), p. 103
[124] Refer to Gladen, W. (2014), pp. 96

not always exactly one key figure superordinate to every key figure. Certain indicators might influence not only one superordinate key figure but also several higher-level key figures simultaneously.

- Participation: The participation of experts is essential in developing the KFS.

KFS include computing systems and classification systems. Computing systems are based on logic and use logical relations and mathematical calculations to compute a peak key figure. The ROI-tree (also known as Dupont-scheme) is a typical example of a computing system shown in Figure 13. Contrary to computing systems, classification systems can incorporate indicators that cannot be linked mathematically by logical definition, reflecting the higher flexibility of these systems. However, the quantitative relationships between the key figures cannot be mapped explicitly. Also, a certain degree of subjectivity in selecting indicators is unavoidable.[125]

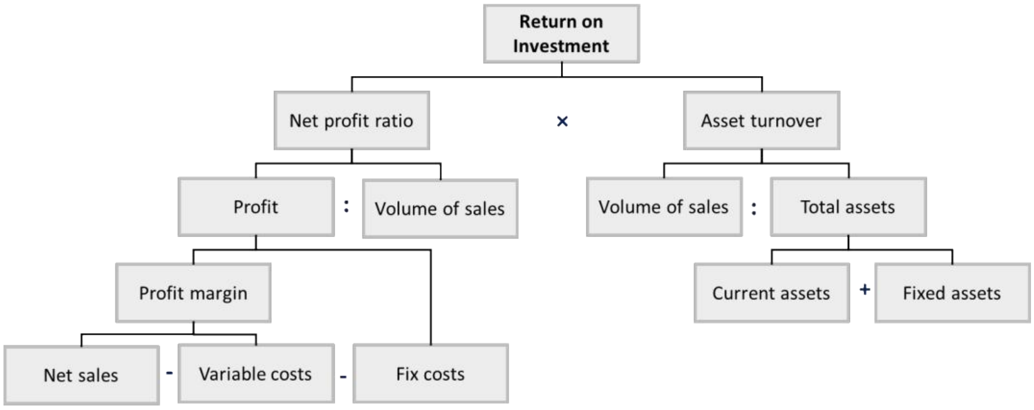

Figure 13: ROI tree[126]

Key figures are analyzed and assessed by performing comparisons. Methods incl. time comparison and operation/intercompany comparison serve as key figure analysis for monitoring company performance. The time comparison compares the same key figures over different periods, e.g. maintenance costs between the first and second quarter of a year. The goal is to track development trends such as improvements and evaluate performance over time. An operational comparison contrasts similar KPIs between different departments within the company or between the company and other companies, such as its best-in-class competitors. Besides, the target-actual comparison checks the actual values of the KPIs with the target values and measures the deviation, which is why this comparison is more meaningful for evaluating profitability.[127]

The BSC is an example of performance measurement systems. Still, the BSC has some weaknesses, such as the lack of a mathematical model, a weighting scheme and the lack of standardization for performance comparisons.[128]

A decision environment consists of various criteria, alternatives, and preferences that influence decision making, and the multitude of criteria complicates this process.[129] KPIs included in the decision-making process have different values and importance for the

[125] Refer to Gladen, W. (2014), pp. 98
[126] Source: adapted from Gladen, W. (2014), p. 106
[127] Refer to Gladen, W. (2014), pp. 103
[128] Refer to Dewi, A. C.; Zaman, A. N. (2018), p. 27
[129] Refer to Theron, E. (2016), p. 79

organization, and so they must be compared with each other to calculate their values. Therefore, Section 4.4.1 deals with the Multi-Criteria Decision Making (MCDM) approach as a tool to support the decision-making process that involves multiple, conflicting criteria or objectives. Consequently this chapter ends with introducing the Analytical Hierarchy Process (AHP) approach.

4.4.1 Multi-Criteria Decision Making (MCDM)

BELTON and STEWART (2002) define MCDM as „an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore decisions that matter."[130]

MCDM helps to analyze the decision context, improves mutual understanding and discussion among decision-makers, and increases coherence in objectives and final decisions. Various MCDM methods are used for multi-criteria structures. Some well-known mechanisms are the Simple Pairwise Comparison, the Equal Weighting Technique, the Rank Order Centroid, the Rank Sum Method, and the Multi-Attribute Utility Theory. EZELL et al. (2021)[131] discuss eight primary MCDM techniques in their paper and compare the advantages and disadvantages of these methods. As mentioned in Chapter 1, the objective of this study is to define a framework that is practical and easily applicable to any organization, in this context, the BRP-Rotax company. For this reason, the pairwise comparison respectively the AHP was chosen as the MCDM approach for comparing the KPIs. Section 4.4.1.1 shall elaborate on the AHP approach.

4.4.1.1 Analytical Hierarchy Process (AHP) approach

The Analytical Hierarchy Process (AHP), developed by THOMAS L. SAATY (2008) as a popular pairwise comparison method, engages perceptions, feelings, and judgments of decision-makers and experts besides quantitative data in the decision-making process.[132] Maintenance management seems to have incorporated the AHP method during the second half of the 1990s, when the method had already been recognized as a reliable method for evaluating multi-criteria decisions in engineering applications.[133]

Some question this approach as it is based on subjective assessments rather than objective methods, which are based on numbers and standard criteria. SAATY believes that even figures derived from objective methods are ultimately subjectively interpreted.[134] The AHP steps are as follows:[135,136]

Step 1: The goal comes at the top, the associated criteria are ordered on the second level below the goal, the sub-criteria of each criterion on the third level, and so it goes on to the last level. By doing so, a hierarchical structure is created. To maintain

[130] Refer to Belton, V. and Stewart, T. (2002) quoted by Theron, E. (2016), p. 80
[131] Ezell, B. et al. (2021)
[132] Refer to Theron, E. (2016), p. 82
[133] Refer to Goossens, A. J. M.; Basten, R. J. I. (2015), p. 33
[134] Refer to Saaty, T. L. (2008), p. 85
[135] Özcan, E. et al. (2019), pp. 5
[136] Yap, J. Y. L. et al. (2018), pp. 5

consistency and ensure meaningful comparison, the number of sub-criteria in each group and at each level should be low.

Step 2: The experts perform a pairwise comparison between the criteria according to their importance concerning the higher-level criteria. „For instance, every two criteria in the second level are compared at each time with respect to the goal, while every two attributes of the same criterion in the third level are compared at a time with respect to the corresponding criterion."[137] To compare criteria with each other, Table 2 helps the experts by providing a scale of numbers that reflects the criterion's importance compared to the other criteria.

Table 2: Saaty scale of numbers[138]

Importance intensity	Definition
1	Equal important
3	Moderate important
5	Strong important
7	Very strong important
9	Extreme important
2,4,6,8	Intermediate value between two adjacent judgements
Reciprocals of above	If activity i has one of the above non-zero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i, e.g. when a_{12}=5, then a_{22}=1/5

Table 2 indicates how much more important or dominant one element is over another when it comes to the higher level or target, they are being compared to.[139] The pairwise comparison results are entered into an n-element (n is the number of criteria) symmetric matrix whose eigenvector A is as shown in Equation 6:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix}$$

Equation 6: Pairwise comparison Matrix

Step 3: By solving the principal eigenvalue problem (A - λI) B = 0, the column vector B as represented in Equation 7 is formed:

$$B_i = \begin{bmatrix} b_{11} \\ b_{21} \\ \vdots \\ b_{n1} \end{bmatrix} \; i = 1,2,\dots,n$$

Equation 7: B vector

And the normalization is carried out in Equation 8:

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[137] Ho, W. (2008), p. 212
[138] Source: Saaty, T. L. (2008), p. 86 (slightly modified)
[139] Refer to Saaty, T. L. (2008), p. 85

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad i, j = 1,2, \dots, n$$

Equation 8: Normalization

Step 4: In this step, the weighting of the criteria is calculated by dividing the results of the last step by the number of criteria as follows and forming the W_i vector, as given in Equation 9 and Equation 10. Once the weights for each criterion are determined, steps 5 and 6 are performed to ensure that the results are consistent.

$$W_i = \sum_{i=1}^{n} \frac{b_{ij}}{n} \quad i, j = 1,2, \dots, n$$

Equation 9: Criteria weighting

$$W_i = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \; i = 1,2, \dots, n \qquad \sum W_i = 1$$

Equation 10: W_i vector

Step 5: To evaluate the coherence of the results obtained by judgments, the consistency ratio (CR) needs to be calculated. For this purpose, first the matrix D must be calculated as shown in Equation 11, which results from the multiplication of the matrix A and the vector W. Then, the base value vector (E) of each evaluation criterion can be obtained according to Equation 12 and then the base value (λ) will be calculated as shown in Equation 13.

$$D = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ . \\ . \\ . \\ w_n \end{bmatrix}$$

Equation 11: Matrix D

$$E_i = {}^{d_i}/_{w_i} \quad i = 1,2, \dots, n$$

Equation 12: Value vector

$$\lambda = \sum_{i=1}^{n} {}^{E_i}/_{n} \quad i = 1,2, \dots, n$$

Equation 13: Base value λ

To calculate CR, the consistency index (CI) must still be calculated, as shown in Equation 14. Subsequently, CR will result from Equation 15 by dividing the CI to Random Index (RI) value.

$$CI = \frac{(\lambda - n)}{(n - 1)}$$

Equation 14: CI calculation

$$CR = \frac{CI}{RI}$$

Equation 15: CR calculation

RI is determined based on the number of criteria involved in the process, as shown in Table 3:

Table 3: Random Index for n=11[140]

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**…**
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	…

If the CR value of less than 0.1, then the application is consistent. Otherwise, the above steps and pairwise comparison needs to be repeated until a CR value of less than 0.1 is obtained.

Step 6: The criterion with the highest value is selected as the best alternative. In the context of this study, this approach is used in Chapter 6 to calculate the weighting of the different KPIs considered to determine the criticality of the asset and as a result calculate its criticality.

Since the decision process in applying the AHP method requires the participation of multiple decision makers, resulting in each individual making different pairwise comparisons, Equation 16 helps to obtain a consolidated measure of these comparisons of all participants. Considering m participants, the geometric mean is calculated as below to obtain a unified evaluation as a group score, where a_i is the weight per pairwise comparison done by participant i with i Є {1, ..., m}. As a result, geometric standard deviations can be used to determine where participants agree and disagree most.[141]

$$\bar{a}_g = \sqrt[m]{a_1.a_2...a_m}$$

Equation 16: Geometric mean

The AHP implementation has great advantages, such as its ease of use and scalability, i.e. it can be easily adapted to the size of the decision problem. Moreover, it is appropriate for group decision-making and it is not data intensive. However, the interdependence between alternatives can lead to inconsistent results, and adding or removing an alternative also leads to a change in the ranking which is the method’s weakness.[142]

As the basics of KPIs and KPIs' assessment methods are also discussed, Chapter 5 builds upon the literature reviewed in previous chapters to develop an asset management assessment system for evaluating the criticality of assets using KPIs.

140 Source: Saaty, T. L. (1980) modified by Yap, J. Y. L. et al. (2018)
141 Refer to Goossens, A. J. M.; Basten, R. J. I. (2015), p. 34
142 Refer to Velasquez and Hester (2013) quoted by Theron, E. (2016), p. 84

5 Asset management evaluation system

Production assets are characterized above all by their high degree of wear which leads to a reduction in their availability and quality, and in the worst case, asset shut down, which causes losses in production and organization success. Resource-efficient and effective asset management model, characterized by high asset availability and low costs that considers all the AMS interfaces mentioned in Chapter 3, is essential for the organization's profitability and high performance.[143]

Therefore, Section 5.1 discusses the theoretical structure of the required asset management evaluation system, and Section 5.2 addresses the methods for determining asset criticality. Subsequently, Section 5.3 represents the main factors that trigger asset replacement or contribute significantly to the decision-making process on repairing, retrofitting, or replacing critical assets. Finally, Section 5.4 discusses the KPI-driven action plans derived from the last steps. The decisions reached through this process result in one of the following scenarios: Adjustment of the planning of maintenance resources (material, machines, personnel) as well as the maintenance strategy, overhaul or retrofitting of equipment (modernization), or to the timely replacement of equipment.

5.1 Theoretical build-up of the AMS framework

As mentioned previously, an effective AMS is essential for the continuous assessment of assets. Therefore, an assessment method that includes the company-specific criteria helps to determine the criticality of the assets and subsequently identify the focal assets. Finally, appropriate actions, i.e. improvement of maintenance strategies, retrofitting, or replacement, can be derived for the critical production assets.[144] In this regard, the following sections deal with the development of an asset management model, which builds on the fundamentals of the previous chapters of this work and reflect the main objective of this master's thesis. The goal is to develop a model that addresses the AMS requirements and is customizable, so that it can be used as a framework by any organization and tailored based on the organization's needs and the available data. Hence, the model should meet the following requirements:

- The model should consider both practical and scientific aspects, incorporating the organization's goals and available data.
- The model should be easily customizable, efficient, and not too complex so that all users can understand and work with it. Thus, changes, such as new KPIs selection, can be implemented into the system as effortlessly as possible.
- The model should be integrated with other organizational management systems to involve their considerations into the model and develop the information exchange with them. Accurate data is one of the essential prerequisites for achieving meaningful results.

[143] Refer to Kinz, A. et al. (2017), pp.185
[144] Refer to Kinz, A. et al. (2017), p. 190

- Eventually, the model should be applied not only by the maintenance management system but also by all other management systems, such as financial management, to facilitate asset-related decision-making processes, such as resource allocation or investment decisions.

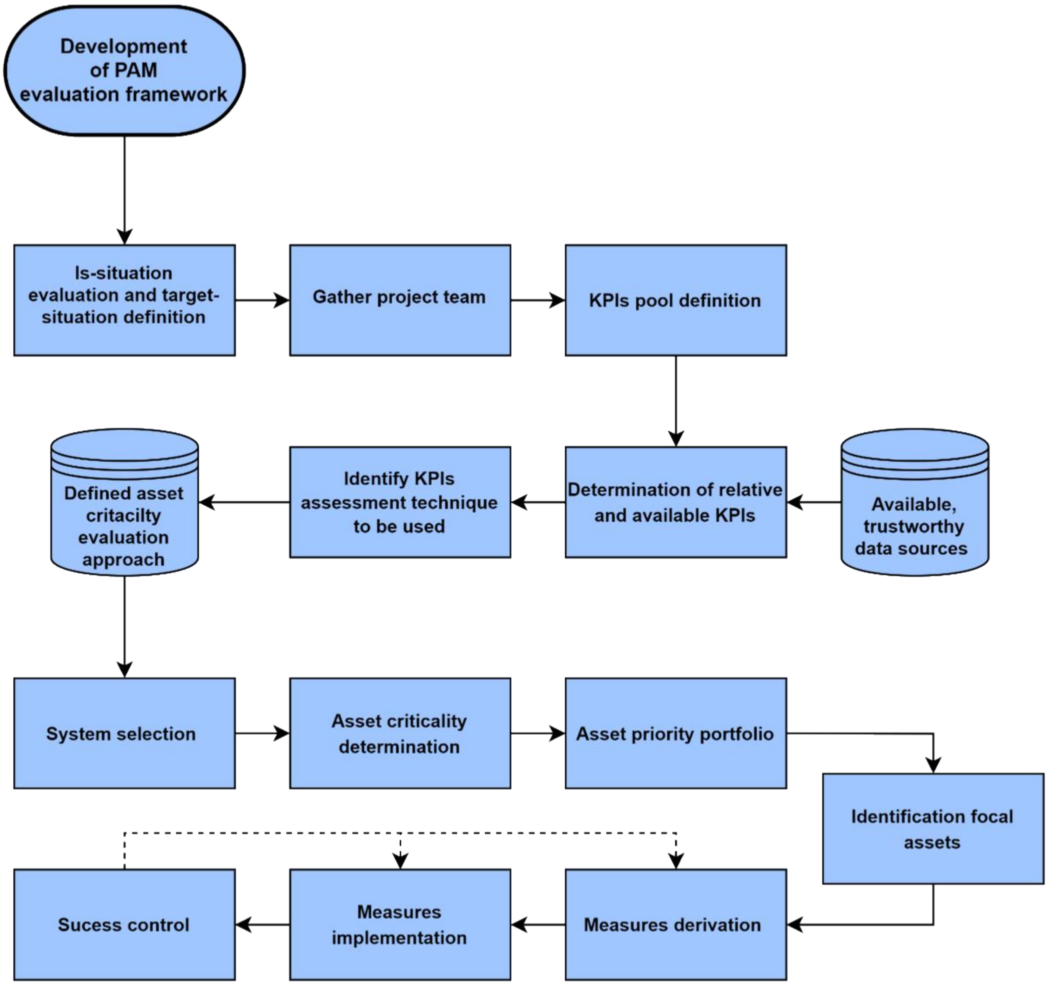

Figure 14: AMS framework[145]

Figure 14 represents the steps required in the development of the asset management evaluation framework. The first step contains the gap analysis between the current state and the target state as defined by the organizational goals and requirements. As the next step, an expert team should be formed. It must be emphasized that experts with the necessary know-how from production and maintenance, but also from other departments such as quality management and facility management, constitute the expert panel for the model development to ensure that the model is consistent with other management objectives. Subsequently, an asset criticality determination method must be developed, applying one of the methods presented in Section 5.2. Figure 14 illustrates the KPI-based criticality assessment method as the selected method for the scope of this study. Once the criticality method is determined, the next step includes the system selection respectively selecting the assets for the framework's implementation and evaluation.

[145] Source: Own representation refer to Biedermann, H.; Kinz, A. (2021), pp. 190

Then, the selected assets must be evaluated using the criticality evaluation approach and entered into an asset priority profile.

Appropriate action plans must then be derived based on the assets' technical condition and criticality to minimize their wear and tear level by optimizing the maintenance strategy, resource allocation focusing on the more critical assets, and to perform cost analysis to reduce costs. In addition, action plans help us to decide whether to make improvements to the equipment, incl. overhauls and retrofits, or to replace the equipment at the optimal time. The last two steps are discussed in detail in Section 5.4. Success control and result evaluation constitute the final step to validate the efficiency and applicability of the applied model and to improve it. To perform the above steps, Section 5.2 outlines some methods enabling organizations to determine asset criticality, and Section 5.3 lists the factors that trigger asset improvement or replacement.

5.2 Asset criticality assessment - scientific benchmarking

Benchmarking is a continuous, ongoing analytical process to assess, evaluate and compare an organization's internal performance with external standards and those recognized as "Best in Class."[146] This comparison is not limited solely to observing the best companies in the same industry in which one's own company operates. For instance, when benchmarking the evaluation methods used to assess the equipment criticality of an automotive manufacturer, benchmarking is not limited to the automotive industry but also considers all other industries (e.g., mining) and their best practices. In the end, the evaluation method suitable for the organization and its performance will be selected. In this study, scientific benchmarking is conducted by reviewing various scientific papers to choose the best approaches for determining asset criticality.

The advent of mechanization and automation has placed a premium on asset availability and reliability. Additionally, asset management, incl. maintenance, is expected to meet quality and environmental standards, comply with safety regulations, and extend asset life.[147] In this context, continuous asset criticality analysis is vital to identify the most critical assets, prioritize maintenance activities, and optimize maintenance resource planning strategies to eliminate major losses and extend asset life through proper maintenance. On the other hand, it helps companies find the optimal time to replace an old asset rather than wasting resources and budget.

There are several methods used in the literature to determine asset criticality. Some used the following methods to assess component criticality, while others used these methods to determine asset criticality. Nevertheless, all assessments require the active involvement of maintenance personnel, operations, and technical personnel when conducting the assessment process. Admittedly, determining asset criticality is a time-consuming and tedious process, especially for asset-intensive companies, given the number of assets and components in each asset.

[146] Refer to Kurt, M. (2005), p. 85
[147] Refer to Tale, T. (2019), p. 2

5.2.1 Risk level matrix — FMEA

As defined in Section 3.8, risk is the result of the probability of failure multiplied by the consequence of failure.[148] The risk matrix is one of the methods for ranking assets based on their criticality, as shown in Figure 15. The X-axis determines the consequence respectively the scale of failure, while the Y-axis represents the failure likelihood. As a result, risks are classified as low, medium, high, or extreme. The risk level matrix shows which risks are tolerable and which are not; the limits of the matrix above which risks are intolerable vary depending on the organization and must be defined or approved by management.[149] Based on the risk level, appropriate actions are required:[150] Extreme risk requires immediate executive action and high risk demands executive action. There must be an assignment of activities and responsibilities by the management by risk level medium. Low and low medium levels can be managed with routine processes. As the next step, the identified risks are entered into an FMEA form to calculate the associated Risk Priority Number (RPN) for each failure mode. RPN is the result of the multiplication of failure occurrence probability (O), failure detectability probability (D), and failure severity (S), as each factor will be evaluated on a scale from 1 to 10.[151]

Likelihood	Consequence				
	Insignificant	Minor	Significant	Major	Severe
Almost certain	Medium	Medium	High	Extreme	Ex
Likely	Low Medium	Medium	Medium		Extreme
Moderate	Low	Low Mediu	um	High	Extreme
Unlikely	Low	Low	Low Medium	Medium	High
Rare	Low	Low	Low Medium	Medium	High

Low critical — Medium critical — High critical — Extreme critical

Figure 15: Risk level matrix[152]

Therefore, failure modes can be prioritized according to their calculated RPN and the RCM approach can be applied for highly prioritized failure modes aimed at optimizing the maintenance strategy; the RCM approach will be discussed in Section 5.4. Table 4 provides an exemplary FMEA form, in which the damage scale is divided into several subcategories. PATIL and BEWOOR (2022) apply the FMEA approach to identify critical components.[153] Components identified as medium/high critical are processed through the RCM logic tree to be evaluated based on their failure impact.

[148] Refer to ISO 31000: 2018-02, pp. 1
[149] Refer to Biedermann, H.; Kinz, A. (2021), p. 189
[150] Refer to Hastings, N. A. J. (2021), p. 323
[151] Refer to Filz, M.-A. et al. (2021), p. 3
[152] Source: adapted from Hastings, N. A. J. (2021), p. 323
[153] Patil, S. S.; Bewoor, A. K. (2022)

Table 4: FMEA form[154]

Asset		Damage (severity) assessment							Evaluation			
Assembly group	Risk	Repair Time [h]	Wait time for spare part [h]	Downtime [h]	Downtime costs [€]	Repair costs [€]	spare part costs [€]	Total damage costs [€]	S	O	D	RPN: S×O×D

5.2.2 Consequence category

Using this method, the type of risk is divided into consequence categories. Then the asset's criticality is calculated based on the severity of the consequences of a failure in each defined category. As mentioned earlier, the term "consequences" refers to any event that results in loss or damage, such as loss of life or equipment failure. HASTINGS (2010) considers safety, cost, function, and environment as consequence categories, with consequences rated on a scale of 1 to 5, where 1 represents very low risk, and 5 means very high risk. [155] Table 5 illustrates an example of this method.

VISHNU and REGIKUMAR (2016) consider the impact on production, safety, equipment availability, and cost of capital as consequence categories with risk scores of 1, 2, or 3.[156] In this method, unlike the above method, each category is assigned a different weighting based on its importance. Then, the asset criticality is determined by multiplying the associated score of each category by the respective weighting.

Table 5: Consequence category example

Asset	Health and Safety	Environmental	Cost	Operation	Asset Criticality
Milling machine	5	2	1	5	13
Grinding machine	2	1	4	3	10

5.2.3 KPIs-based asset criticality determination – selected approach

To implement this method, KPIs must be defined based on the business objectives, AMS interfaces, and the model's intended use. Asset evaluation is an iterative process meaning that the assets must always be reevaluated by the organization at certain intervals. Hence, the selected KPIs and the developed model should enable an evaluation process that will not require much effort. This real-time asset prioritization supports short- and long-term maintenance or asset management decisions.

The evaluation model can consist of quantitative KPIs such as asset availability as well as permanently constant KPIs such as asset location. Permanently constant KPIs cannot be evaluated quantitatively and will be assessed on a one-time basis. Quantitative KPIs are assigned a numerical value and therefore, can be used for a dynamic and static asset evaluation and also be divided into gradations using their measured numerical values.

[154] Source: Biedermann, H.; Kinz, A. (2021), p. 191 (slightly modified)
[155] Refer to Hastings, N. A. J. (2010), pp. 173
[156] Vishnu, C. R.; Regikumar, V. (2016)

Thus, the more quantitative KPIs are included in the model, the more accurate the result will be. On the other hand, qualitative KPIs will be assessed by experts' experience, which is why they are only suitable for static asset valuation. Yet, an objective evaluation result can only be achieved if all KPIs considered in the model are quantitative. However, this is impossible because not all required data is available, and not all KPIs can be quantified. Hence, qualitative KPIs are allowed in the model, but to get the most powerful results, the number of these KPIs should be minimal. Also, the evaluation period - how often the organization carries out the evaluations - and the type of evaluation - dynamic or static – should be considered by selecting KPIs.[157]

When defining potential KPIs, it is important to consider that they must be usable for all assets so the model is applicable to the whole plant. After listing potential KPIs for the asset criticality determination, the list should be narrowed down to five to ten KPIs to reduce the assessment burden. In this step, those KPIs are selected that are appropriate for criticality determination and available within the organization. The challenge is to keep the number of KPIs low while still considering all relevant perspectives. The next step is to define a rating scale for KPIs by dividing each KPI into three to five gradations. A description for each gradation is necessary for qualitative KPIs, like output relevancy, as these are to be described subjectively. So, the gradings will be understandable and clear for everyone. The gradings will be assigned values that represent the criticality value for each KPI. The scaling of the KPIs can be considered as the last step. However, this is not mandatory and depends on the perspective of the experts, for whom each KPI is more or less important by determining the asset's criticality.[158]

KINZ et al. (2017) divide each KPI into three to five gradations, assigning each one a numerical value between 1 and 10.[159] The asset's criticality thus results from the sum of the scale values achieved by each KPI. ÖZCAN ET AL. (2019) implement the AHP method for criteria weighting calculation.[160] Either way, the evaluation results in a number representing asset criticality, where the highest number is 100. The next step is to determine whether the asset can be preserved or whether it needs to be replaced. In this context, Section 5.3 presents factors that influence this decision.

5.3 Asset Improvement/Replacement

As discussed in Chapter 2, many reasons, such as asset obsolescence, wear and tear, and technological changes, lead to its improvement or replacement. The term "improvement" in this study refers to actions taken to make changes to the equipment, such as retrofit, modernization, or other terms used in the literature to refer to equipment condition enhancement. Replacing or upgrading physical assets plays a vital role in asset-intensive organizations regarding investment strategies and avoiding high meaningless O&M costs resulting from old assets.

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[157] Refer to Kinz, A. et al. (2017), pp. 190
[158] Refer to Biedermann, H.; Kinz, A. (2021), pp. 176
[159] Kinz, A. et al. (2017)
[160] Özcan, E. et al. (2019)

Asset replacement is considered simultaneously an investment decision aiming to maximize profitability, prevent severe risks and maintenance costs caused by old assets and sustain production performance quality. Still, companies struggle to find the correct answer to these questions:[161]

- Repair or replace the asset?
- When to replace the asset to incur less O&M and capital immobilization costs and generate more profit?

While premature asset replacement brings losses to the company instead of profits, keeping old assets longer than their expected optimal lifetime results in high safety and environmental risks, high energy consumption, lower asset availability, and high maintenance costs. Whether repairing, improving, or replacing the asset, the trade-off between the expected benefit and costs associated with each decision should be considered to obtain the best deal with a higher value.[162] Thus, a replacement plan that considers all the factors that influence the decision-making process and leads to an optimal decision should be developed in the framework of the asset management evaluation system. The following are the most commonly used terms in regard with asset improvement/replacement:

Overhaul: Preventive actions carried out at specified intervals or after a specified number of operations to sustain the performance of the equipment at the desired level; this may include complete or partial disassembly of the equipment.[163]

Rebuilding: Measures to dismantle the asset to repair or replace the components nearing the end of their useful life or needing to be replaced regularly. Rebuilding aims to extend the useful life of the asset. ISO 13306 states that rebuilding, as opposed to overhaul, might involve modifications, improvements, or modernization.[164]

Modification: „Combination of all technical, administrative and managerial actions intended to change one or more functions of an item."[165]

Modernization: „Modification or improvement of the item, taking into account technological advances, to meet new or changed requirements."[166]

Obsolescence: An item (tangible) becomes obsolete and unmaintainable when its essential resources, such as its sub-items, software, or necessary know-how, are no longer available on acceptable technical and/or economic terms. This resource unavailability may be due to technological changes, the market situation, regulations, or the fact that the manufacturer no longer produces the item with the original specification. Also, it is essential to understand that obsolescence is not the same as aging.[167] BS EN IEC 62402 lists materials, chemicals, components, electronics, and mechanical hardware as examples of the item. Obsolescence management aims to mitigate the

[161] Refer to Madusanka, W. M. L. et al. (2016), p. 5
[162] Refer to Madusanka, W. M. L. et al. (2016), pp. 931
[163] Refer to BS EN 13306: 2017-11, p. 43
[164] Refer to BS EN 13306: 2017-11, p. 45
[165] BS EN 13306: 2017-11, p. 37
[166] BS EN 13306: 2017-11, p. 37
[167] Refer to BS EN 13306: 2017-11, pp. 23

components and equipment's obsolescence over their expected useful life and the potential risk through planned measures and upgrades.[168]

5.3.1 Factors involved in the decision-making process

HARTMAN (2004)[169] considers the replacement of multiple assets in his work, and YATSENKO and HRITONENKO (2015)[170] consider finite time horizon asset replacement in their work. This thesis focuses on entire asset replacement, considering a finite time horizon. In the literature, many factors have been introduced that influence the strategic decision to repair/improve/replace assets. The factors listed below are a selection of these.

Asset reparability: An asset's repairability depends on the number of its obsolete components. If most of the asset's components are no longer functional, repair may no longer be profitable, given the associated costs. The availability of spare parts and qualified technicians are other parameters that play a role in this context.[171]

Spare parts availability: Availability of spare parts is one of the factors that should be considered with great importance in repair/replacement decisions. The number of available manufacturers, the expected remaining life of the equipment, and the ratio between available stock and consumption rate are some other parameters in this context.[172]

Technology: Industry 4.0 is characterized by digitalization, IoT, CPS, and AI, leading to better communication, remote control, and real-time data collection, e.g., vibrations, for implementing predictive maintenance. Retrofit, as a cost-effective solution, leads to the upgrade of assets by equipping them with sensors or connecting them to an external embedded system or CPS to make them compatible with the latest Industry 4.0 technologies.[173] On the other hand, the technology can be represented by new equipment that can perform two tasks parallelly, saving time and workforce compared to the old equipment. If the asset is technologically obsolete and retrofitting is also not economically and/or technically feasible, replacing the asset might be a better solution, as the new asset has lower O&M costs and performs better.[174] Consequently, all factors must be considered together to determine whether the switch to the latest technology is worthwhile. In reality, however, it is difficult to determine all these characteristics or the rate of technological change for future decisions. YATSENKO and HRITONENKO (2015) consider replacement under both exponential and non-exponential technological change rates to calculate replacement cost and optimal lifetime.[175]

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168 Refer to IEC 62402: 2019-05, pp. 12
169 Hartman, J. C. (2004)
170 Yatsenko, Y.; Hritonenko, N. (2015)
171 Refer to Madusanka, W. M. L. et al. (2016), p. 939
172 Refer to Rojo, F. J. R. et al. (2012), p. 5
173 Refer to Al-Maeeni, S. S. H. et al. (2020), pp. 369
174 Refer to Theron, E. (2016), p. 43
175 Refer to Yatsenko, Y.; Hritonenko, N. (2015)

Replacement asset value (RAV): The replacement asset value is the cost to replace the old asset with an identical new asset with the same functions.[176] Organizations use the world-class RAV to estimate the maintenance costs as a percentage of RAV for an asset in its early stage or to evaluate the maintenance costs of the asset over its lifetime.[177] It indicates whether the asset's maintenance costs are proportionate; for manufacturing companies, a range of 3% to 8% of RAV is given, although most fall in the 4% to 7% range.[178]

Assets criticality: Asset criticality is another factor that must be considered in decision-making to avoid any hazardous consequences and high maintenance costs. In this context, a highly critical asset requires more in-depth analysis before being upgraded or replaced.[179]

Sunk cost: Sunk costs are those costs that have already been expensed and cannot be recovered. An asset with high acquisition costs and other significant costs already spent on it is most likely to be retained until the end of its remaining useful life to make the best use of its capacity.[180]

Capital Budget: The capital budget limits the allowable funding for investment in new assets. The organization must undertake the repair if it cannot afford the new asset acquisition costs for the current or next fiscal year.[181]

Risk cost: Estimated risk cost, obtained by multiplying the risk probability and the resulting cost, should be considered in the LCC calculations of the old asset.[182]

Spend limit: The spend limit is set by organizations to restrict the amount allowed to be spent on asset improvements. This factor is determined based on the age and type of the asset and the alternatives available to replace it. Therefore, asset replacement shall be chosen if the estimated improvement costs exceed the expenditure limit.[183]

Asset economic life: The economic life of an asset is different from its physical life. The economic life, defined as the optimum age for replacement of the asset, is the age at which the total cost of the asset over its lifecycle is the lowest, shown in Figure 16.[184]

Ownership cost, also known as capital cost, consists of the cost of debt and the cost of equity, which decreases with the age of the asset. The cost of debt is the interest rate on e.g. the loan that the company owes to a bank or other sources. Equity cost is the money provided by investors, and the company owes them.[185] The cost of capital, disregarding the time value of money, can be calculated as the result of the acquisition cost less the resale value of the asset at the time of replacement divided by the age of the asset at the time of replacement. Fixed costs refer to the steady costs over the asset

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176 ServiceChannel, https://servicechannel.com/blog/balance-replacement-asset-value-maintenance-cost/ (Retrieved: 02.08.2022)
177 Refer to Mitchell, J.S. (2002) quoted by Schuman, C. A.; Brent, A. C. (2005), pp. 571
178 Refer to Campbell, J. D.; Reyes-Picknell, J. V. (2015), p. 198
179 Refer to Madusanka, W. M. L. et al. (2016), p. 940
180 Refer to Barham (2015) quoted by Madusanka, W. M. L. et al. (2016), p. 937
181 Refer to Madusanka, W. M. L. et al. (2016), p. 940
182 Refer to Hastings, N. A. J. (2021), p. 553
183 Refer to Hastings, N. A. J. (2021), pp. 551
184 Refer to Hartman, J.C. (2001) quoted by Theron, E. (2016), p. 32
185 Refer to Theron, E. (2016), p. 57

lifecycle; in other words, they are independent of the asset age and, therefore, can be ignored in economic lifetime calculations.[186]

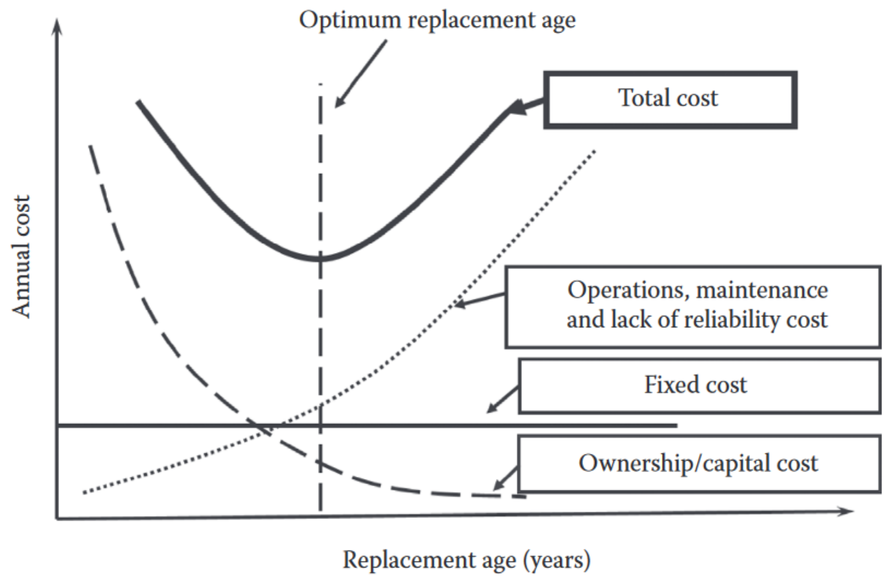

Figure 16: Asset economic life[187]

Economic life analysis is based on equivalent annual cost (EAC), and the optimal time is obtained by comparing the EAC over the life cycle; the year with the least value is considered the optimal time to replace the asset. In this context, LCC analysis assists in determining the asset's economic life. The United States Department of Energy provides a comprehensive definition of LCC: „The sum total of the direct, indirect, recurring, nonrecurring, and other related costs incurred or estimated to be incurred in the design, development, production, operation, maintenance, support, and final disposition of a major system over its anticipated useful life span. Where system or project planning anticipates use of existing sites or facilities, restoration and refurbishment costs should be included."[188] For LCC calculation, it is also necessary to know some financial basics:

Interest rate (r): The interest rate is the amount that must be paid as the cost of borrowing money and is expressed as a percentage of the total amount borrowed.[189]

Discount Factor (p): It is used to compute the present value (PV) of the future cash flows, calculated as shown in Equation 17:

$$p = 1 \,/\, ((1 + r))$$

Equation 17: Discount factor[190]

Net present value (NPV): NPV compares the value of money today with its value in the future, calculating the present value of a series of future values received or spent over certain years. NPV is a powerful tool for investment decision-making, in this case, asset acquisition, as it helps to calculate the net present value of the estimated expected costs

[186] Refer to Campbell, J. D.; Reyes-Picknell, J. V. (2015), p. 337
[187] Source: Campbell, J. D.; Reyes-Picknell, J. V. (2015), p. 337
[188] Cost Estimating Guide (1997), p. A-13
[189] Refer to Hastings, N. A. J. (2021), p. 103
[190] Hastings, N. A. J. (2021), p. 104

and returns of the asset to be acquired and compare this to the costs and gains of the existing asset.[191]

Consider n as the age at which replacement occurs, A as the asset acquisition cost, M_i as O&M cost in the year i (for each period, i = 1, 2 ..., n, is a period-end payment assumed), and S_n as resale value at the replacement year, so the NPV of the asset over n years is calculated as shown in Equation 18:

$$NPV = A + \sum_{i=1}^{n} p^i \, M_i - \, p^n S_n$$

Equation 18: NPV calculation[192]

Equivalent annual cost (EAC): „EAC is the amount of a regular annual cost which, over a given period of years, has the same net present value as any given series of costs. The EAC converts the NPV into an equivalent annual amount."[193] EAC is calculated as shown by Equation 19:

$$EAC = \frac{r \times NPV}{(1 - p^n)}$$

Equation 19: EAC calculation[194]

Note: It has been shown that in most cases, the salvage value can be neglected in the calculations, as it mostly does not have a high value at the end of the asset's life.[195]

Nevertheless, LCC has some limitations, considering the amount of data required and the difficulties in estimating costs for calculations. In addition to economic life, the term "useful life" is also used in the literature. ISO 13306 defines useful time as the „time interval from first use until the instant when a limiting state is reached"; the term first use does not include testing activities conducted before its delivery to the end user. This limiting state may be a specific age, physical condition, failure rate, or other relevant factors.[196]

It is worth still emphasizing that the calculated economic life of the asset is less than its lifetime. Therefore, it should not be the sole determining factor considered in the asset replacement decision, and not to replace the asset just as it reaches its economic life. This factor must be considered along with other factors in the decision-making process to prevent premature replacement and unnecessary investment.[197]

Like-with-Like Replacement: In the case of like-with-like replacement, the LCC approach is used to estimate and compare the current costs of the old asset (current as we do not consider the sunk costs) vs. the costs associated with the new asset, incl. its acquisition costs, estimated O&M and salvage costs, calculated into its EAC. The old asset will then be replaced when its current year costs exceed the EAC of the new asset.

[191] Refer to Hastings, N. A. J. (2021), pp. 105
[192] Hastings, N. A. J. (2021), p. 538
[193] Hastings, N. A. J. (2021), p. 108
[194] Hastings, N. A. J. (2021), p. 538
[195] Refer to Regnier et al., 2004 quoted by Yatsenko, Y.; Hritonenko, N. (2015), p. 5
[196] BS EN 13306: 2017-11, p. 22
[197] Refer to Theron, E. (2016), p. 40

As shown in Figure 17, if the old asset's annual costs increase steadily, the replacement takes place in the year before the old asset's costs exceeds the EAC line of the new asset. In this example, the second year is the year to replace the old asset.[198]

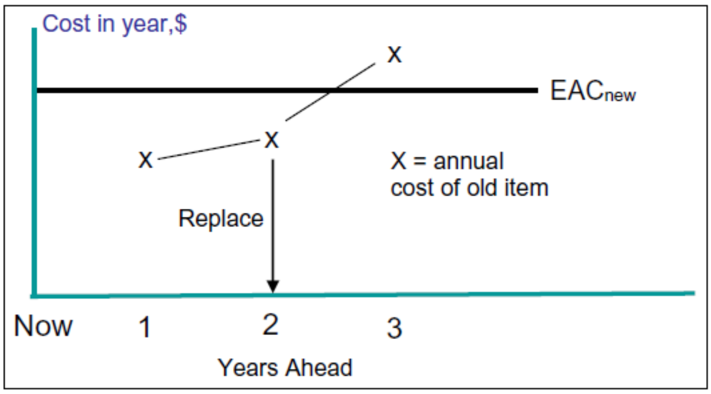

Figure 17: Replacement analysis - steadily increasing costs[199]

Savings: In this case, the estimated cumulative costs of the old asset over the coming years will be compared to the EAC of the new asset, and the year at which the savings are maximum is the asset's optimum replacement age, as shown in Figure 18.[200]

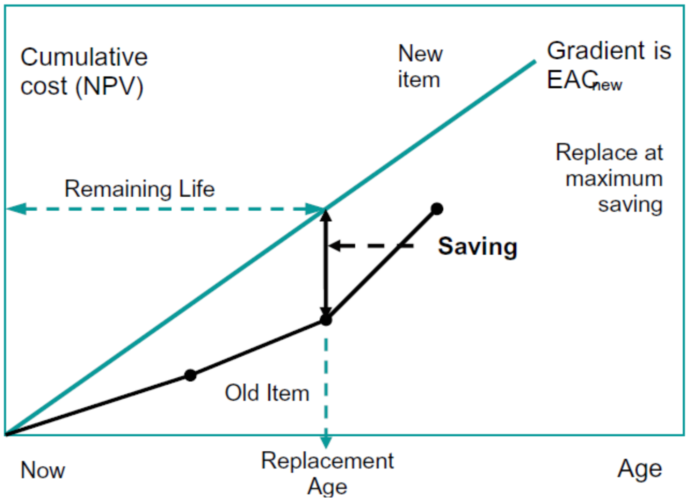

Figure 18: Replacement analysis - cumulative cost comparison[201]

Asset improvement costs: Costs associated with the overhaul or retrofit of the old asset need to be estimated to check which of them are economically accepted. These costs result from forecasts based on the number of assembly replacements or the expected retrofit cost. FERREIRA et al. (2019) consider the retrofit cost to the RAV ratio as one of the KPIs for the Improvement/ Replacement decision. [202] LCC helps to analyze and compare the cumulative cost curve for the old asset and the new asset's EAC line to determine if the proposed improvement is financially worthwhile. In the example shown in Figure 19, the improvement costs are initially higher than the EAC of the new asset.

[198] Refer to Hastings, N. A. J. (2021), pp. 548
[199] Source: Hastings, N. A. J. (2021), p. 549
[200] Source: Hastings, N. A. J. (2021), p. 549
[201] Source: Hastings, N. A. J. (2021), p. 550
[202] Ferreira, S. et al. (2019), p. 1431

However, the costs will fall below the EAC of the new asset in subsequent years, which proves that the improvement is worthwhile. Also, the maximum savings is reached in the third year, which is the optimal remaining lifetime of the old asset.[203]

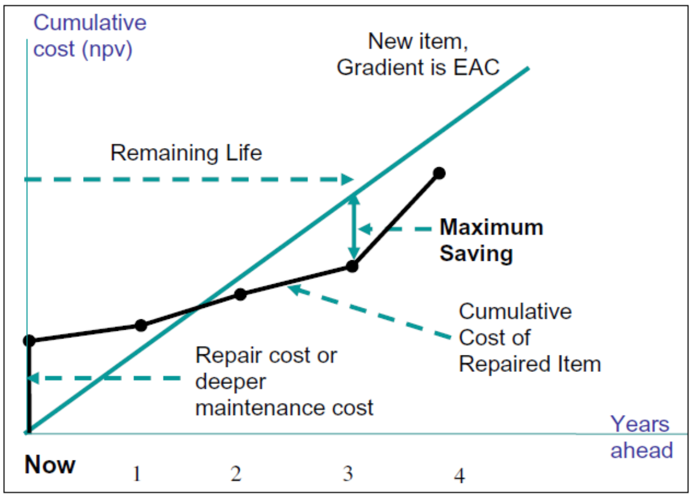

Figure 19: Variable cost case[204]

Lead time: Another factor to consider when replacing equipment is the lead time, i.e. the time from ordering the new equipment, incl. all necessary steps such as feasibility studies and equipment design, to handing over the equipment to the organization and performing all acceptance tests. If the lead time is quite long, it makes sense to repair and use the old equipment, and then replace it when the new equipment arrives and is ready for operation. ABDI and TAGHIPOUR (2019) call this situation "repair-and-replace."[205]

Finally, it should be noted that a degree of uncertainty and risk is involved in decision-making, and moreover, all factors must be viewed together in the decision-making process. It also needs to be emphasized, that the outcome of the physical asset improvement/replacement decision is still mostly dependent on the discretion of the decision-making team or organization's business units' heads. Given all these factors, Section 5.4 discusses the action plans to be derived based on the assets' criticality and the factors mentioned in this section.

5.4 Decision finding – KPI-driven action plan

This section addresses the determination of appropriate actions based on the condition and criticality of the asset, i.e. maintenance strategy and resource adjustment, asset improvement actions such as retrofit, or replacement of the asset. For assets that are nearing their defined end of life or are becoming obsolete, the factors outlined in Section 5.3.1 help to decide whether improvements are technically and economically feasible. If

[203] Refer to Hastings, N. A. J. (2021), pp. 550
[204] Source: Hastings, N. A. J. (2021), p. 551
[205] Refer to Abdi, A.; Taghipour, S. (2019), p. 120

the decision leads to the asset replacement, financial calculations are required for the timely replacement of the asset.

Section 5.2 presented methods for determining asset criticality. Applying one of these methods determines the asset criticality, and the asset priority portfolio can be created, as shown in Figure 20.

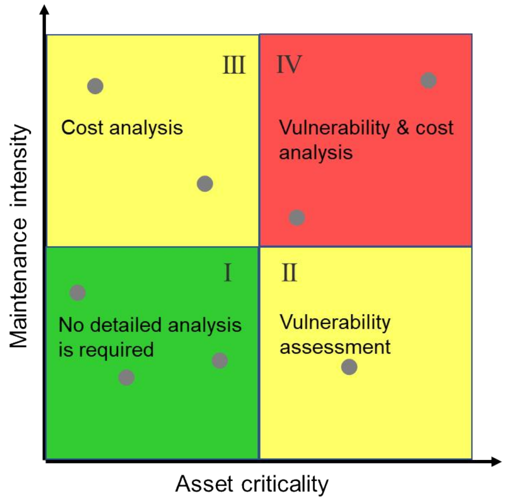

Figure 20: Asset priority portfolio[206]

The priority portfolio, divided into four fields, represents the maintenance intensity on the Y-axis and the criticality number of the asset on the X-axis. The portfolio limits should be set on both axes. The cut-off on the X-axis is in the middle between the minimum and maximum values of the criticality determination. The cut-off on the Y-axis depends on the cost evaluation method. Pareto analysis or calculating the mean of maintenance costs as the cut-off are two ways of determining the cut-off on the Y-axis; the Y-axis in the KINZ ET AL. (2017) work represents maintenance costs. [207] As mentioned earlier, one of the main features of the model is its adaptability. Therefore, the portfolio, incl. the defined boundaries, can be adapted depending on the organization's perspective. The organization must determine from which criticality number the asset is considered critical and what level of maintenance intensity is deemed high.[208]

Assets are placed in one of these four fields based on their criticality rating and maintenance intensity percentage. Figure 21 provides an overview of the following steps and actions to be taken, given the asset position in the priority portfolio. The logical sequence illustrated in Figure 21 shall assist decision-makers through the decision-making process. As shown in Figure 21, the assets in area I do not require detailed analysis as they are neither critical nor have a high maintenance intensity. The assets within field II are suspected to be under-maintained because they have a high criticality score, while the assets within field III are suspected of being excessively maintained as they have a low criticality value. Therefore, the assets within field III must be subjected to a cost analysis.[209]

[206] Source: Kinz, A. et al. (2017), p. 196 (slightly modified)
[207] Kinz, A. et al. (2017)
[208] Refer to Biedermann, H.; Kinz, A. (2021), p. 170
[209] Refer to Biedermann, H.; Kinz, A. (2021), pp. 180

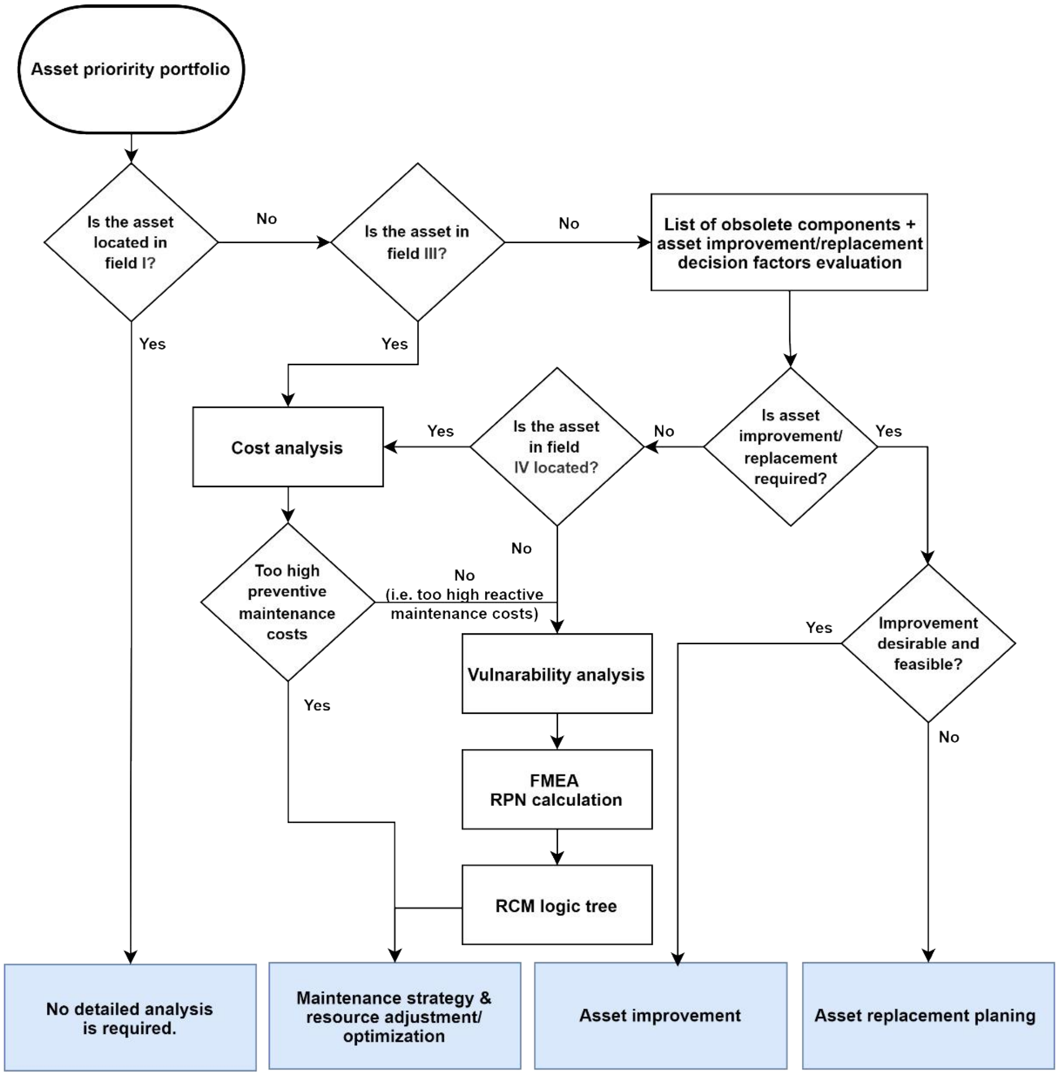

Figure 21: Action plan logic tree[210]

Assets in areas II and IV should be evaluated based on the factors defined in section 5.3.1 to verify their economic life, availability of spare parts, and other relevant factors that influence the decision-making process for asset improvement/replacement. Obsolescence is a significant issue in this context, especially with old equipment once it reaches a point where spare parts or technical support are no longer available.[211] Therefore, Obsolescence is a decisive factor for the next steps and should be given a high weight. For instance, HASTINGS (2021) provides the replacement logic tree considering factors in Section 5.3.1, as shown in Figure 22.

The selection of decision parameters from Section 5.3.1 for this part is entirely dependent on the organization, especially on the data available in the organization and the organization's investment strategies. The factors selected at this stage can also be evaluated using the AHP approach and be assigned a weighting factor based on their importance/relevance to the asset improvement/replacement decision. In case the asset improvement is required but is not feasible, the asset should be replaced. This also

[210] Source: Own representation refer to Kinz, A. et al. (2017), p. 204
[211] Refer to Hastings, N. A. J. (2021), p. 545

applies when the asset is obsolete, and improvement is no longer reasonable. Therefore, asset replacement and new asset acquisition should be planned in advance.

Unfortunately, there are not enough sources in the literature pointing out at what point asset improvement besides financial aspects is considered futile.

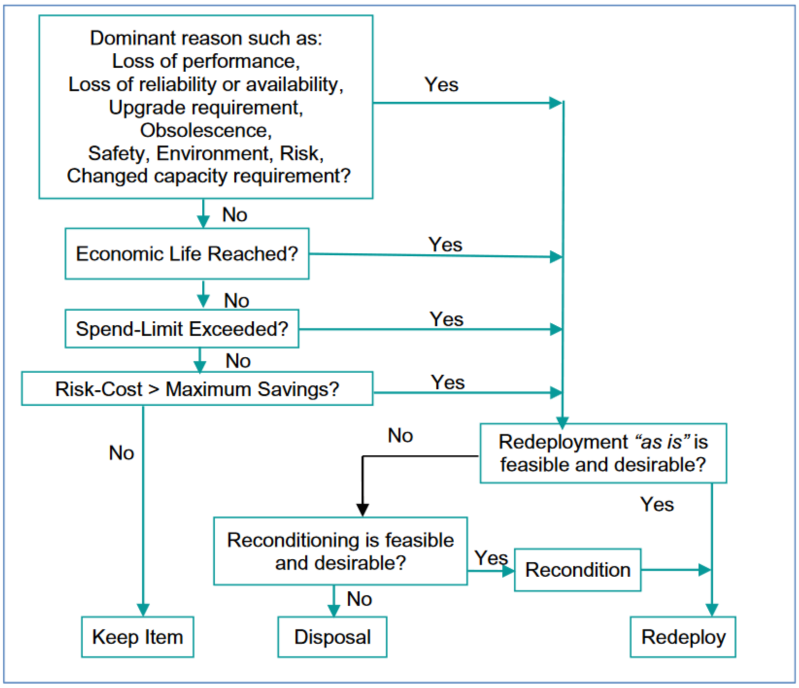

Figure 22: Replacement analysis flow chart[212]

If, on the other hand, asset improvement/replacement is not required, further detailed cost and vulnerability analyses must be performed for maintenance strategies and resource optimization. Assets within fields II & IV are subjected to vulnerability analysis. By performing an in-depth analysis, it is helpful to divide the workstation or a unit into its equipment and consider each asset individually. In addition, for more complex equipment, it makes sense to perform the analysis at the assembly level.[213]

The cost and vulnerability analyses are discussed in detail as follows:

5.4.1 Cost analysis

For the cost analysis, first the type of costs and their origin must be determined, classified as follows, to analyze the main cost drivers in more detail:[214]

- Unplanned/planned personnel costs
- Unplanned/planned external activity costs
- Unplanned/planned material costs

The individual maintenance orders for the observed period should be summarized and sorted according to their cost amount to identify the most significant cost drivers. Distinguishing maintenance costs by the categories listed above, also differentiating

[212] Source: Hastings, N. A. J. (2021), p. 546
[213] Refer to Biedermann, H.; Kinz, A. (2021), pp. 180
[214] Refer to Biedermann, H.; Kinz, A. (2021), pp. 182

between planned and unplanned costs, is case-specific and must be decided by the organization, but it is advisable to do so. It is essential to clarify the service type for the costs incurred (equipment maintenance, inspection, improvement, etc.). For instance, an asset’s high maintenance costs might be due to its planned improvement and not due to its repair. If the highest cost drivers result from planned (preventive) maintenance, then maintenance strategies need to be investigated. The goal is to evaluate current and alternative maintenance strategies to determine an optimal strategy and optimize the allocation of maintenance resources. In this context, a cost-benefit analysis considering maintenance costs is required when implementing new measures. In addition, changes in equipment criticality, product quality, and other factors such as HSE must be considered when determining new measures. As a result, the proposed alternative measures should compare the actual cost and criticality of the asset to the same expected factors resulting from those measures. The goal is to find an optimal balance between the asset's minimum maintenance cost and minimum criticality.[215]

If there is no suitable alternative that improves the situation and provides a cost-effective solution, then the issue could be due to inefficiencies in maintenance execution and management, so they must be evaluated by maintenance controlling and considered at a strategic level.[216] SCHUMAN and BRENT (2005) also suggest that if no suitable strategy is found, the reactive maintenance approach is to be adopted.[217]

Suppose the highest cost drivers are unplanned (reactive) maintenance costs. In this case, the root causes of the costs are to be determined using vulnerability analysis and a more detailed assessment of the cost drivers (if necessary, at the level of subcomponents and components). It mainly concerns the assets within area IV. Therefore, cost analysis for this area has precedence over vulnerability analysis.[218]

5.4.2 Vulnerability analysis

DIN 31051 defines vulnerability as the „unit where failure occurs more frequently than is consistent with the required availability and where improvement is possible and economically feasible.”[219] Vulnerability analysis examines the causes of component failures or damage; the vulnerabilities could have been caused by the reasons below:[220]

- Information management system issues due to inadequate information technology support, data deficiency, interface problems in integrating systems, etc.
- Process-organizational weaknesses due to inefficient maintenance procedures, such as unclear process flows.
- Incorrect maintenance implementation
- Improper operation and handling of equipment
- Structural-organizational weaknesses, e.g. unclear clarification and assignment of responsibilities, poor runtime scheduling

[215] Refer to Biedermann, H.; Kinz, A. (2021), pp. 182
[216] Refer to Biedermann, H.; Kinz, A. (2021), p. 193
[217] Refer to Schuman, C. A.; Brent, A. C. (2005), pp. 574
[218] Refer to Biedermann, H.; Kinz, A. (2021), pp. 182
[219] DIN 31051: 2012-09, p. 7
[220] Refer to Biedermann, H.; Kinz, A. (2021), pp. 184

- Asset-related weaknesses due to obsolete components, age of equipment
- Inadequate plant infrastructure and environment (e.g., plant location, vibration, or temperature in the plant surroundings can contribute to plant failures)
- Health, Safety and Environmental (HSE) risks

Consequently, as a further step, the RCM approach assists in identifying component failures. As discussed in Section 5.2.1, by applying the risk level matrix RPN for each failure mode can be calculated determining intolerable risks. Thereafter, the RCM logic tree can be applied to items (assembly group, component, …) with high RPN to prevent failure occurrences and optimize maintenance strategies.

5.4.2.1 Reliability Centered Maintenance (RCM)

Reliability Centered Maintenance is a methodology that goes beyond failure detection and aims to develop a meaningful and valuable mechanism for improving maintenance strategies. RCM integrates reactive, preventive, predictive, and proactive maintenance practices and their strengths to define the most suitable and tailored maintenance strategy for each asset and its components based on asset criticality and reliability parameters.[221]

When a comprehensive analysis is needed, RCM is the ideal approach.[222] By implementing RCM, the risk of failure should be reduced by improving asset reliability and minimizing or eliminating the failure consequences. As a result, asset availability will increase, repair and downtime costs will be diminished, and the asset can be utilized for a longer time. On the other hand, maintenance activities are focused on the most critical assets, while unnecessary maintenance activities are avoided.[223] Maintenance, engineering, and management expertise deliver the knowledge for successful RCM implementation, and communication between them plays an important role.[224] RCM analysis builds on the following seven main questions:[225]

1. Given the current operating environment of the asset, what are the asset function and performance standards?
2. In what way can the functional performance of the equipment be disturbed?
3. What are the functional disturbance causes?
4. What happens when each failure occurs?
5. What are failure consequences, and how significant are they?
6. What measures are required to prevent the failures?
7. In case no suitable preventive measure can be found, what should be done? (Actions like design change or reactive maintenance)

Consequently, RCM minimizes possible adverse safety and environmental consequences, prolonged asset lifetime, higher asset availability, improved quality and customer service, and maintenance resource optimization by deriving suitable tasks and

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[221] Refer to Vishnu, C. R.; Regikumar, V. (2016), p. 1082
[222] Refer to Hastings, N. A. J. (2021), p. 466
[223] Refer to Chopra, D. A. (2021), p. 15
[224] Refer to Hastings, N. A. J. (2021), p. 466
[225] Refer to Eriksen, S. et al. (2021), p. 2

eliminating unnecessary maintenance tasks resulting in reduced costs and increased productivity. Documentation of all performed steps, analyses, and results is essential when performing RCM.[226] Appendix A provides an overview of the RCM logic tree; a more detailed discussion of this topic is beyond the scope of this study.

All in all, as already mentioned in Section 5.1 and illustrated in Figure 14, Performance evaluation is essential to assess the successful implementation of the asset management framework developed and to optimize and/or define new strategies. The assessment is carried out at least once a year to review the maintenance cost reduction and asset criticality mitigation improvements. Furthermore, the CAPEX budget for replacement and new investments, as well as the O&M costs for the next fiscal year, are forecasted. Needless to say, changes require a certain amount of time to take effect. Therefore, their effectiveness can only be assessed after a sufficiently long period of time. Altogether, the asset criticality assessment and subsequent steps should be performed annually (or at intervals determined by the organization) to reassess the assets' criticality based on their current condition, review the AMS performance, and enhance it.[227]

[226] Refer to Tale, T. (2019), p. 7
[227] Refer to Biedermann, H.; Kinz, A. (2021), p. 197

6 Practical case study

The practical part of this thesis is defined and applied by the BRP-Rotax company to evaluate the suitability and validity of the theoretical framework developed in Section 5 in a practical decision-making environment. Therefore, this chapter starts with the actual state analysis and the current AMS assessment of the company. Next, Section 6.2 addresses the development of the AMS for the company through the selection of KPIs for asset criticality assessment, the weighting of these KPIs, and the creation of the risk priority portfolio. Section 6.3 then covers the implementation of the developed AMS for the selected machine park. This chapter ends with the proposed measures for the selected assets.

6.1 Introduction

BRP-Rotax GmbH & Co KG, based in Gunskirchen, Upper Austria, is the subsidiary of BRP Inc, specializing in the development and production of drive systems for recreational and power sports vehicles. Founded in 1920, BRP-Rotax has developed 350 engine models over the past 50 years and is also a pioneer in the field of alternative drive models. BRP-Rotax manufactures core components such as cylinder blocks, cylinder heads, and crankshafts for four-stroke and two-stroke high-performance engines used in its products. BRP-Rotax products include Ski-Doo and Lynx snowmobiles, Sea-Doo personal watercraft, Can-Am on-road and off-road vehicles, as well as high-quality engines used and operated in motorcycles, karts, and in light and ultralight vehicles. Industry 4.0, automation technology and digital assistance systems are some of the current topics BRP-Rotax deals with.[228]

6.1.1 Current state analysis - Rotax Asset Management System

BRP-Rotax's manufacturing division consists of four business units (BU), namely the Crankshaft and Camshaft (CCK), Turbo Systems and Connecting Rods (CCT), Work Specific Components (CCS), and Cylinder Head and Casing (CCZ) departments. Each BU consists of several departments and is headed by the respective business unit head. Each BU has its own AM team, which is responsible for the representative BUs and manages its own production unit. In other words, each BU team/BU manager is responsible for evaluating the assets of the associated BU. The assets are evaluated based on six common KPIs presented in the next section. The current AMS of BRP-Rotax is managed by the Central Maintenance (CM) department, which takes care of the strategic planning, while the decentralized maintenance handles the operational part.

One of the major challenges encountered during the as-is analysis, is the large gap between the data required for the successful AMS implementation and the data available

[228] Rotax, https://www.rotax.com/en/100-years/company-history.html (Retrieved: 11.10.2022)

at BRP-Rotax. Additionally, when data are available, they are often unreliable due to the lack of an appropriate AM software for data maintenance, the lack of documentation, and the fact that most data are entered by the machine operator rather than systematically, which calls into question the accuracy of the data. On the other hand, as mentioned earlier, each BU team only deals with its assigned BU, so each BU has its own approach for calculating and weighting the same KPIs, assessing asset criticality based on those KPIs, and, in a nutshell, for the AMS implementation. Each BU knows its own focal assets, as these usually require a high level of attention due to their low availability or high fault frequency. Therefore, each BU focuses mainly on those assets what it considers to be the most critical ones, as the performance of each BU is determined by the performance of the critical assets assigned to it. This type of evaluation runs the risk of producing a subjective result based on the experience of the evaluator, making it difficult to compare results with those of another BU.[229]

Chapter 3 addressed the AMS interfaces and their role within the AMS. It is important to view the AMS with all its interfaces to ensure a successful implementation of the AMS. Unfortunately, within BRP-Rotax there is usually no data exchange between different management systems with the AMS. As an example of the issues mentioned above, there are different approaches for calculating the KPI scrap rate and the asset analysis based on it. In addition, the data regarding the causes of scrap are entered manually, so there is a relatively high influence of the human factor here, firstly to enter the data at all and secondly to select the cause of scrap correctly. Data evaluation and results are entered into Excel files, which counteracts the lack of suitable software and its accessibility to other management systems such as AMS. As a result, the AM team often has to request the latest Excel file from the associated management system.

Regarding the asset improvement/replacement, the decision at BRP-Rotax is strongly driven by the availability of spare parts; retrofits are also relatively infrequent. Moreover, cost analysis is neither performed for comparing the costs of old and new assets ($NPV_{old\ equipment}$ vs. $EAC_{new\ equipment}$), as introduced in Section 5.3.1, nor for analyzing the maintenance costs of the old assets and estimating their economic life. The only cost analysis performed when making investment decisions is to estimate the acquisition cost and calculate the internal rate of return (IRR) for the new assets. Not to mention that many other factors, such as the investment budget set by the parent company and the capital tied up (e.g. when there are so many manufactured products in stock that only the most urgent investments may be made), also play an important role in strategic asset improvement/replacement decisions that cannot be converted into KPIs but are mostly situation dependent.

6.1.1.1 BRP-Rotax current asset criticality assessment system

The BRP-Rotax implemented asset evaluation framework consisted of six KPIs as listed below:

- Capacity and utilization: This KPI measures to which extend the asset is utilized compared to its maximum possible utilization. The worst case is defined as when

[229] Refer to Biedermann, H.; Kinz, A. (2021), p. 170

the asset is used to the maximum capacity but would be required to operate at more than 125% of its maximum possible capacity. The best case, on the other hand, is when the asset is being used at less than 50% of its capacity. A critical aspect of this KPI is that the equipment capacity utilization depends on seasonal fluctuations respectively calendar time, and planned downtimes. For this reason, this KPI is not suitable to be considered for the asset criticality evaluation.

- Compliance with regulations: This KPI considers compliance with all defined HSE regulations. However, no detailed explanation or measurable parameter is defined for this KPI.
- Asset technical condition: This KPI addresses the maintenance cost of the asset compared to the expected average cost for comparable assets, the asset's attrition rate, and the degree to which the asset meets reliability requirements. The problem, however, is that there simply exists no quantitative data defined to evaluate the reliability of the asset, the maintenance cost, or the wear rate with it. In short, this KPI is defined so imprecisely and is evaluated almost only by the opinion of the evaluator.
- Spare parts availability: The expected availability period for the critical spare parts, the delivery times, and the procurement effort required to obtain the spare parts that are not available on the market are included in this KPI. According to the equipment performance specification, the manufacturers supplying BRP-Rotax equipment are obliged to provide the required spare parts as well as the maintenance software serviceability and required hardware for 10 years. For this reason, the latter KPI and the following KPIs receive points based on the period of 10 years and more. For example, the highest score i.e. 2, is given to the case where the availability of spare parts is expected in the next 10 years and critical parts are available at the site. The criticism on this KPI is that, firstly, there is no 10-year warranty from the suppliers, but this is only a written condition requested by BRP-Rotax. In fact, the supplier only provides a two-year warranty. Moreover, this KPI is defined in such a general way that it does not specify which delivery time is then defined as acceptable or unacceptable
- Software serviceability: This KPI concerns the availability of programming devices, executable maintenance software, suitable hardware and qualification of employees, and the period for which these factors are available. Though, after meetings with IT-experts, it turned out that this KPI is only defined in the AM framework, but no detailed analysis is performed nor is available in the system so far in terms of asset criticality assessment.
- Effectiveness and efficiency: This KPI examines raw material, fuel, and energy consumption as well as the technology status of the equipment. The technology is evaluated by the company in terms of personnel savings, e.g. if the company needs two fewer machine operators to work with the new asset than with the old one, the new asset would be more efficient.

Overall, the criticism of these KPIs is that they are all divided into parameters that do not reflect any quantitative data but are based on subjective descriptions and assessments. In addition, the descriptions are too general and do not include further details. On the other hand, most of these KPIs are listed in the assessment model but are not used appropriately by the associated management system.

As for the validation logic of the mentioned KPIs, all KPIs have the same weight and are divided into five categories reflecting the possible parameters for each KPI. Then, the asset is rated based on its current condition and the associated parameters for each KPI on a rating scale from -2 to 2, where 2 represents the new condition of the asset or the best case and -2 represents a high-risk condition. The individual KPIs are then colored based on the score obtained, with each color representing a level of risk. Consequently, the measures are derived based on the asset's final score represented in color, as shown in Figure 23.

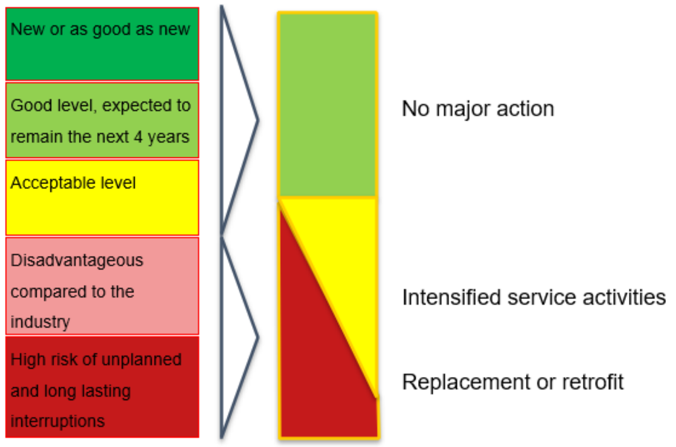

Figure 23: Color-based validation logic by BRP-Rotax[230]

This evaluation method is performed based on assumptions to predict the criticality of assets for the next three to five years and also after investment (either retrofit or replacement). Figure 24 shows this matter perfectly. Assessments are then conducted every six months and the high-risk equipment are prioritized in a retrofit/replacement list for investment decisions and CAPEX estimates.

Asset	Present						In 3-5 years						Condition after investment					
	capacity	compliance	technical condition	Spare parts availability	software	Effectiveness and efficiency	capacity	compliance	technical condition	Spare parts availability	software	Effectiveness and efficiency	capacity	compliance	technical condition	Spare parts availability	software	Effectiveness and efficiency
Machine A	-2	0	-2	-2	-1	0	2	0	0	-2	-2	0	2	0	0	-2	-2	0
Machine B	2	0	-2	-2	-2	0	2	0	-1	-1	-2	0	2	0	0	-1	-2	0

Figure 24: Asset criticality assessment example by BRP-Rotax[231]

6.1.2 Determining the target situation

The last section provided an insight into the implemented AMS at BRP-Rotax and the challenges for its successful implementation. Therefore, developing a structured asset management assessment model is essential for the company. As a first step, a team of experts from the CM department is formed, in direct contact and data exchange with other management systems, to define the target situation and to develop the required AMS framework, presented in the following sections. The goal is to define new KPIs based on available and reliable data on the company, determine the KPI's weighting

[230] Source: The current AMS Excel file of BRP-Rotax
[231] Source: Own representation

approach and to weight them, and subsequently to develop a strategic decision-making AMS framework aligned with the company's goals. The developed framework enables the asset criticality assessment and aids the decision-makers in making asset improvement/replacement decisions. This would allow the company to achieve higher asset availability and OEE, avoid unplanned interruptions, and minimize costs and risks. The comprehensive literature basis developed in the last chapters serves as the foundation for this framework.

Another important objective in the development of the AMS framework is to either acquire enterprise asset management software or adopt BRP-Rotax's existing SAP system to meet the AMS data source requirements, incl. providing a platform for other management systems to feed their data and analysis instead of using Excel files, as well as providing all information accessible to the AMS. Also, continuous data exchange and communication between different management systems needs to be improved while developing the framework.

Consequently, the structured AMS delivers the following advantages:[232]

- Timely adaptation to changing environmental conditions by considering fluctuations in capacity utilization on the market side when prioritizing assets
- Involving AMS interfaces in the framework and consideration of all important influencing variables: Operational personnel evaluate assets based on their experience and do not consider all relevant perspectives. A structured AMS assists company to consider all relevant factors.
- Identification of all critical equipment, and not just those identified as critical by individual BUs
- Quantified comparability of assets
- Data and know-how exchange among different management systems
- Independence from the internalized knowledge of a few experts and involving the know-how of other experts

As the target situation is determined, the next step deals with the KPIs selection for the asset performance evaluation and criticality assessment. Section 6.2 shall elaborate on this topic.

6.2 The tailored AMS for BRP-Rotax

Chapter 5 of this thesis presented some standard methods for determining asset criticality, incl. KPIs-based approach as the selected method for the scope of the practical part. Hence, the expert team first shall define the potential KPIs based on the organization's requirements. As mentioned in Section 5.2.3, both qualitative and quantitative KPIs are allowed for the assessment model. Subsequently, the number of potential KPIs is to be narrowed down, considering the data available at BRP-Rotax and reducing the evaluation effort. One of BRP-Rotax's main expectations of the assessment model is that the model should assist decision-makers in asset retrofit/replacement decisions. In this context, the KPIs selected for asset criticality determination are those that address the factor machine rather than other factors influence such as the human

[232] Refer to Kinz, A.; Biedermann, H. (2015) quoted by Biedermann, H.; Kinz, A. (2021), p. 170

factor. For instance, for the KPI scrap rate those scrap figures are accounted that are caused by the equipment and not by faulty process or unqualified personnel.

6.2.1 Selection of implementable KPIs regarding AMS interfaces

This step consists of identifying potential KPIs that determine the asset's criticality and those that lead to the asset's retrofit/replacement. The next step is to reduce the number of identified KPIs to 5 to 10 KPIs in order to reduce the effort required for the criticality assessment; Section 5.2.3 discussed the concept of KPIs-based asset criticality evaluation approach in detail. Consequently, the outcome yields multiple KPIs that influence the strategic repair/replacement decision, which need to be integrated into the proposed AMS framework.

In selecting KPIs, emphasis is placed on those that have the greatest impact on BRP-Rotax performance and are also sufficiently meaningful to indicate asset criticality. In addition, the selection of appropriate KPIs must consider the availability, but also the trustworthiness and accuracy of the data sources, as the quality of the data collected plays an important role in achieving meaningful assessment results as well as deriving appropriate action plans. Eventually, assessment intervals need to be defined, i.e. how often assets need to be re-evaluated based on the defined KPIs.

6.2.1.1 Challenges by defining KPIs

To determine KPIs for the criticality assessment, numerous discussions, interviews, and workshops were conducted with the participation of the team of experts formed as well as those responsible for the associated management systems, such as facility management, quality management, the IT department and financial management. The goal is to ensure the availability and reliability of the data sources by selecting KPIs and to include the AMS interfaces in the framework development process so that the developed framework would be consistent with the objectives of the other management systems. However, it was a big challenge to find suitable, but also available and trustworthy KPIs. Below are some of the obstacles that hindered the process of KPI determination:

Problem 1: The production area of BRP-Rotax consists of several workstations, where one workstation often includes several machines as well as robots. Despite the existing equipment number for each asset, the data available in the company’s database, i.e. SAP system is only available at the workstation level. In addition to SAP, the Manufacturing Operation Cockpit (MOC) is also used to provide data on assets, such as asset failure history or asset availability; each asset has a MOC interface with which the shopfloor staff cooperates.

As mentioned, SAP does not provide data for the individual equipment, also the employees enter the confirmations in the system with the workstation number. The main problem is therefore that KPIs such as MTBF, MTTR, and quality rate are entered for the entire workstation and not for a specific machine. For example, workstation 1 includes 2 main machines, a robot, and a washing machine. The data available for the scrap rate represents this KPI's amount for the entire workstation 1, so this KPI cannot be evaluated for each machine individually.

Solution: For this reason, and in view of Section 6.3.1 for the model practicality verification, those assets are selected whose associated workstations contain comparatively less equipment or possibly only other ancillary equipment (such as robots, conveyors). In a further step, it is proposed to define the equipment numbers in the SAP system instead of the workstation numbers to be able to enter and evaluate data at the equipment level. This SAP conversion will be fully implemented by the end of March 2023.

Problem 2: As mentioned in Section 3.1, the interface between energy management and AMS should also be considered when implementing the AMS. Therefore, relevant EnPIs should be included both in the criticality assessment of the assets and in the replacement decision. As mentioned in the last section, in addition to the lack of required data, the main problem is that most of the data are not available at the asset level as they are entered and filed for the workstations; this problem also applies to the EnPIs. Data on energy consumption and CO_2 per production hour are currently measured and observed for the entire site and not for individual equipment. However, energy meters have been installed at all major equipment since 2015. Using an energy meter, it can be determined the amount of energy consumption over time by measuring the electrical power consumed.[233]

Solution: As for the analysis between the old and the new asset, some rules are considered in the equipment procurement, such as the minimum energy efficiency class that electric motors should have, or the required certificates and declarations of conformity. Nevertheless, there is currently no comparison between them for acquisition decisions, but it is planned to achieve this in the near future.

Problem 3: Process capability is the other factor to be considered as an adequate KPI for the criticality assessment. Process capability is defined as the suitability of a production process to reliably produce the generated features within the defined tolerance, i.e. upper specification limitation (USL) and lower specification limitation (LSL). Process capability can be used as the generic term for the machine capability, though machine capability serves as a short-term analysis especially used by equipment acceptance. Briefly explained, for the process capability analysis, typically 25 samples each consisting of 5 parts are taken from the continuous production process during a determined period and the values of the characteristic under investigation are measured to check if they lie within the scope of tolerance limits. All the parameters influencing the process, such as batch changes, shift changes, changes in room temperature should be captured during analysis.[234] Using process capability and transforming real-time data into state data, the equipment reliability respectively the operation stability can be assessed, and the equipment fault can be diagnosed. Indices C_p and C_{pk} are the most known used parameters for the process capability and performance determination.[235] More details on

233 Finder, https://www.findernet.com/en/worldwide/news/energy-meters-what-are-the-types-and-how-do-they-work/ (Retrieved: 28.10.2022)

234 Refer to Q-DAS GmbH (2016), p. 1

235 Refer to Liu, G.; Li, W. (2021), p. 3

this topic would be out of the scope of this study, hence DIN ISO 22514-7:2020 is recommended for further information.

The process capability is calculated monthly by BRP-Rotax, but the data behind this KPI are observed for components and not the machine. In other words, the quality management is not interested in the process capability of the individual machines, but in the component characteristics. In addition and with respect to the Ishikawa diagram, the so-called 6M factors, i.e. "Manpower", "Machine", "Material", "Measurement System", "Mother nature" (Environment) and "Method", all affect the process capability rate, although calculating the influence proportion of each of these factors is quite difficult. This means that in the case of a defective product, each of these mentioned causes such as poor raw material, untrained labor, or equipment itself could have caused the scrap. [236,237] Since distinguishing these factors and calculating their corresponding values on process capability is a complex as well as time- and cost-intensive process, the causes of process variability are not currently examined separately by the quality management. Only if the process capability is poor, the investigation and problem solving is carried out by industrial engineers, quality engineers or technicians. All in all, this KPI cannot be considered for the evaluation model.

Solution: The quality rate respectively the scrap rate can be an optimal alternative to be considered in the evaluation model instead of the process capability.

Problem 4: Consideration of financial factors such as the maintenance costs trend over the asset lifetime, budget deviations, and asset economic life calculation are other KPIs can be considered in the evaluation model. However, not all the data are available for the calculation nor are they trustworthy due to incorrect data assignments. Figure 25 shows an example of the development of maintenance costs over years for an asset. As it can be seen, the maintenance cost changes show almost no trend over the years, which is due to incorrect entries in the system.

Solution: To overcome this problem, it is decided to include maintenance intensity in the evaluation model, since both data on equipment acquisition costs and recent maintenance costs are almost available and reliable. However, for some assets, there are no acquisition costs available in the SAP system.

[236] Refer to Sousa, S. et al. (2018), pp. 13

[237] Investopedia, https://www.investopedia.com/terms/i/ishikawa-diagram.asp (Retrieved: 28.11.2022)

Figure 25: Maintenance cost development example[238]

The problems mentioned above are only part of the hurdles that the team must overcome when selecting the KPIs. Several meetings and personal interviews were held to determine the final KPIs for the criticality assessment and the AMS framework. Thereby, the relevance of the possible KPIs is discussed and the final KPIs are selected. Due to the lack of availability of the required data and the trustworthiness of the data sources, and in order to consider not many but the most relevant KPIs, the pool provided is reduced to the KPIs introduced in the next section for evaluating the asset criticality. As mentioned earlier, qualitative KPIs are also allowed in the model, but they require a clear explanation to be understandable to everyone and should be evaluated by expert knowledge and experiences.

6.2.1.2 Selected KPIs for BRP-Rotax's AMS

The first 5 KPIs listed below are considered for the first phase of the AMS framework to identify the focal assets, while KPIs 6 to 9 are to evaluate the identified focal assets to determine if these assets need to be retrofitted or replaced, or if they can continue to operate without improvements but with modified maintenance strategies. Table 6 shows the defined scales of KPIs considered for phase one. Three to six scales are determined for each KPI, each of which is assigned a numerical value. The numerical values range from 1 to 10, with 1 representing the best condition and 10 the poor parameter. Sublevels by quantitative KPIs are delimited by numbers, while the classification of the qualitative KPIs is based on experts' perspectives. The asset criticality is then calculated by summing the values obtained by multiplying the weight of each KPI by the numerical value of its selected sublevel. Section 6.3.1.1 provides an example on how to calculate the RPN using Table 6. Listed below are the selected KPIs for the BRP-Rotax AMS framework:

1. Equipment availability

[238] Source: Own representation

Due to high demand, the production of BRP-Rotax operates 24 hours a day and in 3 shifts. Therefore, equipment availability should be considered with high importance aiming to guarantee the reliable production. The equipment availability can be calculated then as illustrated earlier by Figure 10 using Equation 20, Equation 21 and Equation 22 as follows: [239]

$$Runtime = Calendar\ time - Planned\ shutdowns$$

Equation 20: Runtime calculation

$$Net\ operating\ time = Runtime - Loss\ due\ to\ downtimes$$

Equation 21: Net operating time calculation

$$Asset\ availability = \frac{Net\ operating\ time}{Runtime}$$

Equation 22: Asset availability calculation

Asset availability is to be assessed twice a year, each time for the last six months. BRP-Rotax has a large variety of products, with each equipment normally processing many different component types (Equipment x processes 5 different types of connecting rod), which leads to high changeover times. Since set-up times have a significant impact on asset availability, availability of over 85% is considered as a good rate. In contrast, availability of less than 60% is considered poor. It should be noted that not only equipment failures can cause poor availability, but also many unnecessary changeover times can have a noticeable impact on this KPI.

2. Output relevancy

As shown in Table 1, this KPI considers both the interlinking degree of the asset with other assets in a workflow and its redundancy, i.e. the presence of other asset that can perform the same work step. Here, the question arises concerning when an asset is to be considered redundant.

To answer this question, it is necessary to consider the capacity utilization factor, i.e. two identical machines with 100% capacity utilization are basically not redundant because the second machine cannot cover the demand of the first or does not have the spare capacity to produce the components that should be produced by the first machine. On the other hand, two machines with a capacity utilization of 75% each, which are able to take over the task of the other machine, can be called redundant, because in case of a failure of one machine, the other machine can take over the lost capacity – completely or partially – to carry out the required work step. The purpose of asset redundancy is to prevent production interruptions by ensuring a high level of reliability. This means that in the event of a machine failure, at least one other machine is available to take over the function of the failed machine. Hence, the workload of the second machine respectively

[239] Refer to Löschnauer, J. et al. (2006), p. 102

its vacant working capacity to take over the function of the failed machine is a decisive factor in this respect.[240,241, 242]

As can be seen from Table 6, rows 1 and 2 considered for this KPI have higher values because redundancy has a higher weighting factor compared to the chaining degree.

3. Scrap rate

The scrap rate is calculated by dividing the number of scraps by the total production quantity for a given period, as shown in Table 1. There is a scrap code list defined by BRP-Rotax quality management, which consists of about 116 codes. These codes represent the factors that can cause poor quality, such as defects in raw materials (poor supply quality), process capability faults, or incorrect setting of the machine for processing the next component (human error). As also mentioned above by problem three, any of the 6M factors can cause a scrap.

There exists also a fixed form containing fixed criteria for quality inspection by the operator. When a batch is produced, the produced components are checked by the machine operator against these criteria. As can be seen in Figure 26, these components are either all in order from the operator's perspective or some components are not acceptable. The operator enters the scrap quantity for the respective workstation into the SAP system, selects (from the scrap code list) the reason for the defective component, and notes when and by whom the scrap is discovered. The component(s) is then put on hold for further quality inspections by the quality engineer.

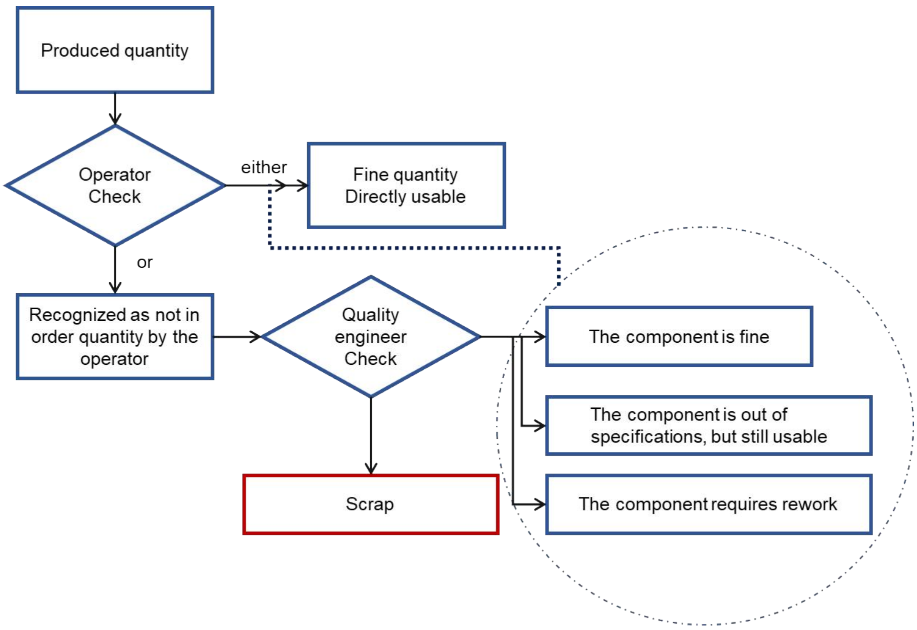

Figure 26: Quality check by BRP-Rotax[243]

As the quality engineer inspects the components that the operator has determined as out of order ones, four scenarios may arise:

1) The component is fine and can be used.

[240] Refer to Brom, A. E. et al. (2018), p. 1
[241] Refer to Ling, W. C. et al. (2021), p. 2
[242] Limble CMMS, https://limblecmms.com/blog/equipment-redundancy/ (Retrieved: 03.12.2022)
[243] Source: Own representation

2) The component is out of specifications, but it is still usable.

3) The component requires rework, or

4) The component is detected as bad quantity and thus as a scrap.

Minimum quality rate defined by the quality management is considered to be 95%, but target is to reach 99%. For calculating the scrap rate for the practical part of this study, it is decided to consider only the scrap codes that are caused by the equipment, i.e. other factors such as operator error are not considered. In other words, the other 5M effects (Material, Manpower, Measurement system, Method, and Mother nature) are not considered in the calculations, but only the equipment failure factor, which only indicates the amount of scrap caused by the faulty equipment. Coaxially, cylindricity, waviness, chatter marks, process capability not in order, machine defect, and machine acceptance are the descriptions of the selected codes indicating the equipment fault. This is because the asset management model is ultimately intended to assist decision-makers in making asset improvement/replacement decisions. Thus, it is attempted to include, as much as possible, those factors that are informative about the asset's condition, rather than other factors.

4. Possible consequences in case of machine shutdown

Asset failure can have different consequences depending on the failure. A failure can result in environmental damage, micro stops, functional deficits, and, in the worst case, impairment of the company's delivery capability and its loss of sales. This KPI considers particularly the case when the asset failure leads to the asst shutdown and its impact on the delivery capability by the company, which in further stages can lead to loss in orders, profit and sales. To simplify the evaluation, the main focus is on the supply capability and not the further impact levels. Figure 27 illustrates this matter perfectly.

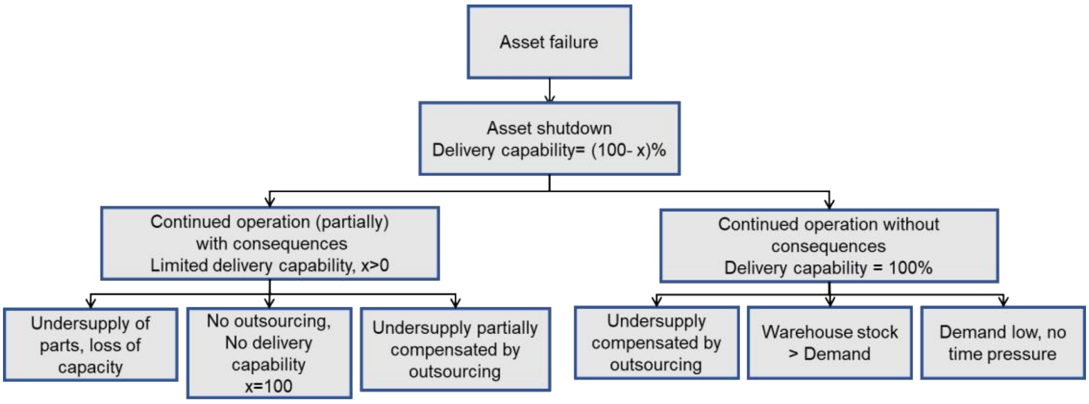

Figure 27: Possible asset shutdown consequences considered for BRP-Rotax[244]

As illustrated in Figure 27, the consequences by the asset shutdown are classified into continued operation with and without consequences. Considering the case of continuous operation without consequences, where the delivery capability is not affected, the lowest score in Table 6 is assigned to the case where the demand respectively the planned number of components to be produced by the asset is so low that there is no time pressure for the asset start up. There is also a case that there exists enough stock available by the company that it would cover the demand till the asset runs again.

[244] Source: Own representation

Therefore, this case is also considered under the latter category. In addition, there is the possibility of outsourcing the production of components, thus compensating for the undersupply.

Continued operation with consequences is the result of three possible scenarios. In the first case, the undersupply can only be partially compensated by outsourcing, which affects the delivery capability. In the other case, part of the demand can still be met, e.g. by using available components in buffer stations, but the company would still suffer a loss of capacity. Finally, the worst case occurs when the company can neither outsource the demand nor has it available parts such as safe inventory in its warehouse. In this case, the delivery capability would be zero.

Table 6: Assessment KPIs for asset criticality determination in phase 1[245]

KPI	Scala		Numerical equivalents of each scala
Output relevancy	The asset is strongly interlinked, but there is no redundancy for it.		10
	The asset is not strongly interlinked and has no redundancy.		7
	The asset is strongly interlinked but has a redundancy.		3
	The asset is not strongly interlinked but has a redundancy.		1
Asset availability	x < 60%		10
	60% ≤ x < 70%		9
	70% ≤ x < 80%		5
	80% ≤ x < 85%		2
	85% ≤ x		1
Possible consequences in case of asset shutdown	Continued operation with consequences	No outsourcing. Therefore, no delivery capability is guaranteed.	10
		Undersupply of parts, loss of capacity.	8
		Undersupply will be partially compensated by outsourcing.	7
	Continued operation without consequences	Undersupply will be completely compensated by outsourcing.	5
		Warehouse stock > Demand	2
		Demand low, no time pressure	1
Scrap rate	5% < s		10
	1% < s ≤ 5%		7
	s ≤ 1%		1

5. Maintenance intensity

[245] Source: Own representation

The fifth selected KPI for the criticality assessment and cost analysis in phase 1 is the maintenance intensity. As shown by Table 1, the maintenance intensity is the outcome of the annual maintenance costs divided by the asset replacement value. Maintenance costs by BRP-Rotax consist of external materials costs, internal material costs, external and internal wage costs. As for the asset replacement value, there are several ways to calculate the RAV. One option could be searching for assets with similar characteristics to estimate how much it would cost if the company wanted to replace the old asset with a brand new and identical one, which is usually difficult and requires too much effort, especially considering the number and age of the company's old assets. The simplest solution is to calculate the present value of an asset by multiplying its acquisition cost by the inflation variation over all the years from the date of acquisition of the asset to the present day.[246] For this purpose, the price index for capital expenditure on machinery and equipment, which represents the inflation rate for the machinery sector only, is taken from the website of Statistik Austria. The Statistik Austria as a federal institution that provides statistical information on economic, demographic, social, ecological and cultural matters with regard to Austria.[247] The data for the price index are provided in Appendix B. As the price index is available only since 2006 (2005 is considered as the base year, i.e. price index in 2005 equals 100), the compounded annual growth rate (CAGR) is calculated as shown in Equation 23 to be considered as the inflation rate for the years before 2006; p is the number of years between the base year and the last year.

$$CAGR = (((\frac{Price\ index\ of\ the\ last\ year}{Price\ index\ of\ the\ base\ year})^{1/p}) - 1)\ \times 100$$

Equation 23: CAGR Calculation[248]

To determine the maintenance intensity threshold for the Y-axis, the maintenance intensity is calculated for 12 assets with different ages based on their year of acquisition to verify the average maintenance intensity of the company. As a result, and considering the benchmark value for maintenance intensity, 4% is set as the limit value for the Y-axis. This means that all assets whose maintenance intensity is above this limit should be subjected to a cost analysis.

The goal of the developed framework is to assist the company in making decisions about improving maintenance strategies, retrofitting assets, or replacing assets, and subsequently supporting investment decisions and budget allocation plans. Therefore, the second phase of the framework is developed to evaluate the focal assets identified in Phase 1 against the asset improvement/replacement KPIs as presented in Section 5.3.1. Hence, the first five introduced KPIs above are used to determine the asset criticality and to find focal assets, as they will be entered in the asset priority portfolio (See Figure 20). Thereafter, the focal assets should go through more detailed analysis based on their location on the portfolio, as discussed in Section 5.4. However, there is a difference here, which concerns the assets that are older than 8 years, meaning that all

[246] UpKeep, https://www.upkeep.com/learning/estimated-plant-replacement-value (Retrieved: 05.08.2022)
[247] For the further information refer to: https://www.statistik.at/en/statistics/national-economy-and-public-finance/prices-and-price-indices/price-index-on-producer-durables
[248] Investopedia, https://www.investopedia.com/terms/c/cagr.asp (Retrieved: 01.11.2022)

the assets older than 8 years old which positioned in area II, III, or IV must be evaluated based on the KPIs phase 2. The reason for choosing 8 years as the useful life is due to the least assured expected period for the availability of spare parts after the asset is acquired. According to discussions with employees responsible for spare parts management, 8 years is a certain period of time in which the company can confidently expect the availability of the mechanical and electrical components as well as the control components, either by the main supplier or available on the market.

As mentioned, KPIs phase 2 are selected based on the KPIs introduced in the theoretical part, as these KPIs contribute to the timely improvement or replacement of the asset.

6. Spare parts availability

Spare parts availability during the asset's lifetime can be divided into 5 phases, as shown in Figure 28. When the company acquires the asset, it usually receives a 2-year warranty from the asset manufacturer. After these two years, it is assumed that the required asset parts can still be supplied by the asset's main manufacturer. If the manufacturer informs that he can no longer provide the parts, the company looks for offers on the market. The delivery time for the spare parts plays an important role in this phase.

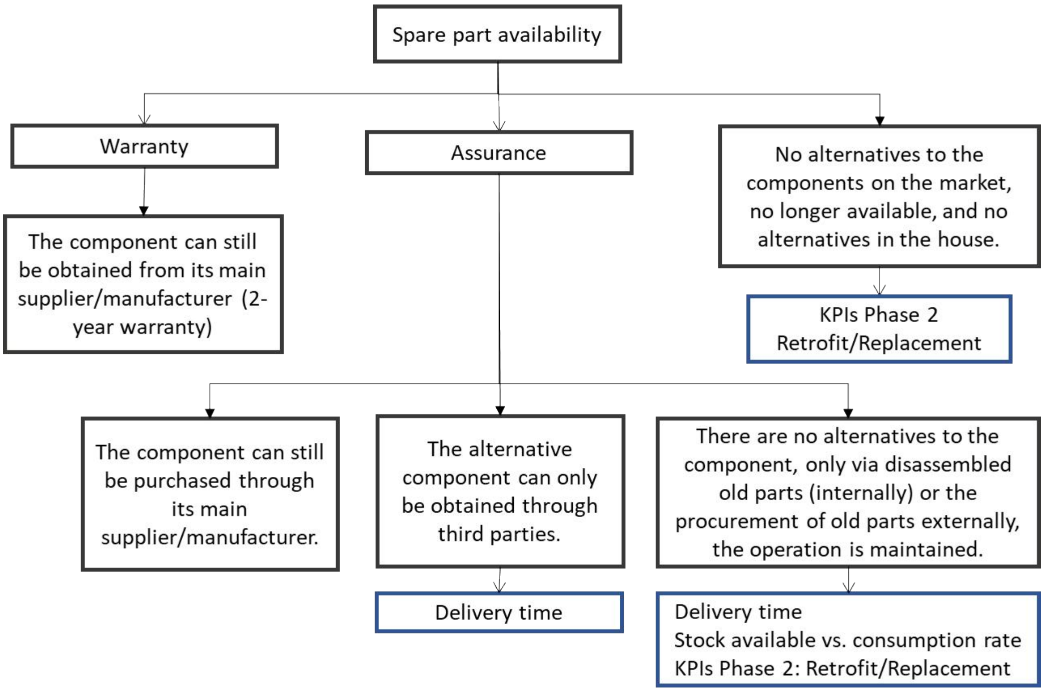

Figure 28: Spare parts availabilty stages by BRP-Rotax[249]

It goes one stage further if there are no alternatives to the component and the company must either provide the required spare parts via internally removed old parts of the other assets or purchase the old parts externally. The delivery time of the spare parts and their consumption rate compared to the stocks available in the company are decisive factors here. This phase can result in equipment being rebuilt or replaced, as shown in Figure 29. Other factors such as the time required for the retrofit, the cost of the retrofit compared to the cost of the old parts, and the extension of the service life of the asset after the retrofit should also be considered with great importance in this context. The

[249] Source: Own representation

extension of service life in this context refers to the years that can be expected for the availability of spare parts.

The last three stages are called assurance stages because there is still a possibility to obtain spare parts. The worst case occurs when there is no other way to obtain the spare parts. The only options at this stage are either retrofitting or replacing the asset. It goes without saying that all the market and obsolescence analyses required in this context must be carried out regularly in order to take action before the worst-case scenario occurs and the decision is made to reactively acquire a new asset. In addition, the other factors mentioned, such as spare parts delivery time or consumption rate, are the KPIs that must be defined and improved by spare parts management. As far as the scope of this study is concerned, only the five stages presented in Figure 28 are to be considered and evaluated. Table 7 represents the classification of this and the following KPIs to their sublevels. The classification of KPIs in Phase 2 is done exactly as in phase 1, by defining possible sublevels for each KPI and assigning an appropriate numerical value to each sublevel.

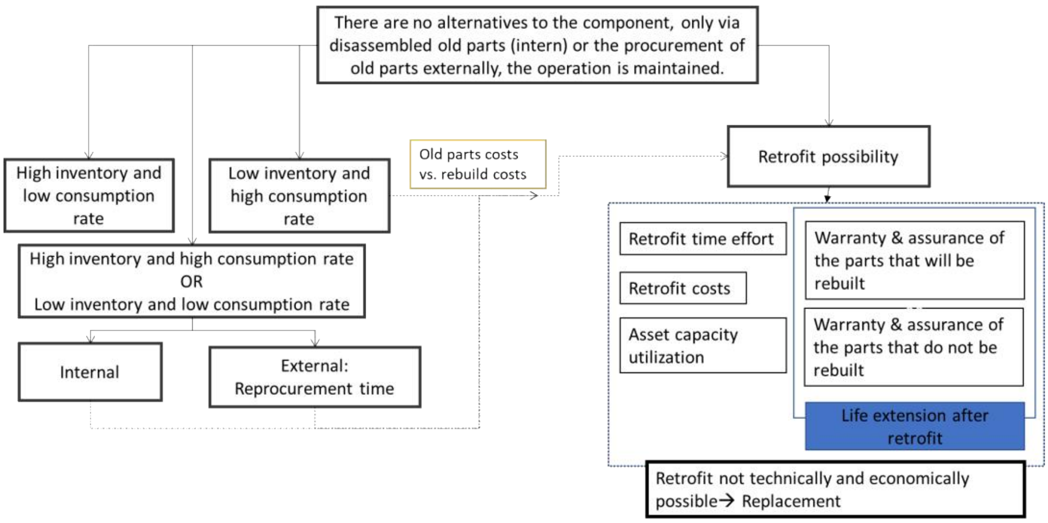

Figure 29: Improvement/replacement factors for the outdated parts

7. IT-relevant KPIs

Software availability, control component availability, service availability, and required know-how are the IT KPIs selected for evaluating the criticality of the assets, where:

- Software availability considers the data backup.
- Service availability accounts for the accessibility of support, like remote maintenance possibility, if this is necessary at the asset.
- Know-how addresses the availability of expertise, internally or externally.

Since the control components are the so-called IT spare parts, they are anyhow considered and classified under the KPI category spare parts availability. The possible parameter by each of these KPIs are presented in Table 7.

8. Degree of downtime

This KPI as represented in Table 1, includes the unplanned downtime in its formula and not the organizational planned downtimes like set up time.

Table 7 shows the defined scales for the latter four KPIs selected for phase 2 and the associated numerical equivalents of the scales.

Table 7: Assessment KPIs for asset criticality determination in phase 2[250]

KPI	Scala	Numerical equivalents of the scala
Spare parts availability	No alternatives to the components on the market, terminated and also no alternatives in the house.	10
	There are no alternatives to the component, only by disassembling old parts or procuring old parts externally, the operation is maintained. Availability of control component <= 2 years	7
	The component can still be purchased through its main supplier/manufacturer or through third parties.	1
	The component can still be obtained from its main supplier/manufacturer (2-year warranty)	1
Degree of downtime	$20\% \leq d$	10
	$15\% \leq d < 20\%$	7
	$10\% \leq d < 15\%$	4
	$d < 10\%$	1
Software availability	No backups available.	10
	Software versions can be obtained from the machine manufacturer.	7
	Programmable logic controller (PLC) program and PC are backed up manually when changes are made.	4
	PLC program and PC are regularly backed up automatically.	1
Service availability	No remote maintenance as well as no local support possible	10
	Only partial remote maintenance feasible	5
	Local support or remote maintenance of all necessary components (PC, PLC, …) is possible, 24/7	1
Know-how	Already the last one, who knows about it, has passed away, i.e. no specialists available for this matter	10
	There is hardly any expertise available externally.	7
	No know-how internally, external support available.	3
	State of the art; the availability of skilled workers is not a problem.	1

9. Retrofit/replacement coefficient

As it comes to decide whether to retrofit the asset or to replace it, many factors come into consideration, as also presented in Figure 29. The new asset acquisition cost vs. cost required to retrofit the old one, and the time that retrofit takes in relation with the asset utilization rate play an important role to make the right decision. Since the magnitude of these factors is entirely situation and asset dependent, there is no specific amount or timing that can be set for them. Besides, there is no spend limit set by the company for the amount allowed to carry out the retrofit. Therefore, it is decided to define

[250] Source: Own representation

the KPI retrofit/replacement coefficient, which considers the ratio of the above factors to each other as presented by Equation 24:

$$Coefficient\ c = \frac{Utilization\ rate_{old\ asset}\ \times Retrofit\ time\ \times 100}{\left(\frac{Aquisition\ cost_{new\ asset} - Retrofit\ cost}{\frac{Retrofit\ cost}{Aquisition\ cost_{new\ asset}}}\right)}$$

Equation 24: Retrofit/replacement coefficient[251]

As can be seen from Equation 24, the difference between the acquisition and retrofit costs is not the only cost factor that needs to be taken into account; the ratio between the retrofit costs and the acquisition costs is also important as shown by the example below:

Example: Consider asset A, which would cost about €1,000,000 to retrofit, while the acquisition cost for the same asset would be €2,000,000. On the other hand, the retrofit costs for asset B would amount to €900,000,000, as its acquisition costs would be €1,000,000,000. As a result, the retrofit costs for asset A is 50% of its acquisition costs and the retrofit costs for asset B is 90% of its acquisition costs, though the difference between the acquisition costs and the retrofit costs for both assets is €100,000. As this example also shows, it is necessary to consider the ratio of retrofit costs to acquisition costs by the defined coefficient. As can also be seen from Equation 24, the higher the coefficient, the more likely it is that the decision will be made to replace the asset and acquire a new one.

Since the KPIs for phase 2 are also defined, a retrofit/replacement matrix is created as shown in Figure 30, where the X-axis represents the RPN calculated in phase 2 by evaluating the asset against KPIs represented in Table 7. The cut-off on the X-axis lies in the middle between the minimum and maximum values of the criticality determination, i.e. the value 5.

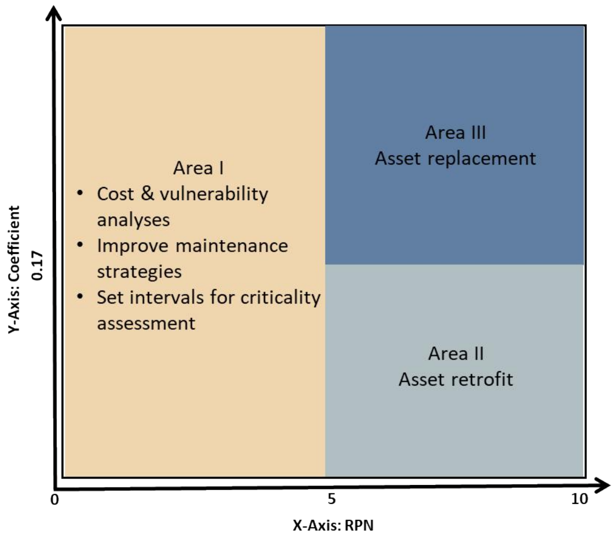

Figure 30: Retrofit/Replacement Matrix[252]

251 Self-defined coefficient in consultation with the AMS team
252 Source: Own representation

The coefficient c is considered as a representative of the Y-axis. Therefore, it is necessary to set a limit value for this coefficient as the Y-axis cut-off value. Different possible random numbers are generated for all parameters involved in Equation 24. Then, each time one factor varies, as the others are considered constant. So, different coefficients are calculated for different utilization rates, as well as retrofit times, retrofit costs, and acquisition costs in order to find a balanced value for c. Finally, the value 0.17 is set as the upper value for retrofitting, i.e. a c-value higher than 0.17 leads to a decision to replace the asset (addition to the consideration of the RPN of the asset). As a real example in this regard, for a robot with acquisition cost of €30,000, retrofit cost of €17,7000, utilization rate of 85%, and a 40-hour retrofit (4 days × 10 working hours per day), c receives the value of 0.163 as calculated by Equation 24. Since the value of c here is less than 0.17, this indicates that the robot needs to be retrofitted, which was also the case at that time.

6.2.2 The developed AMS framework

As the KPIs are selected, this section deals with development of the AMS framework for the practical part. In reference to Figure 14, the same steps are also performed in practice to develop a customized AMS framework for BRP-Rotax. Complementing Figure 14, Figure 31 presents the steps for determining asset criticality to deriving actions based on determined KPIs in last section in more detail.

Some of the steps shown in Figure 31 are already discussed in the theoretical part as well as in the last section, but not the actions to be taken after the evaluation of the assets based on the KPIs in phase 2. Depending on the position of the asset in the retrofit/replacement matrix, three scenarios can occur, namely maintaining, retrofitting, or replacing the asset. If the asset is in area II, it should be retrofitted, whereas if the asset lands on area III, the action required is to replace the asset with a new one.

Shall the asset be retrofitted or replaced, they must be entered in the company's so-called investment priority list, which should be updated and adjusted continuously after each interval respectively the assets criticality determination. Moreover, the estimated budget required for the investment must be included in the company's investment/CAPEX plan, which must be submitted by June of the respective fiscal year, as shown in Figure 32. Therefore, March is set as the main interval for conducting the criticality assessment of all the company's assets. After the investment plan is submitted, the investments must be reviewed and approved by the company's internal risk committee. This includes a detailed breakdown of costs and calculations of financial metrics such as IRR before the investments can be finalized. Therefore, September is set as the next evaluation interval for evaluating the assets' criticality. This allows for any necessary adjustments to the investment list, if there is a change, or any new investment must be also considered.

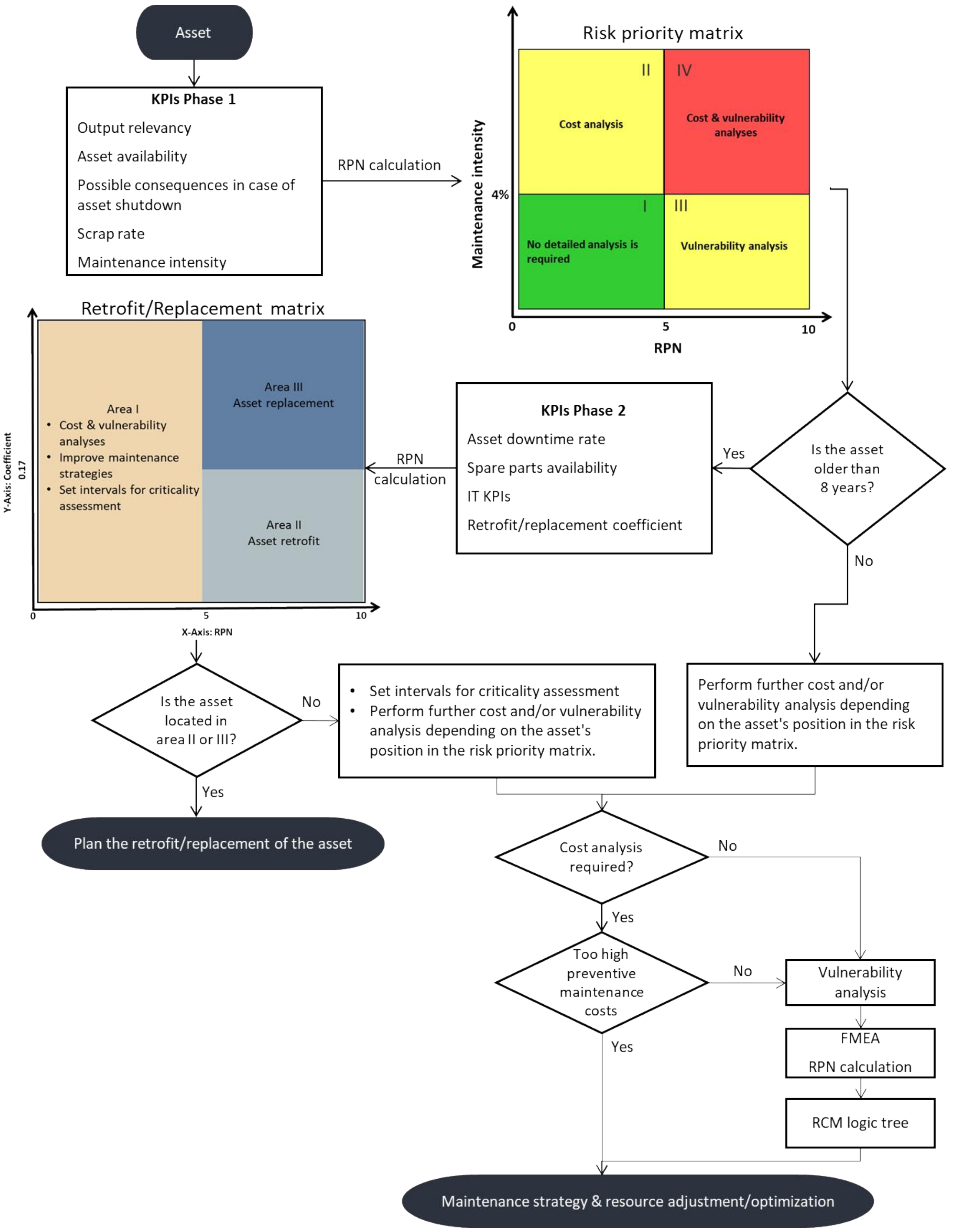

Figure 31: Steps from the asset criticality assessment to the measure derivation [253]

On the other hand, if the asset falls into area I, it does not need to be rebuilt or replaced, but as the asset was classified as critical in phase 1 and is also older than 8 years, it requires high attention. Therefore, the intervals for reassessing its criticality need to be defined according to its current state and its expected state in the next 1 to 4 years in relation to the KPIs of phases 1 and 2 (e.g. the expected duration of assured availability of spare parts). These intervals are either semi-annual or annual, which means that some assets only need to be evaluated once a year, while others need to be evaluated every

[253] Source: Own representation

six months; the 2 fixed intervals are March and September as mentioned above. These assets also require the cost and/or vulnerability analyses based on their position on the risk priority portfolio.

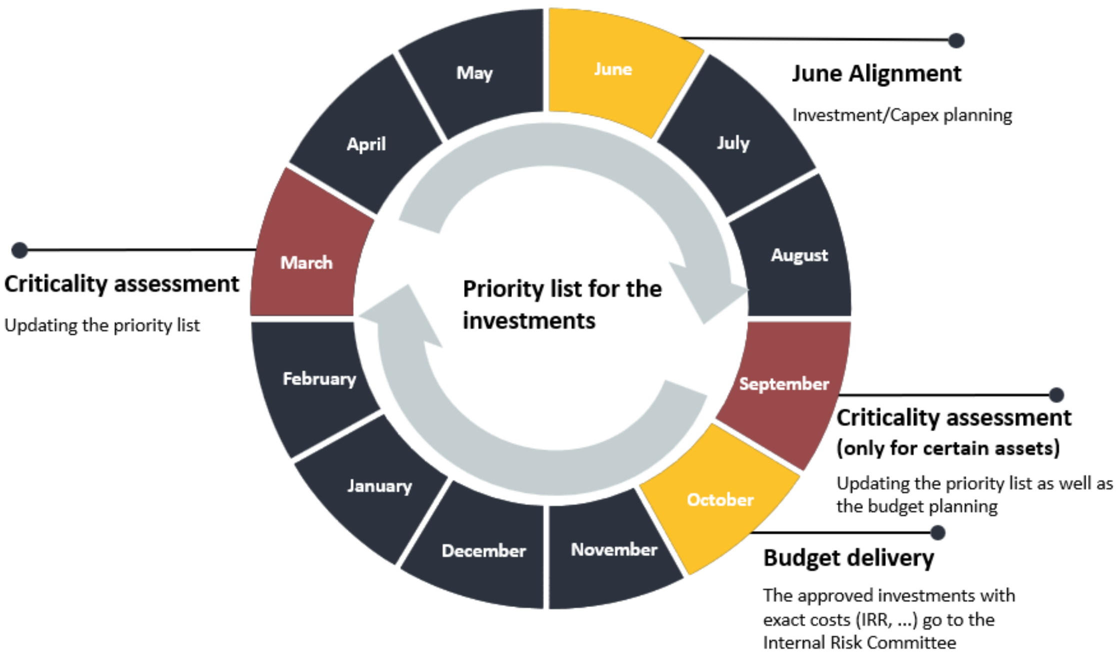

Figure 32: The evaluation intervals by BRP-Rotax[254]

It should be noted that the KPIs used in phase 2 and the matrix developed all help to decrease the number of assets which need more analyses and the effort instead of checking for all assets. Nevertheless, the focal assets and in particular their components, should be subjected to a more detailed analysis. Also not to forget that the outcome of the improvement/replacement decisions are mostly dependent on the discretion of the BU' heads, and the available budget at the time and for sure every decision has its own uncertainties.

6.2.3 KPIs weighting

Once the relevant KPIs are selected and scaled, the next step is to assign them an appropriate weighting, as they are of varying importance to the decision-making process. This step is done applying the AHP approach introduced in Section 4.4.1.1 as the pairwise comparison method. The AHP approach allows each KPI to be assigned a scoring weight that reflects its importance to the objective of the framework. As a result, each KPI is assigned a percentage weight, whereby the sum of these weights should equal 100%.

As mentioned in the last section regarding KPIs phase 1, the KPI maintenance intensity is considered to represent the Y-axis and therefore does not need to be assigned a weight. However, in order to weigh the other KPIs by applying the AHP approach, these KPIs are entered into the rows and columns of the comparison matrix A, as shown in

[254] Source: Own representation

Table 8, to be compared with each other. The pairwise comparison is performed by the expert team using Table 2: Saaty scale of numbers, comparing each KPI with other KPIs in terms of its importance and informativeness about the asset's criticality. This step is represented by Table 8 by forming the pairwise comparison matrix A, as by Equation 6.

Table 8: Pairwise comparison matrix A[255]

KPIs	Output relevancy	Asset availability	Possible consequences in case of asset shutdown	Scrap rate
Output relevancy	1	0.29	0.33	2
Asset availability	3.5	1	2	4
Possible consequences in case of asset shutdown	3	0.5	1	3.5
Scrap rate	0.5	0.25	0.29	1
Sum	8	2.04	3.62	10.5

The normalization as represented by Equation 8, is carried out by Table 9 . For instance, B_{11} is calculated by dividing A_{11} by the sum of its associated column, i.e. column 1, and B_{12} is calculated by dividing A_{12} by the sum of column 2, i.e. 2.04.

Table 9: Normalized matrix B[256]

KPIs	Output relevancy	Asset availability	Possible consequences in case of asset shutdown	Scrap rate
Output relevancy	0.125	0.140	0.092	0.190
Asset availability	0.438	0.491	0.553	0.381
Possible consequences in case of asset shutdown	0.375	0.246	0.276	0.333
Scrap rate	0.062	0.123	0.079	0.095

Applying Equation 9, each KPI's weight is calculated as follows:

$$W_{Output\ relevancy} = \frac{\sum_{j=1}^{4} B_{1j}}{Number\ of\ KPIs} = \frac{0.125 + 0.140 + 0.092 + 0.190}{4} = 13.7\%$$

$$W_{Asset\ availability} = \frac{\sum_{j=1}^{4} B_{2j}}{Number\ of\ KPIs} = \frac{0.438 + 0.491 + 0.553 + 0.381}{4} = 46.56\%$$

$$W_{Shutdown\ consequences} = \frac{\sum_{j=1}^{4} B_{3j}}{Number\ of\ KPIs} = \frac{0.375 + 0.246 + 0.276 + 0.333}{4} = 30.76\%$$

$$W_{Scrap\ rate} = \frac{\sum_{j=1}^{4} B_{4j}}{Number\ of\ KPIs} = \frac{0.062 + 0.123 + 0.079 + 0.095}{4} = 8.99\%$$

With a weighting factor of 46.56%, asset availability represents the most important evaluation criterion in determining the risk priority number. After the KPIs weighting is done, the coherence of the results and the consistency ratio still need to be checked.

[255] Source: Own representation
[256] Source: Own representation

Hence, it is necessary to calculate the Matrix D, the value vector E, and the base value λ (see Section 4.4.1.1):

$$D = \begin{bmatrix} 1 & 0.29 & 0.33 & 2 \\ 3.5 & 1 & 2 & 4 \\ 3 & 0.5 & 1 & 3.5 \\ 0.5 & 0.25 & 0.29 & 1 \end{bmatrix} \times \begin{bmatrix} 0.137 \\ 0.4656 \\ 0.3076 \\ 0.0899 \end{bmatrix} = \begin{bmatrix} 0.5523 \\ 1.9197 \\ 1.2659 \\ 0.3626 \end{bmatrix}$$

$$E_i = {d_i}/{w_i} \qquad i = 1,2,3,4 \ \rightarrow E = \begin{bmatrix} 4.0313 \\ 4.1233 \\ 4.1159 \\ 4.0351 \end{bmatrix}$$

$$\lambda = \sum_{i=1}^{n} {E_i}/{n} \qquad i = 1,2,3,4 \rightarrow \ \lambda = 4.0764$$

As the base value is calculated, the CI and CR values are to be calculated as follows:

$$CI = \frac{4.0764 - 4}{4 - 1} = 0.0255$$

$$CR = \frac{CI}{RI} = \frac{0.0255}{0.9} = 0.0283$$

As the CR value is less than 0.1, thus this value shows a good consistency meaning that the results are consistent.

At the same time, it is also necessary to compare the KPIs of phase 2 with each other and to assign an appropriate weight to them as well. The same steps must be taken by applying the AHP approach to calculate KPIs' weights. As a result, the KPI spare parts availability receives a weighting of 47.6%, the equipment failure rate a weighting of 21.06%, software availability and know-how each a weighting of 12.12%, and service availability a weighting of 7.10%. Since the consistency ratio for these results is also less than 0.1 (CR= 0.0115), the obtained values are adopted.

Once the KPIs are determined, the AMS framework is developed, and each KPI is assigned a weighting factor that corresponds to its relative importance, the next section deals with the implementation of the developed AMS framework for the selected assets by the company to check for the framework's practicability.

6.3 Implementation and results

To implement the developed framework and to verify the practicality of the framework by BRP-Rotax, it is decided to apply the model to three assets. Therefore, the first step should be to assess the selected assets against the defined KPIs, then appropriate measures for them should be derived. Once the results are obtained and meaningful, the framework is validated. Consequently, once the framework is validated, it can be applied to all the BRP-Rotax assets.

6.3.1 Selection of the machine park to be assessed

As mentioned in Section 6.2.1, the company's current SAP system contains data at the workstation level and not for individual assets. Therefore, the assets selected for model implementation are those whose associated workstation has fewer assets assigned to it and also fewer secondary assets such as robots and conveyors. The selected assets are each from a different BU, as shown in in Table 10.

Table 10: Proof of Concept Assets[257]

Workstation number	Asset	BU	Acquisition year	Acquisition value
1	Asset A	CCZ	2014	€965,000
2	Asset B	CCK	2014	€1,439,000
3	Asset C	CCP	2018	€863,075

All associated workstations of the assets selected above also include secondary equipment (such as dry ice machine, washing machine, gantry loader, and robot) in their respective stations, all of which work together to perform a specific process step. Since the maintenance costs in SAP are recorded for the workstation, the acquisition costs and the acquisition year of all machines assigned to the respective workstation must also be considered in the calculations in Section 6.3.1.1 for the criticality assessment of the selected assets.

6.3.1.1 Criticality assessment of the selected assets

The first step to evaluate the selected assets is to calculate their RPN based on the KPIs phase 1. The KPIs output relevancy as well as the possible consequences in the event of the asset shutdown must be answered by the experts of the respective business units for the corresponding assets.

To calculate the KPI asset availability, the data are taken from the MOC system and calculated for a period of 6 months. The calendar time is obtained by multiplying the number of weeks for the period under consideration by the number of shifts per week, where each shift corresponds to 8 hours. This results in a calendar time of $26 \times 19 \times 8 = 3952$ hours.

As it can be seen form the Figure 33, downtimes in MOC are divided into 5 groups, namely failure, organizational downtime, unknown, micro stops, and setup time.

[257] Source: Own representation

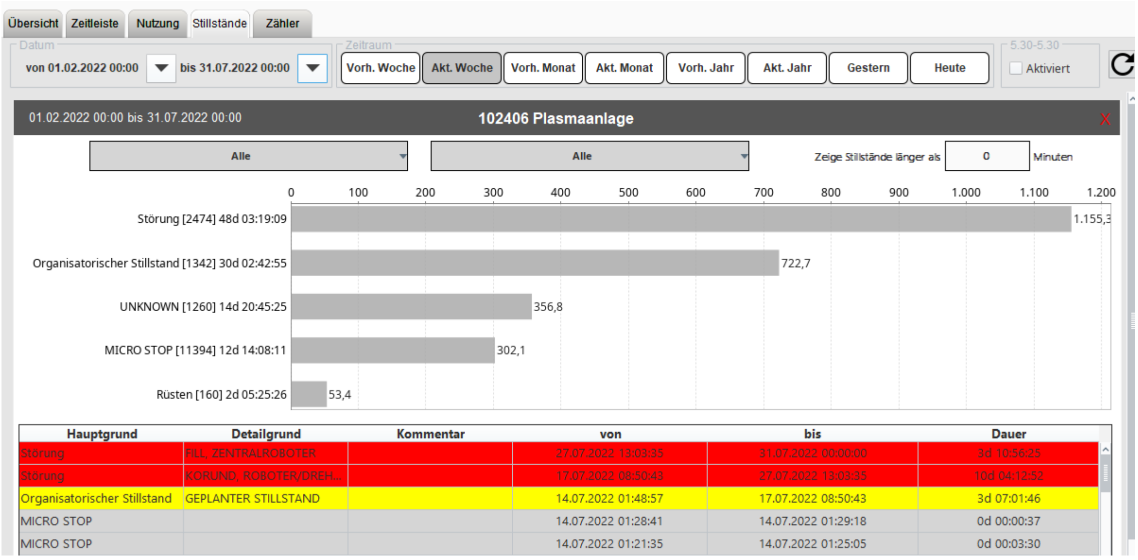

Figure 33: MOC system- Asset downtime categories[258]

To calculate the runtime, the planned downtimes must be subtracted from the calendar time as shown by Equation 20. Activities like workshops, scheduled maintenance, TPM execution, or shift transfer account for the planned downtime. As the runtime is calculated, the net operating time should be calculated as shown in Equation 21. Thus, total losses due to downtime, incl. micro stops, failures, setup times, unplanned organizational downtime, and also hours under the category "unknown" are summed up first. The differentiation between the running time and the loss due to downtime then results in the net operating time and the availability of the three selected assets can be calculated as follows:

$$Asset\ availability_{Asset\ A} = \frac{1612.96\ (s)}{3510.04\ (s)} \times 100 = 45.95\%$$

$$Asset\ availability_{Asset\ B} = \frac{2415.83\ (s)}{3663.16\ (s)} \times 100 = 65.95\%$$

$$Asset\ availability_{Asset\ C} = \frac{1535.82\ (s)}{3423.81\ (s)} \times 100 = 44.86\%$$

The KPI scrap rate is also calculated for the selected assets considering the scrap codes mentioned earlier in Section 6.2.1.2. Using Table 6 and the KPIs weights calculated according to Section 6.2.3, the RPNs of the selected assets are calculated as shown in Table 11, whereby the rows highlighted in blue represent the KPIs' scales for asset A, those highlighted in yellow represent asset B, and the ones highlighted in green represent the asset C.

258 Source: Own representation – Screenshot from the MOC system

Table 11: Criticality calculation of the Proof-of-Concept assets in phase 1[259]

KPI	Scale	Numerical equivalents	KPI's Weight	Numerical equivalent × weight
Output relevancy	The asset is strongly interlinked, but there is no redundancy for it.	10	13.7%	1.370
	The asset is strongly interlinked but has a redundancy.	3		0.411
	The asset is strongly interlinked, but there is no redundancy	10		1.370
Asset availability	x < 60%	10	46.56%	4.656
	60 ≤ x < 70	9		4.190
	x < 60%	10		4.656
Possible consequences in case of asset shutdown	Continued operation without consequences: Undersupply compensated by outsourcing	5	30.76%	1.538
	Continued operation with consequences: No outsourcing, no delivery capability	10		3.076
	Continued operation with consequences: No outsourcing, no delivery capability	10		3.076
Scrap rate	s= 0.01% ≤ 1%	1	8.99%	0.090
	s= 0.04% ≤ 1%	1		0.090
	s=0% ≤ 1%	1		0.090
		RPN Asset A		7.654
		RPN Asset B		7.767
		RPN Asset C		9.192

Subsequently, the RPNs of these three assets is calculated as follows:

$$RPN_{Asset\ A} = 1.370 + 4.656 + 1.538 + 0.090 = 7.654$$

$$RPN_{Asset\ B} = 0.411 + 4.190 + 3.076 + 0.090 = 7.767$$

$$RPN_{Asset\ C} = 1.370 + 4.656 + 3.076 + 0.090 = 9.192$$

As the RPNs are calculated, the next step is to calculate the maintenance intensity of the selected assets. As mentioned before, the maintenance costs considered for this part are the maintenance costs for the entire workstation, since the maintenance costs for the individual assets are booked in SAP for their associated workstation and not for the equipment number itself. Thus, the acquisition costs of all assets (plus secondary equipment) for workstations 1, 2, and 3 are totaled respectively considered as a whole. Then, the RAV values of all assets located in workstations 1, 2 and 3 must be calculated to subsequently determine the ratio between the maintenance costs for year 2021 to the RAV values for each workstation.

Using the price index provided in Appendix B, the RAV values are calculated as follows by applying the Equation 25, which calculates the future value of an amount V_0 invested at year x with interest year r:

$$Future\ value = V_0 \times (1 + r)^{present\ year - x}$$

Equation 25: Future Value calculation[260]

In the context of this study, the inflation rate serves as the parameter 'r'. Since the inflation rate varies over the years, the RAV values are calculated by multiplying the total acquisition cost by the inflation rates over the years from acquisition to today. The

[259] Source: Own representation
[260] Refer to Hastings, N. A. J. (2010), p. 106

following example shows how the RAV value is calculated for the workstation of asset C.

$$RAV_{Workstation\ 3} = 2{,}400{,}000 \times (1 + 0.015) \times (1 + 0.011) \times (1 + 0.013) = €2{,}496{,}321$$

Asset C and also all the assets located in workstation 3 are all acquired in 2018. So, the total acquisition costs is multiplied with the inflation rate for the years 2019, 2020, and 2021, i.e. 0.015, 0.011 and 0.013.

The RAV values for the other two workstations are calculated like as for asset C resulting in €2,343,408 and €2,210,018 for the associated workstations of assets A and B. Eventually, maintenance intensity values are calculated by dividing each workstation's maintenance costs for 2021 by their calculated RAV as follows:

$$Maintenance\ intensity_{\ Workstation\ 1} = \frac{298{,}190.52}{2{,}343{,}408} \times 100 = 12.72\%$$

$$Maintenance\ intensity_{\ Workstation\ 2} = \frac{97{,}287.59}{2{,}210{,}018} \times 100 = 4.40\%$$

$$Maintenance\ intensity_{\ Workstation\ 3} = \frac{70{,}572.92}{2{,}496{,}321} \times 100 = 2.83\%$$

It should be noted that once the SAP is converted to equipment numbers, and all data are available for individual assets, the maintenance intensity should only be calculated based on the acquisition and maintenance costs of the asset itself and not the entire workstation. As no such data are currently available, this KPI is calculated for each workstation to provide an example of the application of the AMS framework.

Based on the determined RPN and maintenance intensity values, the assets can be placed in the risk priority portfolio, as shown in Figure 34.

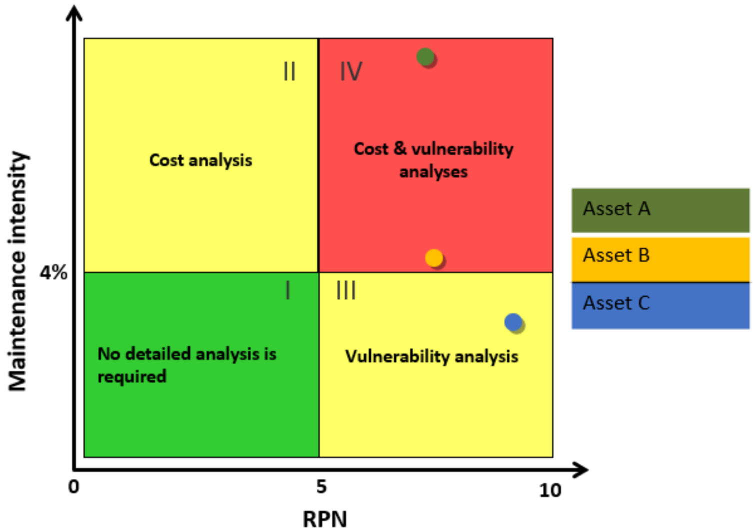

Figure 34: Risk priority portfolio for the Proof-of-Concept assets[261]

As the risk priority portfolio shows, all the three assets are recognized as critical. Since the present framework will later be used for the evaluation of all the company’s assets (about 2000 assets), it is recommended to order the criticality results by descending criticality values to obtain a good overview of the most critical assets.

[261] Source: Own representation

After identifying the focal assets in the asset priority portfolio, the next step is to determine the cause of the high maintenance costs and/or high asset criticality. But in accordance with Figure 31, prior to executing the cost and/or vulnerability analysis, it is imperative to ascertain whether the asset in question possesses an age of less than 8 years or not. If the asset is older than 8 years, it needs to be evaluated against the KPIs in phase 2 to determine whether it needs to be replaced or retrofitted. If there is no such need, the asset requires the detailed cost and/or vulnerability analysis based on its position in Figure 34 risk priority portfolio. Hence, the next section addresses the next steps required to be taken for assets A, B, and C.

6.3.1.2 Proposed actions for the selected equipment

This section addresses the proposed measures for the selected assets, but it is important to reiterate that the KPI maintenance intensity, as well as the following KPIs used in this section as phase 2 KPIs, are all assessed in relation to workstations 1, 2, and 3, which should not be the case. Regrettably, due to the limited time and the unavailability of data by the company, this section is unable to present precise measures for the studied assets. Nevertheless, the steps taken are the maximum feasible at this stage to offer an understanding of the functionality of the proposed framework. Following are the next steps for the asset assessment and proposed actions:

Asset C: Since asset C is younger than 8 years, it does not need to be assessed against the KPIs in phase 2. However, due to its position in the risk priority portfolio, vulnerability analysis is required as the next step. As depicted in Table 11, asset availability is identified as one of the KPIs that contributes to the high RPN of the asset. Furthermore, with regard to the KPI consequences of asset shutdown, the company experiences a nearly complete loss of delivery capability. Asset C processes various components, but for some of them and also for the most critical part to be processed, the company usually experiences a shortage when the asset fails. This applies especially when there are seasonal trends. In addition, asset C does not have redundancy.

Considering all factors mentioned above, it is necessary to perform a vulnerability analysis to optimize the maintenance strategy of the asset and increase its availability and reliability. This can be done by applying the FMEA approach to calculate the RPN for each failure mode, visualize them in a risk matrix, and consequently apply the RCM logic tree for the selection of the maintenance activities, as presented in Sections 5.2.1 and 5.4.2.1.

In order to optimize the current maintenance strategy of the asset in terms of its maintenance costs and criticality, it is critical to perform an in-depth analysis of the asset's existing maintenance strategy. As a result, the asset's maintenance strategy and maintenance resource planning are to be adjusted accordingly.[262] For example, if the asset is experiencing frequent breakdowns due to a particular issue, it may be necessary to perform more proactive maintenance tasks to prevent those breakdowns from occurring. This issue could be also for instance human errors, which requires the need for a training program. The history of failures and their frequency can be found in the

[262] Refer to Kinz, A. et al. (2017), p. 202

downtime list provided by the MOC for a given period and should be analyzed as mentioned. For asset C, the unplanned downtime[263] accounts for 36.20% of the total downtime, which is about 55%. This underlines the need to optimize the maintenance strategy.

Thus, as mentioned above, the percentage of failure reports caused by any given factor and the average downtime per failure due to that factor should be calculated. Consideration of adequate inventory buffers and safety stock, outsourcing options, or investment in a new additional asset are other suggested measures which can prevent the production interruptions in the event of an asset failure.

Asset A and asset B:

As shown in Figure 34, both a cost and a vulnerability analysis are required for asset A as well as asset B. As both assets are older than 8 years, therefore they need to be first evaluated based on KPIs phase 2 as shown in Table 12:

Table 12: Criticality calculation of the Proof-of-Concept assets in phase 2[264]

KPI	Scale	Numerical equivalents	KPI's Weight	Numerical equivalent × weight
Spare parts availability	There are no alternatives to the investigated component, only by removed old parts or the procurement of old parts externally, the operation is maintained. Availability of control component <= 2 years	7	47.6%	3.332
	No alternatives to the components on the market, terminated and no alternatives in the house.	10		4.760
Downtime degree	10% ≤ d=13.84 < 15%	4	21.06%	0.842
	20% ≤ d=49.90%	10		2.106
Software availability	Software versions can be obtained from the machine manufacturer.	7	12.12%	0.848
	No backups available.	10		1.212
Service availability	Only partial remote maintenance feasible	5	7.10%	0.355
	No remote maintenance as well as no local support possible.	10		0.710
Know How	No know-how internally, external support available.	3	12.12%	0.364
	There is hardly any expertise available externally.	7		0.848
		RPN Asset B		5.741
		RPN Asset A		9.636

Since the associated workstations for both asset A and asset B have RPNs greater than 5, based on the retrofit/replacement matrix shown in Figure 30, retrofit or replacement must be considered for the workstations 1 and 2. That applies in particular to workstation 1 in view of its high RPN. Yet, since the evaluations are done at the workstation level, the coefficient c cannot be calculated in this step.

The unavailability of data for individual assets was one of the biggest obstacles to this work, making it impossible to evaluate individual assets. Converting the company's SAP database from workstation numbers to equipment numbers so that all data and KPIs can be entered and evaluated at the asset level is a crucial step that has to be taken as quickly as possible. After several discussions with the IT department, it is finally decided to make this change, which has already started and should be fully implemented by the

263 The unplanned downtime is calculated as the result of the sum of micro stops, unplanned organizational downtime, downtime due to unknown reasons, and asset failures.

264 Source: Own representation

end of March 2023. With this change and the complete implementation of the developed AMS framework in SAP, it is then possible to perform a meaningful asset evaluation for all assets in BRP-Rotax and, above all, to derive appropriate decisions. Moreover, it would be the possible to plan the maintenance budget specifically for each individual asset and not for the entire workplace.

To also provide an example of the cost analysis introduced in Section 5.4.1, it is assumed that the calculated RPN for workstation 1 is the calculated RPN for asset A and the decision is to improve the asset's maintenance strategies and resources rather than to retrofit it. Therefore, based on the location of the asset in Figure 34, both the cost and vulnerability analysis are required. Figure 35 represents the maintenance cost analysis for the year 2021 for asset A.

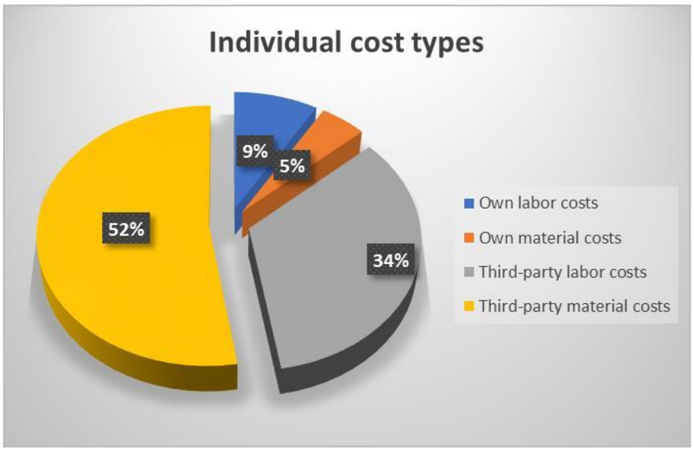

Figure 35: Detailed cost analysis for asset A[265]

It becomes apparent that the maintenance costs are largely made up of external material costs. Therefore, in the next step, the third-party material costs, the respective share for failures, and planned maintenance and inspections are analyzed. Depending on whether more material is recorded for failure-related or planned maintenance activities, appropriate measures can be derived. As shown in Figure 36, the higher proportion is made up of maintenance measures due to asset failure, i.e. reactive maintenance activities.

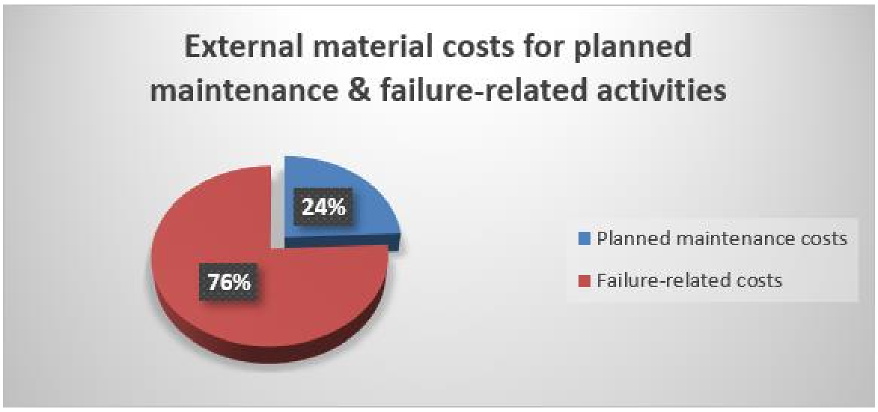

Figure 36: External material cost analysis for asset A[266]

[265] Source: Own representation
[266] Source: Own representation

The cost analysis must also clarify which activity type caused the high costs incurred. Subsequently, the maintenance strategy and resource planning must be optimized by evaluating the alternative measures and, finally, the alternative with the most favourable cost-risk ratio would be selected as the asset's new maintenance strategy.

All in all, the next steps include conducting a thorough cost-benefit analysis and a vulnerability analysis, but these detailed analyses fall outside the scope of the current work. Changes in outsourcing, the need for training and qualification of machine operators, investment in new additional equipment, and optimization of spare parts management are some improvement suggestions that can be considered for critical assets.

Also, to monitor the condition of the assets categorized as critical and also determined as old by the company, it is suggested to apply the condition monitoring techniques more effectively/frequently to gather information about the current state of the asset and to provide an early indication of when replacement is probably necessary. Besides, older assets can be repurposed for less critical tasks or standby roles instead of being discarded.[267]

Finally, it is also important to review the success of the derived measures as part of the target achievement assessment. This means that the assets must be re-evaluated at least once a year and the priority portfolio of the assets must be re-created. The rebuilt portfolio and the position of the assets in it and changes in maintenance costs show whether the new maintenance strategies have been effective in reducing the costs and the risk potential respectively the RPN of the assets or not. Additionally, the development of the KPIs, such as increased asset availability can provide information on the effectiveness of the new strategies during the current observation period. Nevertheless, it is important to note that changes, especially within an organization, require a certain time to be implemented and produce visible results.[268]

[267] Refer to Hastings, N. A. J. (2021), p. 547
[268] Refer to Kinz, A. et al. (2017), p. 209

7 Summary and outlook

This chapter provides a summary of the work conducted as well as the results achieved in Section 7.1. This chapter concludes by follow up projects and improvement recommendations for BRP-Rotax.

7.1 Summary

Implementing an Asset Management System is necessary for asset-intensive organizations seeking to manage their assets throughout their entire lifecycle effectively. The AMS facilitates the assessment of an asset's criticality and enables informed decision-making based on the asset's condition, particularly in regard to assets of significant investment value.

This master's thesis comprises the development of an AMS framework for BRP-Rotax, built on the existing AMS model of the company. The developed model enables the criticality assessment based on the company's available KPIs and proposes appropriate measures to take based on the asset criticality evaluation results.

The theoretical base for the present topic area is elaborated at the beginning of the work. The basics of AMS are introduced, focusing on the asset lifecycle phases and the AMS interface with the other management systems, and prerequisites for the AMS successful implementation. The second focus of the theory part deals with KPIs and KPI systems, by first explaining the fundamentals of KPIs, introducing production and maintenance KPIs, as well as the approach to compare KPIs against each other regarding their importance. Thereafter, the proposed AMS framework is developed based on the concepts of AMS and its KPIs regarding the AMS interfaces involved in the criticality assessment and the decision-making process of the assets.

The practical part builds on theoretical elaborations. Since the development of the AMS framework corresponds to the company's requirement, the analysis of the actual situation and the internal requirements, as well as the company's available and trustworthy KPIs selection and weighting is a necessary step before developing the company's customized AMS framework. As the AMS model is developed, the proposed strategic decision-making framework is validated through its application to the selected assets within the company. The developed framework evaluates the selected assets criticality and provides required measures according to the assets condition, namely maintenance strategies improvement, or retrofit/ replacement of the asset. However, the machine park selected for the case study does not allow the framework to evaluate the criticality of assets or to analyze retrofit/replacement decision alternatives and can merely serve as a recommendation for an individual asset. This is due to the fact that the data are available at workstation level at the time and therefore does not accurately reflect on the specific asset. Still, the AMS framework is able to meet the requirements, both from a practical and theoretical perspective, and changes in the company's database system are already placed on the agenda. Furthermore, the flexibility of the developed framework allows for additional KPIs to be incorporated and the weighting of KPIs can be adjusted when required.

7.2 Outlook

To implement the framework successfully, employees with primary responsibility for each management system and the respective KPI must be designated. These employees must be in direct contact with the AMS team to ensure the adequate flow of information, accompany the complete implementation of the AMS framework, and provide more detailed analysis or take corrective action, if necessary. As mentioned before, one of the most important bases for the AMS successful implementation is the involvement and the commitment of the other management systems which points out the importance of a control loop of measures and feedback.

So, model optimization should take place constantly, mainly when more accurate and relevant data are available. This applies especially to the KPI conformity with regulations which considers the HSE aspects and must be considered besides KPIs phase 2. The other KPI which must be changed is the considered asset's useful life. This KPI is looked at for all type of the company's assets older than 8 years. As a result, the BV for all assets reaches the value zero after 8 years. So, the finance management system should create a list incl. different types of assets, whereby each type has different determined useful life.

In the course of the comprehensive literature research, no real concrete model can be found to determine under what circumstances it is more advantageous to retrofit the asset rather than to replace it. Even in the present work, this cannot be presented in an all-encompassing manner but only by defining the coefficient c, as this case has always been situation dependent. In the future, the importance of asset management will increase since more companies are intending to implement an AMS model. Thus, it should be of great importance to study and cover more real practices in regard with asset retrofit or replacement to create a better model that besides theory can also be used for the real-world cases.

All in all, the foundation stone of the AMS are laid and the path is clearly drawn. Nevertheless, the further implementation of the framework and the software solution, criticality assessment of the individual assets and respectively their components, conducting further maintenance and cost analyses and subsequently developing the company-specific RCM logic tree and a framework for maintenance task selection, as well as optimizations in spare parts management are further aspects which need to be worked by the BRP-Rotax team.

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Appendix

A. RCM logic tree

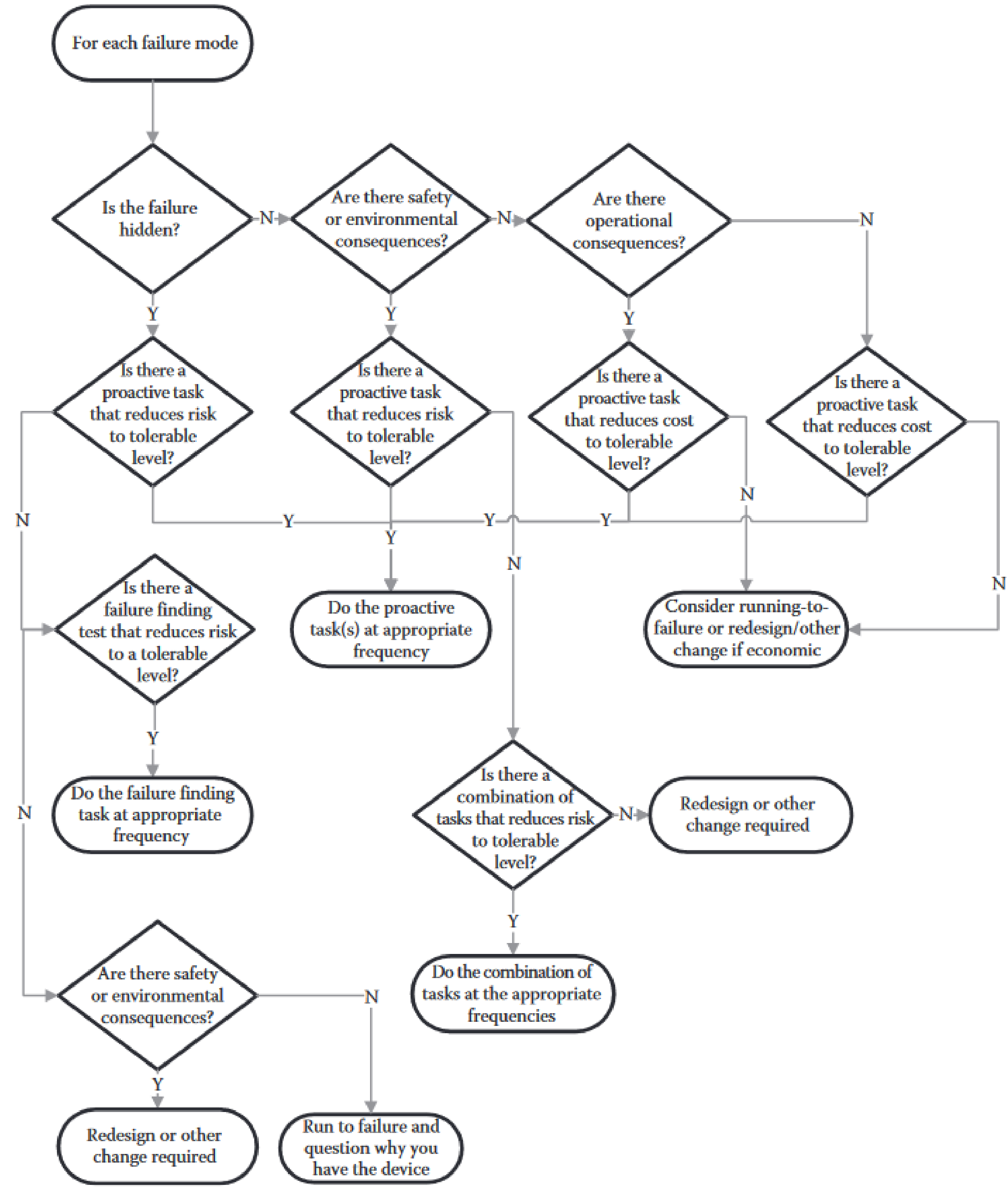

Figure 37: Simplified RCM decision logic diagram[269]

[269] Source: Campbell, J. D.; Reyes-Picknell, J. V. (2015), p. 292

B. Price index for equipment

Price index for capital expenditure on machinery and equipment on CPA 2015 - Classifications

2005=100

Reporting Period	CPA-Sections			CPA-Departments									
	C Manufactured Products	Domestic Goods	Imported Goods	13 Textiles	14 Wearing apparel	16 Wood and of products of wood and cork; except furniture; articles of straw and plaiting materials	22 Rubber and plastic products	23 Other non-metallic mineral products	25 Fabricated metal products, except machinery and equipment	26 Computer, electronic and optical products	27 Electrical equipment	28 Machinery and equipment n.e.c.	29 Motor vehicles, trailers and semi-trailers
Ø 2021	115,2	121,0	112,5	123,1	121,9	144,6	124,9	133,4	121,9	87,3	116,7	124,4	116,6
Ø 2020	113,4	119,7	110,4	121,0	122,2	122,3	117,2	129,7	116,8	87,1	115,2	122,8	114,8
Ø 2019	112,9	118,7	110,0	121,1	121,6	122,9	118,3	128,6	117,9	87,4	114,7	121,4	113,7
Ø 2018	112,0	117,6	109,3	120,4	119,6	123,7	118,7	126,8	117,6	87,5	113,5	119,6	112,7
Ø 2017	111,3	116,9	108,6	119,8	119,3	122,2	118,8	124,3	116,3	87,8	112,6	118,2	111,9
Ø 2016	110,7	116,2	108,0	120,1	119,0	120,8	118,4	122,4	114,4	88,2	112,3	117,3	111,4
Ø 2015	110,1	115,3	107,5	119,9	117,8	120,6	118,4	120,9	114,6	88,4	112,0	116,1	111,3
Ø 2014	109,5	114,6	106,8	119,3	116,4	119,4	116,7	119,5	114,6	87,6	111,4	115,5	111,1
Ø 2013	109,3	114,1	106,8	119,2	116,7	119,9	116,7	119,1	114,5	89,0	112,2	114,4	110,9
Ø 2012	108,9	113,2	106,5	119,3	115,4	119,7	116,7	118,4	115,3	89,8	112,2	113,2	109,6
Ø 2011	107,4	111,5	105,1	118,6	112,2	118,7	115,2	115,9	115,5	90,5	111,5	111,1	108,6
Ø 2010	105,7	109,4	103,4	108,5	107,0	113,9	110,3	112,6	108,7	94,8	108,5	108,1	107,7
Ø 2009	103,5	106,1	102,0	106,5	104,9	110,0	107,3	111,3	107,4	93,4	107,4	106,9	105,6
Ø 2008	103,8	106,4	102,3	106,7	103,2	110,2	107,4	109,4	108,9	96,1	107,7	106,3	103,6
Ø 2007	102,4	104,3	101,4	104,4	101,5	110,2	104,8	106,6	105,9	99,5	106,9	103,9	101,4
Ø 2006	101,0	102,1	100,5	102,0	100,3	101,9	102,1	102,7	102,8	97,0	103,3	101,9	100,7
Ø 2005	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0	100,0

Figure 38: Price index for machinery and equipment since 2005[270]

270 Statistik Austria, https://www.statistik.at/en/statistics/national-economy-and-public-finance/prices-and-price-indices/price-index-on-producer-durables (Retrieved: 05.11.2022)