Instituto Superior
de Engenharia
Politécnico de Coimbra

DEPARTMENT OF CHEMICAL AND BIOLOGICAL ENGINEERING

Medical Asset Management Optimization: Dynamic Replacement Models with an Environmental Integration

Internship Report to fulfill the Master's degree in Engineering and Management of Physical Assets

Author

Luís Miguel Dias Neves

Supervisors

Professor Dr. José Manuel Torres Farinha

Professor Dr. José Luís Ferreira Martinho

Advisors in the organisation Unidade Local de Saúde de Coimbra

Dr. Fernanda Gomes

Dr. Ana Morim

Dr. José Carlos

Coimbra, December 2024

INSTITUTO POLITÉCNICO
DE COIMBRA

INSTITUTO SUPERIOR
DE ENGENHARIA
DE COIMBRA

ACKNOWLEDGEMENTS

This report is a milestone that reflects not only my personal effort but also a collective commitment to pursue knowledge, research, and meaningful progress.

I would like to extend my heartfelt gratitude to Professor José Manuel Torres Farinha and Professor Hugo David Nogueira Raposo, who have been instrumental in shaping my academic journey since my undergraduate studies in Mechanical Engineering. I am deeply thankful for the knowledge they shared, the new concepts they introduced, and their unwavering encouragement over the years. Their belief in me and their openness to my ideas, always treating me as an equal, have been a constant source of inspiration. I am also thankful to Professor José Luís Ferreira Martinho for his patience and sincerity during our meetings. His ability to explain complex concepts with clarity and listen to my ideas has been invaluable throughout this process.

At the host institution, I am sincerely grateful to Dr. Fernanda Gomes, Dr. Ana Morim, and Dr. José Carlos, whose guidance and support made my internship at ULS Coimbra incredibly enriching. They were always available to teach with transparency and showed genuine interest in my ideas, helping to bring them to life.

To my colleagues, Rodrigo Farate and Daniela Loureiro, thank you for fostering meaningful discussions, a shared dedication to improving engineering and asset management practices and above all, thank you for the meaningful friendship. I also want to thank Isaura, Anabela and Raquel for their constant companionship and support throughout the internship.

Lastly, my deepest gratitude goes to my family. Due to language barriers, it is especially meaningful for me to express this in Portuguese, ensuring that everyone can understand:
O maior agradecimento que posso fazer é, sem dúvida, à minha família, com um carinho especial para a minha irmã Mónica, os meus pais Luís e Carla, os meus avós Luciana e Amadeu, e a minha tia Helena. O seu apoio incondicional, a confiança que sempre depositaram em mim e, acima de tudo, os valores e a educação que me transmitiram, são pilares fundamentais da minha vida. Esses princípios inspiram-me diariamente, movem cada passo que dou e sustentam tudo o que procuro alcançar. Toda a minha vontade de melhorar, inovar e ajudar nasceu deles, é dedicada a eles e estendida a toda a gente.

For a better Future!

ABSTRACT

Asset management has become increasingly crucial for economic and environmental sustainability. When applied to the healthcare sector, it gains an additional layer of importance due to its social impact—where well-managed equipment directly influences public health outcomes. This notion served as the driving motivation for this study, conducted at the Local Health Unit of Coimbra (ULS Coimbra).
The internship focused on proposing, developing, and implementing tools to optimize medical asset management, either by minimizing resource consumption or by providing more comprehensive decision-making support.

The first challenge addressed was the identification of inconsistencies in the registration of new assets across poorly integrated management platforms. To tackle this, a monitoring tool was developed in Power BI, not only allowing for a global analysis of received, paid, and registered assets, but also the identification of individual discrepancies.

The second challenge involved understanding the life cycle of a Medical Linear Accelerator to determine the optimal replacement point. Traditional asset replacement models were adapted into a dynamic replacement model capable of integrating alternative replacement options. This model identifies an optimal replacement range and quantifies the economic and environmental impacts of different replacement asset choices.

The findings underscore the importance of efficient asset registration, showing that integrating data across management systems can streamline controls and free up resources for critical tasks. Furthermore, the dynamic replacement models demonstrate the significance of incorporating alternative assets and additional metrics, such as cost-production analyses, into life cycle assessments. These models also highlight how taking climate change into account can shift the optimal replacement timeline, a testament to the adaptability of this approach and its ability to align with organizational priorities.

Keywords: Physical Asset Management, Replacement Models, Decision-support, Eco-Efficiency, Asset Monitoring.

RESUMO

A gestão de ativos tem-se tornado cada vez mais crucial para a sustentabilidade económica e ambiental. Quando aplicada ao setor da saúde, ganha uma camada adicional de importância devido ao seu impacto social, já que equipamentos bem geridos influenciam diretamente os resultados da saúde pública. Essa premissa foi a motivação central para este trabalho, realizado na Unidade Local de Saúde de Coimbra (ULS Coimbra). O estágio teve como foco a proposta, desenvolvimento e implementação de ferramentas para otimizar a gestão de ativos médicos, seja pela minimização do consumo de recursos ou pelo fornecimento de informações mais completas para o suporte à decisão.

O primeiro desafio abordado foi a identificação de inconsistências no registo de novos ativos em plataformas de gestão pouco integradas. Para resolver esse problema, foi desenvolvida uma ferramenta de monitorização em Power BI, que permite não apenas uma análise global dos ativos recebidos, pagos e registados, mas também a identificação individual das fontes de discrepâncias.

O segundo desafio consistiu em compreender o ciclo de vida de um Acelerador Linear Médico para determinar o ponto ótimo de substituição. Modelos tradicionais de substituição de ativos foram adaptados para criar um modelo dinâmico, capaz de integrar alternativas de substituição. Esse modelo identifica um intervalo ideal para a substituição e quantifica os impactos económicos e ambientais de escolher diferentes equipamentos substitutos.

Os resultados destacam a importância de um registo eficiente de ativos, demonstrando que a integração de dados entre sistemas de gestão pode simplificar o controlo e libertar recursos para tarefas críticas. Além disso, os modelos dinâmicos de substituição evidenciam o valor de incorporar ativos alternativos nas análises e métricas adicionais, como o custo por produção, em avaliações de ciclo de vida. Esses modelos também mostram como a integração de impactos ambientais pode alterar significativamente o ponto ótimo de substituição, realçando a flexibilidade da abordagem para se alinhar às prioridades organizacionais.

Palavras-chave: Gestão de Ativos Físicos, Modelos de Substituição, Apoio à Decisão, Eco-Eficiência, Monitorização de Ativos

Long-range planning does not deal with the future decisions,
but with the future of present decisions.
Peter F. Drucker

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

AM	Asset Management
AMT	Asset Management Team
CAPEX	Capital Expenses
CM	Corrective Maintenance
CHUC	Centro Hospitalar e Universitário de Coimbra (Coimbra University Hospital Center)
DECEX	Decomissioning Expenses
EEA	Eco-Efficiency Analysis
ERSE	Entidade Reguladora dos Serviços Energéticos (Energy Services Regulatory Authority)
FES	Facilities an Equipment Management
FMS	Financial Management Service
GHAF	Gestão Hospitalar do Armazém e Farmácia
GIAF	Gestão Integrada Administrativa e Financeira
Global LCI	Global Life Cycle Investment
ISEC	Instituto Superior de Engenharia de Coimbra
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LINAC	Medical Linear Accelerator
MCDT	Meios Complementares de Diagnóstico e Terapêutica (Complementary Means of Diagnosis and Therapy)
MTACM	Minimizing the Total Average Cost Method
MTACM-RPV	MTACM with Reduction to the Present Value
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
OPEX	Operational Expenses
PM	Planned Maintenance
PO	Purchase Order

SAMP	Strategic Asset Management Plan
SGICM-LF	Sistema de Gestão Integrada do Circuito do Medicamento Logística e Farmácia (Integrated Management System for the Medicines Chain Logistics and Pharmacy)
SoD	Sum of Digits Method
UAIM	Uniform Annual Income Method
ULS Coimbra	Unidade Local de Saúde de Coimbra (Local Health Unit of Coimbra)
WHO	World Health Organization

SYMBOLS AND VARIABLES

A	Weight factor for the economic performance
A_O	Operational Availability
AP	Active Energy
ak	Acquisition year
B	Weight factor for the environmental performance
CM_j	Maintenance costs in the year j
C_n	Average cost of ownership for the year n
C'_n	Exploration cost in year n
C''_n	Devaluation value per year n
C_n	Total average cost in year n
CO_j	Operating costs in the year j
CT_n	Cost per Treatment in year n
d_n	Annual depreciation rate
d	Annual depreciation rate
EA	Acquisition Emissions
EEI_s	Eco-Analysis Index for the alternative scenario
E_n	Total average emissions in year n
En_r	Environmental performance for the reference scenario
En_s	Environmental performance for the alternative scenario
EO_j	Operating Emissions in the year j
E_r	Economic performance for the reference scenario
E_s	Economic performance for the alternative scenario
ET_n	Average Emissions per Treatment in year n
FT	Fixed Tariff
f	Inflation rate
i_A	Apparent rate
i	Interest rate
k	Replacement Year

N	Timespan corresponding to R
n	Analysis Year
O_R	Occupancy Rate
PC	Power Charges
R	Residual asset value after N time periods
RP	Reactive Energy
T	Annual depreciation rate
TI_n	Total Investment in year n
T_P	Number of Possible Treatments
T_r	Number of treatments performed in year j
VA	Asset acquisition value
VA_C	Challenger Acquisition Value
VA_D	Defender Acquisition Value
VCD_k	Defender Cession Value in year k
VC_n	Cession value in year n

1 INTRODUCTION

This chapter serves as an introduction to the content presented and discussed in this internship report. Specifically, it provides a brief overview of the host institution and the department where the internship took place, the research questions addressed, and the structure of the report.

1.1 Encouragement

This thesis represents a vital step in advancing asset management practices within a public hospital setting, an area that remains largely underexplored despite its immense potential for positive impact. Every incremental improvement in this domain has the power to drive meaningful change across three critical sustainability dimensions: social sustainability, by possibilitating better and more accessible treatments for patients; financial sustainability, through waste reduction and more effective resource management; and environmental sustainability, by optimizing decision-making to minimize the ecological footprint of hospital operations.

Building on the foundations of a master's program in Engineering and Physical Asset Management, this work integrates key concepts from systems engineering, optimization, management, and decision-making to ensure assets are managed as efficiently as possible. When applied in the context of a public hospital, this internship report seeks to not only contribute to the operational efficiency of the hospital, but also support its overarching goal of delivering better healthcare outcomes. By demonstrating how robust asset management strategies can lead to tangible improvements, this work aims to inspire a shift toward a more sustainable, conscientious, and effective approach to healthcare resource management.

1.2 CHUC/ULS

The Coimbra Hospital and University Center (CHUC) was created in 2011 by Decree-Law no. 30/2011, March 2, with the merger of the University of Coimbra Hospitals, the Daniel de Matos Maternity Hospital, the General Hospital, the Pediatric Hospital, the Bissaya Barreto Maternity Hospital, the Sobral Cid Hospital, the Lorvão Hospital, and the Arnes Recovery Center. It is classified as a public business entity, part of the healthcare network of the Portuguese national health service [1]. In terms of direct catchment area, the CHUC serves approximately 400 000 people, and if indirect areas are considered, this figure reaches around 1.8 million inhabitants [2]. During the development of the present work, it was considered the biggest hospital center in Portugal, with 18 Reference Centers, 11 European Reference Networks, and the highest budget for a Portuguese public health institution in 2023 [3], at 657 897 780 Euros, approximately 8 500 employees, and 150 000 registered assets. These numbers are a direct result of the high volume of hospital activity, as shown in Table 1.1 that exhibits some of the key assistance activity indicators for the year 2022.

Table 1.1: CHUC healthcare activity data for 2022

Activity	**Variable**	**Numbers**	**Daily Average**
Hospitalization	Beds	1 674	-
Surgical Activity	Patients Operated	43 139	118.19
External Consultations	Total EC	900 018	2 465.80
Radiotherapy	Radiotherapy Treatments	21 656	59.33
MCDT's	Radiology Exams	615 298	1 685.75
MCDT's	Clinical Pathology Exams	8 372 409	22 938.11
MCDT's	Physical Med. & Rehab Exams	766 337	2 099.55

During the course of the internship, the organizational framework of numerous national hospitals underwent restructuring. These hospitals became managed according to a model based on local health units, with the objective of guaranteeing the integrated provision of primary and hospital healthcare. These changes were made in accordance with the Decree Law no. 102/2023, November 7th, with an effective amendment on the January 1, 2024. The initiative brings together the CHUC, the Archbishop João Crisóstomo Hospital, the Centre for Rehabilitation Medicine of the Rovisco Pais Central Region, and 26 other health centers in the central region, thus establishing the Local Health Unit of Coimbra (ULS Coimbra).

The scope of the internship lies directly over the Management and Logistics Services, specifically in the Financial Management Service, which is where the Asset Management Team (AMT) is integrated, as seen in Figure 1.1.

In the context of hospital operations, a number of departments exert direct influence on asset management. These responsibilities are described in detail below:

Asset Management Team (AMT): Collecting the characteristics of new assets and documenting them; ensuring the labeling of assets, including when labels are missing; monitoring the recording of asset transactions, such as acquisitions, write-offs, transfers, fixed assets in progress, and disposals; carrying out periodic checks on investment assets; contributing to the improvement of the internal control system, including risk identification, assessment, monitoring, and control; ensuring complete, relevant, reliable and timely financial and non-financial information; and ensuring compliance with legal, regulatory, and ethical requirements.

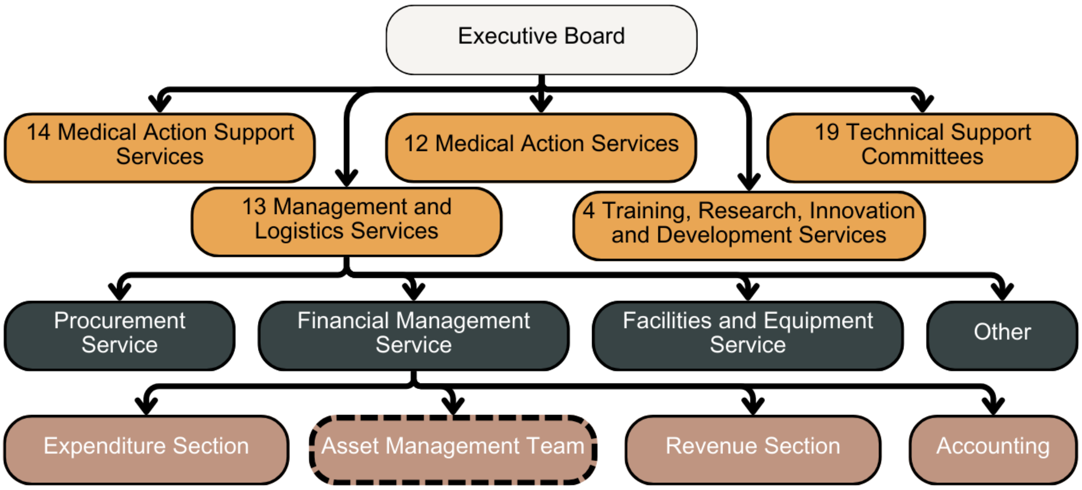


Figure 1.1: Organizational ULS Coimbra chart, situating the area of activity of this internship, Asset Management Team

Procurement Service (**PS**): Acquiring investment goods in accordance with public procurement rules and the procedures outlined in internal manuals, receiving and coordinating the reception of investment goods in collaboration with the relevant services.

Financial Management Service (**FMS**): Guaranteeing accurate accounting of invoices and credit notes, paying invoices after checking and as well as receiving capital goods, and contributing to the improvement the internal control system.

Facilities and Equipment Service (**FES**): Collaborating in the receipt of investment goods and its subsequent registration; responding to repair and maintenance requests of various devices, proposing technically and economically justified investments within the scope of the circular economy to extend the useful life of assets; developing and disseminating procedures for the safe and effective use of equipment; and contributing to the improvement of the internal control system, especially with regard to safeguarding assets, the efficient use of resources, and compliance with legal and regulatory standards.

Information Systems and Technologies Service (**ISTS**): Responding to requests for the repair, maintenance, or replacement of IT equipment; proposing and providing opinions regarding the acquisition of IT equipment; managing the IT park; and collaborating in the reception and inventorying of IT equipment.

Patrimony, Investments and Project Management Office (**PIPMO**): Carrying out periodic checks on investment goods; collaborating in the continuous updating of the inventory of the Equipment Park, and issuing a statement on the acceptance of donated equipment, especially concerning the use of consumables, seeking out legal and technical opinions as necessary.

1.3 Research Questions

The internship provided an opportunity to become familiar with the institution, contribute to solving internal issues, and focus on research aimed at addressing three major questions related to asset management, which are outlined below:

RQ1 – What is the optimum replacement point for the studied medical linear accelerator?

RQ2 – How does technological evolution impact the optimum decisions for asset management and replacement?

RQ3 – How does sustainable management impact the life cycle of equipment and the decision for its replacement?

The answers to these questions are found throughout the present report, being directly addressed in Chapter 7.

1.4 Report Structure

This report is comprised of seven chapters and X appendixes, which are divided into the following topics:

- Chapter One, Introduction: This chapter provides an overview of the host organization, outlines the research questions, discusses the trainee's motivation, and presents the structure of the report;
- Chapter Two, State of the Art: A literature review is presented to familiarize the reader with the concepts applied in this report and to provide support for the work conducted during the internship;
- Chapter Three, Monitoring of Assets Between the Time of Purchase and Registration: This chapter introduces and describes a data analysis tool to mitigate inventory management problems, using a PowerBI Dashboard capable of providing timely and objective information;
- Chapter Four, Replacement Models for Medical Equipment: Asset life cycle is analyzed in monetary terms to determine the global minimum average annual cost and the minimum average annual cost per treatment. A new approach to these problems is also proposed through the introduction of the dynamic model, which directly compares potential replacement assets;
- Chapter Five, Life Cycle Assessment: In an increasingly eco-conscious world, this chapter aims to uncover the environmental impact of the assets during the usage stage;
- Chapter Six, LCC vs LCA Integration: This chapter makes use of an Eco-Efficiency

Analysis, integrating the LCC and LCA assessments in order to estimate an optimal replacement year for the equipment under study, based on both economic and environmental perspectives;

- Chapter Seven, Conclusions and Further Research: This chapter presents a comprehensive overview of the internship project, including key findings, challenges encountered, and potential avenues for future investigation, based on the insights and experiences documented in this report;
- Appendix A, Dashboard for Monitoring of assets between the time of purchase and registration: This appendix shows the template of the dashboard that was developed as part of the work outlined in Chapter 3;
- Appendix B, Interpretation Support Table: Provides a table to support the interpretation of the dynamic model results;
- Appendix C, Replacement Models Results: Gathers all the main results from the utilized replacement models;
- Appendix D, Meta-Analysis: This Appendix shows a simple meta-analysis made for all the books and papers present on the bibliography of this report.

2 STATE OF THE ART

This chapter intends to present a literature review on the main topics and methodologies addressed during the internship, providing a background for a better understanding of the work undertaken.

2.1 Asset Management

The work carried out during the internship was grounded in asset management principles, emphasizing the need to conceptually understand it and distinguishing its holistic management approach from simple maintenance management.

An asset is defined as an item or a thing, tangible or intangible, financial or non financial, that holds potential or real value for an entity. The management of these assets is established by effective asset control and governance, and it can be described as the coordinated activity of an organization to realize value from assets according to its organizational objectives, through risk and opportunity management [4].

Asset management can be adapted to pursue the objectives of every industry and entity, whether finance, health, environment, or safety-related. The benefits of this type of management can be financial, through the improvement of return on investment and the reduction of associated costs; administrative, by gathering and analyzing asset data to perform informed decisions and manage asset-related risk; social, by means of reducing emissions and increasing resource conservation; among others [4]. The application of effective practices is demonstrably linked to enhanced sustainability outcomes across three key areas: economic, environmental, and social performance. These in turn, contribute to the achievement of sustainable development goals [5].

An asset Management System is integrated in the function of Asset Management, as seen in Figure 2.1,it is comprised of tools designed to ensure efficient asset management activities, such as plans, processes, information systems, or even policies [4]. This system is used to monitor and control the aforementioned activities.

The asset portfolio refers to the assets that are within the scope of the asset management system, which the World Health Organization refers to as the medical equipment inventory. From it, one can extract information about technical assessment of the technology, details on equipment types and quantities, and the current operating status, providing the basis for asset management [6].

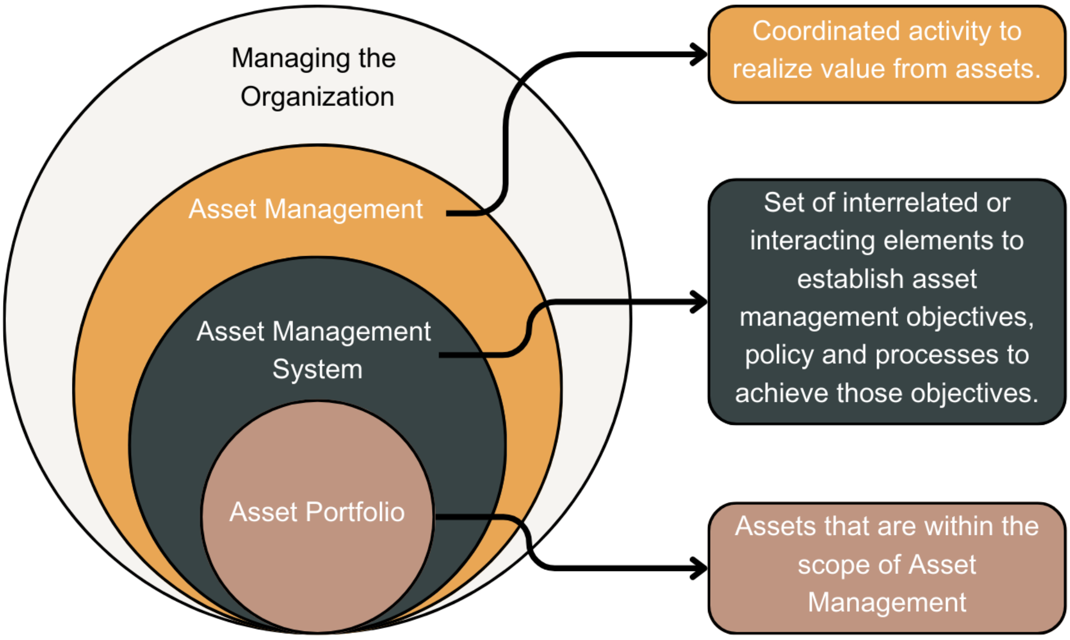


Figure 2.1: Relationship between Asset Management concepts, adapted from [4]

There is a common trend where asset management is typically only associated with maintenance tasks. However, in cases where direct maintenance is not feasible, such as with many medical devices, asset management entails supervising maintenance contracts, guaranteeing legal compliance, monitoring the asset's life cycle, and managing related processes. This encompasses coordinating with external service providers for upkeep, monitoring regulatory requirements, and making informed decisions about the asset's eventual replacement or disposal. This broader scope ensures that assets remain compliant, functional, and cost-effective throughout their operational life and life cycle.

2.1.1 Asset Life Cycle

The standard ISO 55000 defines the life cycle as the "stages involved in the management of an asset," noting that all stages and linked activities are determined by the organization [4].

In his work, Farinha [7] proposes eight phases for the life cycle of a physical asset:

- T1 - Decision about acquisition, describing why the acquisition is necessary;
- T2 - Terms of reference, detailing all the technical specifications, information, and special conditions that the supplier has to honor;
- T3 - Market consultation, summarized as the invitation of proposals, definition of terms of reference, and reception of proposals;
- T4 - Acquisition, the analysis of the received proposals in accordance with the

terms of reference, leading to theoretical evaluation to choose the best solution;

- T5 - Commissioning, testing and checking if the asset performs as expected and is compliant with standards and regulations;
- T6 - Production/maintenance, start of operation and asset management;
- T7 - Economic/lifespan issues, assessment of the economic and life cycle;
- T8 - Renewal/withdrawal, decision for keeping or discarding the asset.

All of this highlights that effective and efficient asset management goes far beyond merely monitoring and maintaining the assets already present in an organization. Asset management begins even before acquisition, having to align with the organization's needs and strategies, in order to achieve successful outcomes. Consequently, the entire life cycle of these assets should be carefully managed using a multidisciplinary approach, considering financial, technical, logistical, and even social criteria to gather comprehensive information that facilitates clear and transparent decision-making.

2.1.2 Life Cycle Costing

Decision support methods are essential to assist management, especially if the organization is planning to invest in emerging systems and technologies to increase business performance. Some of these tools are the Life Cycle Costing (LCC) and the subsequent LCC Analysis (LCCA), which project the economic and engineering performance of the company assets, and can lead to improvements in the effectiveness of its systems through investments and modifications on the asset portfolio.

The LCC begins with the decision for acquisition and ends with the withdrawal or renewal of the asset, with the beginning of a new LCC [8] for a replacement asset. This method is expected to quantify alternative options to reach the best asset configuration, optimizing all life cycle associated costs [9].

These models can be shaped in accordance with the enterprise analysis objective, assisting in decision-making processes through the whole life cycle of the product with the aim of maximizing the ratio between benefits and costs. Whether by improving performance for the same cost, or reducing costs while maintaining the same income, the LCC should not be used for a single decision, but for a chain of decisions. The outputs of an LCC can be interpreted in different perspectives, such as operational or managerial recommendations [10].

2.1.3 Life Cycle Assessment

Analogous to LCC, there is the Life Cycle Assessment (LCA). Instead of quantifying economic data and outcomes, it adopts an environmental sustainability perspective.

The metrics used in an LCA focus on the environmental impact generated by equipment, by measuring emissions in $kgCO_2eq$, as an example.

According to the Standard ISO 14040, the life cycle of a product or service relates to all the stages, from raw material acquisition up to its final disposal. Subsequently, the Life Cycle Assessment (LCA) evaluates all the inputs and outputs generated by these stages, as well as the assessment of the potential environmental impacts [11].

– Methodology for LCA

These standards split the LCA into four steps, those being the Goal and Scope Definition, the Life Cycle Inventory Analysis (LCI), the Life Cycle Impact Assessment (LCIA), and the Life Cycle Interpretation, as shown in Figure 2.2.

- The Goal should clearly outline why the study is being carried out, the audience, and the intended application areas. The Scope must specify the detail of the study, its data requirements, and its limitations, to ensure that the study is in line with the goal.
- Life Cycle Inventory Analysis (LCI) is where the data is collected to quantify the inputs and outputs of materials and energy associated with a product system.
- Life Cycle Impact Assessment (LCIA) evaluates the significance of potential environmental impacts with the results obtained through the LCI. This is done by classifying, characterizing, normalizing, and weighing the results.
- Life Cycle Interpretation uses the data and results from the LCI and the LCIA to deliver conclusions, explain limitations, and propose recommendations coherent with the goals and scope.

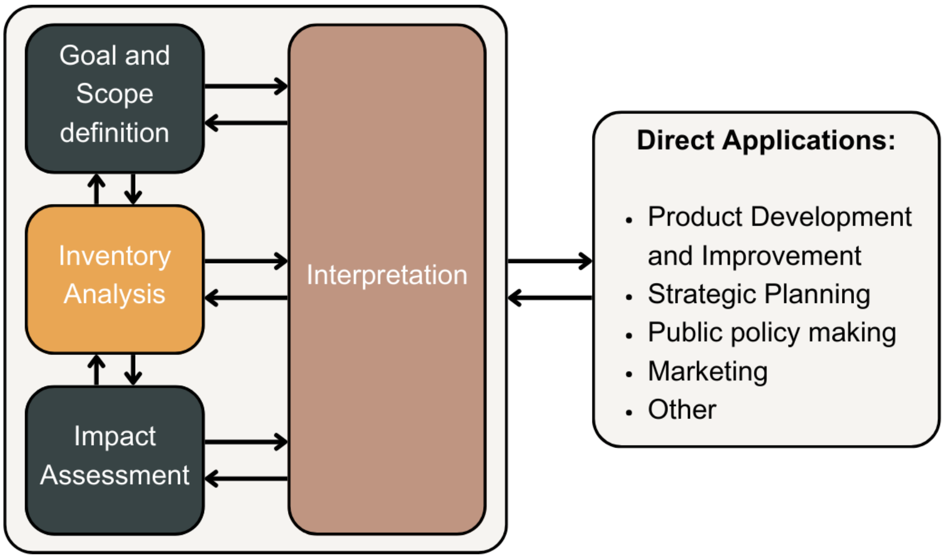


Figure 2.2: Life Cycle Assessment framework, adapted from [11]

LCA has been systematically used for the past three decades, having expanded to identifying and qualifying environmental impacts of a product, process, or activity in an increasingly refined way. Despite its recurrent use, some people support expanding the current LCA framework with the integration of social, cultural, and economic aspects with the aim of improving decision-making towards sustainability. However, broadening and deepening of the LCA can lead to consequences, namely the potential tarnishment of the reputation of the tool. As there is no "one-size fits all" framework, the integration of different aspects becomes subjective to the case study. Not only can the choice of criteria be interest-guided, it may also excessively increase the complexity of the system, making it unattractive for stakeholders. Despite the associated risks, the broadening and deepening of the LCA allows for a detailed and tailored analysis of a product, process, or activity at various levels of governance [12].

2.2 Maintenance

One of the key factors influencing asset life cycle studies is maintenance, service breakdowns, and their associated costs. Continuous usage or inactivity both subjects the equipment to degradation, leading to potential system failures and consequently, unexpected equipment stoppage, poor product quality, or even safety issues [13].

The term maintenance is defined by the Portuguese standard NP EN 13306:2021 [14], as "combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function." This aims to reach targets set by the company, such as "availability, cost reduction, product quality, environment preservation, safety, useful life, asset value preservation" [14].

2.2.1 Maintenance Types

There are several types of maintenance strategies that can be applied to assets, typically categorized into planned maintenance and unplanned maintenance, as shown in Figure 2.3. Planned maintenance (PM) aims to assess and/or mitigate degradation and reduce the probability of failure of an item [14], while corrective or unplanned maintenance (CM) takes place after the fault has been identified [15].

Lately, companies have been realizing that effective maintenance planning and interventions can improve their performance with better spare parts control, production scheduling, and better organization with other company functions, thus increasing their profits [16].

In an attempt to unveil the costs/benefits associated with the investment in superior levels of maintenance techniques, a survey was made by Thomas, *et al* [17], targeting

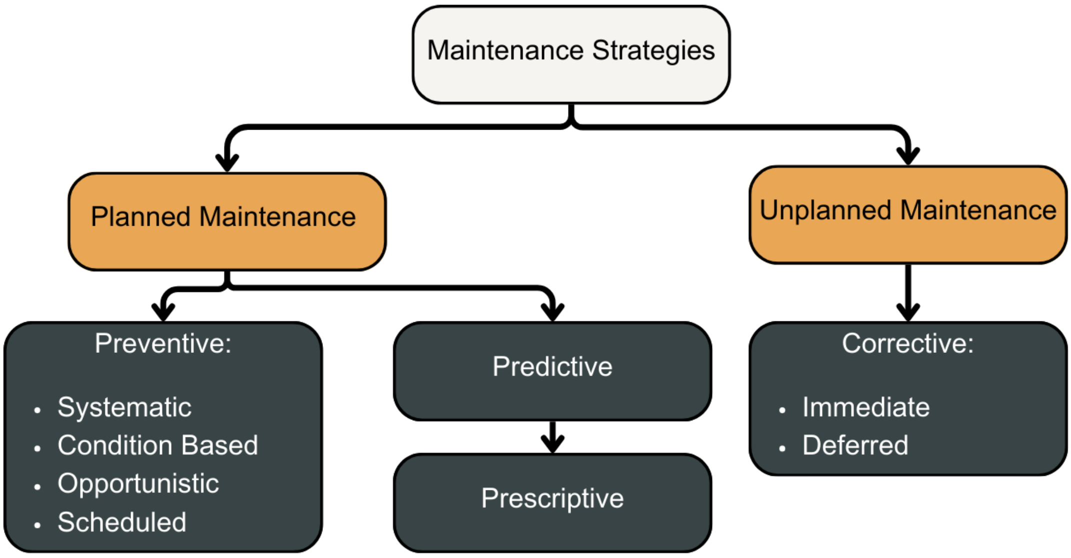


Figure 2.3: Maintenance strategies

managers of machinery maintenance of 13 small, 48 medium, and 9 large organizations in the manufacturing industry. According to the collected data, it was possible to suggest the benefits of moving from unplanned/corrective maintenance into preventive or predictive maintenance, with results showing the half of the surveyed entities which relied more on predictive and preventive maintenance boasted 52,7% less unplanned downtime and 78.5% fewer defects [17].

In a productive and profitability approach, the stoppage of equipment can lead to high losses with direct impact in the organization's finances, mostly due to lost sales [17], the failing of timely services, and the subsequent loss of customers, and potential safety and environmental problems, all of which decrease company reputation. A simple unplanned stoppage for a day is hard to recover from without the application of additional costs, such as emergency spare parts or overtime work [16].

In a particular case study carried out by Alsyouf, *et al* [16], the usage of an improved maintenance policy could result in increased productivity, generating an extra profit of approximately 0.898 million euros (€), which corresponds to a growth of about 4% of the surveyed company's total yearly profit.

Through a study targeting the maintenance costs in flight delays caused by aircraft air conditioning, Gerdes, *et al* [18] calculated that air conditioning costs 5.07 € per flight due to related delays. Through the implementation of Condition-Based Maintenance (CBM) on air conditioning systems, delays could e reduced by up to 80%. However, assuming that the availability of most aircraft parts is limited, they consider a reduction of only 20% of delays to be a likelier estimate. This means that CBM could save up to 1.01 € per flight, with approximately 6 million flights per year in the European Union alone. However, the authors defend that there is still progress to be made in order to implement good condition monitoring without requiring unnecessary work.

2.2.2 Failure Rates

As previously described, maintenance strategies can vary significantly depending on the type of equipment, the nature of the failures, and the frequency of these failures, all of which are directly related to the overall reliability of the asset. Therefore, reliability can be defined as: *the probability that an item will perform a required function without failure under stated conditions for a stated period of time* [19].

The reliability of products over their lifespan can be represented by pattern distributions, with the most generic model being the bathtub curve, seen in Figure 2.4. This hazard function can be organized into three easily recognizable periods [20, 21]:

- Early life failures or burn-in period, where the failure rate decreases over time, usually relating to poor design or manufacturing errors;
- Random failure with a quasi-constant failure rate;
- Wear-out failures, with a progressive positive growth due to mechanism degradation.

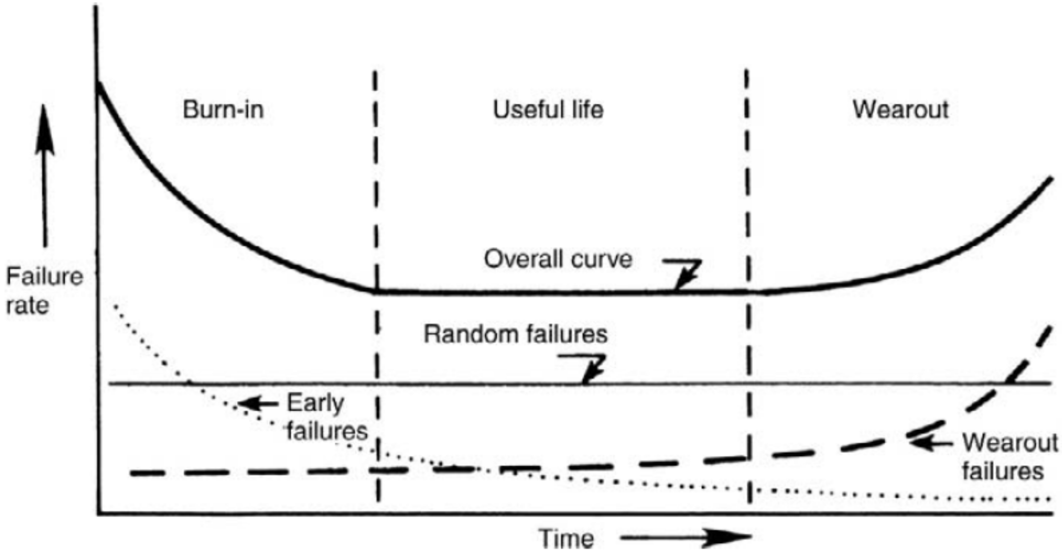


Figure 2.4: Visualization of a Bathtub Curve [22]

Although this model was first applied in life cycle analyses in the 17th century and is currently referenced in much of the literature dealing with reliability engineering, there are several criticisms of the model and its applicability [20]. Among these critics, some have suggested that only a small number of products exhibit a reduction in failure rates during the early life stages, followed by an increase in failure rates during the later stages [23], with the bathtub curve applying to 15% of the applications or fewer [24]. The application of these models to electronic components also raises questions, as they rarely have infant mortality failures. This is because they are designed to handle random failures that can only be formulated using real data, meaning that the traditional bathtub curve can lead to unreliable results that influence various decisions, such as adapting maintenance strategies [25].

After presenting these concepts, it becomes evident that each equipment is unique. One of the most effective ways to achieve more accurate results is, whenever possible, by modeling the equipment's failures based on its historical data.

2.3 Medical Equipment Management

Given the aforementioned host institution, the work primarily focuses on hospital assets, with an emphasis on medical equipment. As this is an industry with many specificities, it is beneficial to conduct a literature review on asset management, particularly those practices tailored for hospitals.

The global medical device market size is projected to grow from 470.86 billion € in 2024 to 587.66 billion € by 2028. [1]Medical device manufacturers report an increasing investment in research and development. Medtronic, for example, recorded a growth of approximately 368.44 million € in 2 years, from 2.15 billion € in 2020 to 2.53 billion € in 2022 [26].

This increase can be attributed to several factors, such as general increases in life expectancy (which does not necessarily translate into healthy life expectancy), a growing prevalence of cancer and other chronic diseases, and a greater demand for earlier diagnosis and treatment [27].

Medical devices and medical equipment are often referred to using the same definition, which is not entirely correct. As transcribed from the European Regulation 2017/745, [28]:

"Medical device" means any instrument, apparatus, appliance, software, implant, reagent, material or other article intended by the manufacturer to be used, alone or in combination, for human beings for one or more of the following specific medical purposes:

- *— diagnosis, prevention, monitoring, prediction, prognosis, treatment or alleviation of disease,*
- *— diagnosis, monitoring, treatment, alleviation of, or compensation for, an injury or disability,*
- *— investigation, replacement or modification of the anatomy or of a physiological or pathological process or state,*
- *— providing information by means of in vitro examination of specimens derived from the human body, including organ, blood and tissue donations and which does not achieve its*

---

[1] Data From Statista: https://www.statista.com/outlook/hmo/medical-technology/medical-devices/worldwide, accessed 07 Apr 2024

principal intended action by pharmacological, immunological or metabolic means, in or on the human body, but which may be assisted in its function by such means.

Complementarily, the World Health Organization (WHO) defines medical equipment as a medical device used for the specific purpose of diagnosis and treatment or rehabilitation following illness or injury that requires calibration, maintenance, repair, user training, and decommissioning. This definition excludes implantable, disposable, or single-use medical devices [6].

According to Willson [29], and complementing Farinha [7], the life cycle of medical equipment starts with the demonstration of need for replacements or acquisitions of additional devices, up to their decommission and disposal, as seen in Figure 2.5.This cycle involves the majority of hospital management and logistics services, making effective communication between them crucial for seamless and comprehensive asset management.

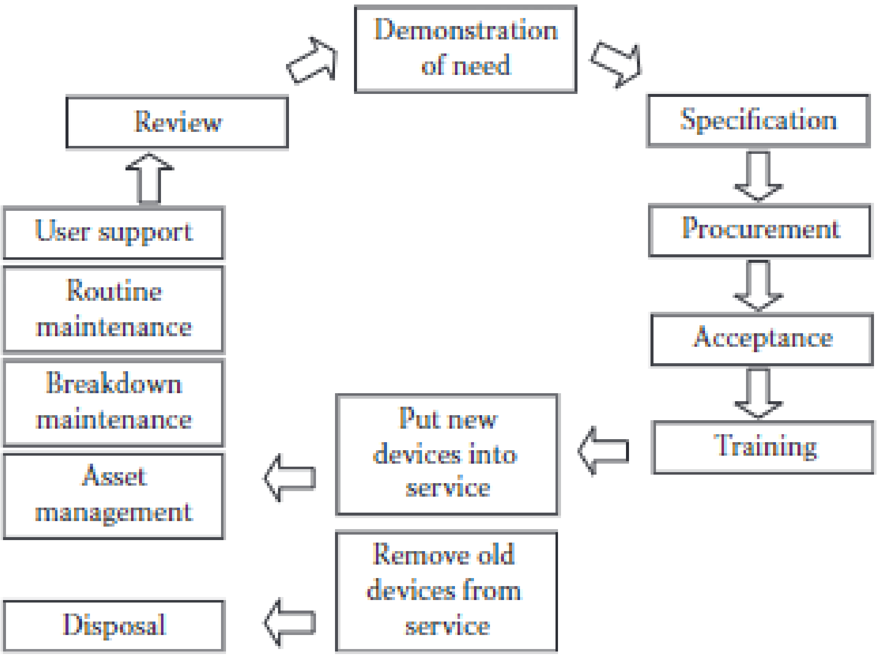


Figure 2.5: Medical equipment life cycle [29]

A successful Medical Equipment Management Program depends on three key elements: the inventory, the methodology, and the resources available to the program, which will ultimately be dependent on financial, human, and operational resources [30]. Given the considerable number of hospital assets and their tendency to increase, maintaining tight control over all equipment is a challenging task, resulting in the potential for some critical equipment to be neglected. One feasible solution to this issue is to classify equipment according to a specific prioritization rule, aiming to ensure that the management program is feasible and aligns with the hospital's operational needs.

The WHO has identified a number of theories of asset prioritization. Mission-based prioritization seeks to identify the most important equipment for providing healthcare services, while risk-based prioritization identifies the equipment most likely to result in adverse patient outcomes should it fail. Resource-based prioritization represents a more comprehensive approach, which considers a wider range of human, financial, and operational resources [30].

2.3.1 Medical Equipment Maintenance

The primary challenges of medical equipment maintenance management in healthcare are linked to quality and cost-effectiveness. These can be influenced by several factors, such as quality control, financial, human, and physical resources, documentation, education, maintenance services, and strategies [31].

The failure to maintain or implement an appropriate maintenance strategy for these assets can result in unnecessary costs, with a particularly pronounced impact in lower-income countries. It is therefore important to account for the costs of downtime - meaning lost revenue due to inoperative equipment - in order to conduct a reasonable analysis.

In addition to the operational costs associated with the lack of proper equipment maintenance, there is an even more significant and important impact: the social implications. This includes adverse effects on patients, such as the lack of adequate treatment and the possibility of misdiagnoses, which would lead to the tarnishment of the image of the hospital and its professional, as well as unfortunate legal implications [32].

The cost of routine and breakdown maintenance of medical equipment usually settles between 5% and 10% of its purchase cost [29]. In some cases, simply having contracted maintenance for medical equipment means that the cost of ownership is considerably lower than having no maintenance at all [33].

In an attempt to have a better data analysis for medical equipment maintenance, Iadanza, *et al* [34] proposes a failure classification through the review of technical reports and clinical engineering, in the context of an hospital with 1 367 beds and 16 209 pieces of equipment. The results possibilitated the development of a histogram by failure type. In this particular case, 410 defibrillator units were analyzed. 60.40% of their CM work orders were linked to battery problems, which prompted suggestions to acquire batteries with better longevity or train users to correctly manage and monitor the equipment [34].

This type of assessment could be enhanced with the integration of costs related to the work orders, possibly applying concepts like the Cost-Benefit Analysis to give a broader insight for asset management.

Eze, *et al* [35] compiled the factors that influence the poor availability of medical equipment with a review of related literature, and used the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method to measure the prominence levels of each factor. The results of the study show that the remanufacturing of medical equipment has a potential contribution of 43,5% in addressing the asset's availability, making it a feasible strategy to improve this Key Performance Indicator (KPI).

2.3.2 Medical Linear Accelerators

A Medical Linear Accelerator (LINAC) belongs to a list of radiotherapy equipments. The Portuguese Oncology Society defines radiotherapy as a form of cancer treatment that uses radiation to target and destroy cancer cells. It is considered a localized treatment because it typically focuses on the specific area of the body where the tumor is located. The radiation can be delivered externally, directed precisely at the tumor from outside the body, or internally, through the placement of small radioactive implants near or within the tumor.

In terms of cancer burden, it is expected to increase by 77% from 2022 to 2050, mostly due to population growth, ageing, and exposure to risk factors

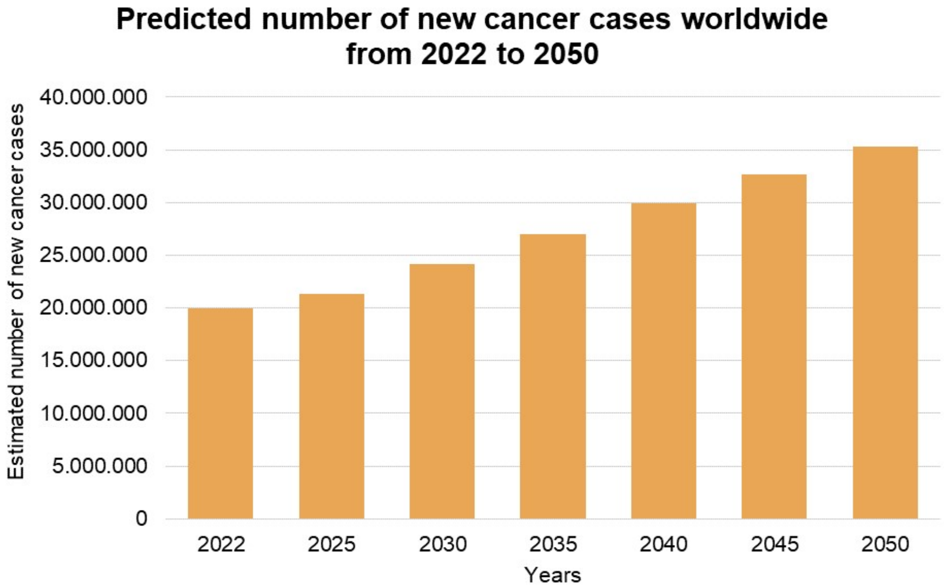


Figure 2.6: Predicted number of new cancer cases worldwide from 2022 to 2050[2]

Despite the rising number of new cancer cases and the existence of waiting lists for radiotherapy treatments, Resolution of the Council of Ministers No. 61/95, dated June 28, based on Decree-Law No. 95/95 of May 9 imposes strict limits on the acquisition and installation of heavy medical equipment. Under this legislation, the number of external radiotherapy devices is restricted to one unit per 250 000 inhabitants. This limitation underscores the critical importance of efficient management of installed equipment.

---

[2] Data from: WHO - International Agency for Research on Cancer, https://gco.iarc.fr/tomorrow/en/dataviz/trends, accessed 23 May 2024

In the hypothetical scenario where a linear accelerator becomes non-operational due to technical or administrative issues, a significant number of treatments may go unperformed. Consequently, this legislation necessitates maximizing the availability of existing equipment, optimizing operational hours, and ensuring the highest quality of care, to address the increasing demand effectively.

2.4 Asset Replacement Models

As gathered by Caropul, *et al* [36], the main reasons that lead to asset replacement the eventual inadequacy of the equipment for its activity, the end of its useful life, technological obsolescence, or other methods proving to be economically advantageous.

Replacing an asset stands on the basic principle of comparing data to understand if the benefits of keeping it for another time period are superior or inferior to the opportunity benefits from a new asset during the same period [37].

Thus, the replacement problem hinges on the definition of the optimum replacement year which maximizes (e.g. profit, production) or minimizes (e.g. costs, environmental impact) one or several metrics specified by the company.

To obtain a solution to this problem, in a financial perspective, specific data is required. According to Ioannou [38], the key parameters for asset life cycle economics are the Capital Expenses (CAPEX), Operation Expenses (OPEX), and Decomissioning Expenses (DECEX). This data is crucial for the LCC analysis, which will then serve as the foundation for the replacement models.

However, the acquisition of this data always carries a certain degree of uncertainty concerning future values or,in other words, to predict what will happen. One of these values is the cession value or withdrawal value, which reflects the price the asset will have in the market in the future.

To define the withdrawal value of an asset, it is necessary to know its present market value, which is not always easy for all types of assets. For these more difficult cases, one can apply depreciation methods with known or calculated variables in order to simulate the cession value [39].

The most common depreciation methods are calculated as follows[7]:

- Linear Method - Constant devaluation throughout the years:

$$d = \frac{VA - R}{N} \tag{2.1}$$

$$VC_n = VA - n * d \tag{2.2}$$

where:

d – Annual depreciation rate
VA – Asset acquisition value
R – Residual asset value after N time periods
N – Timespan corresponding to R
VC_n – Asset value in a certain devaluation period n shorter than N

- Sum of Digits Method - Intermediate devaluation, between linear and exponential methods:

$$SD = \frac{N(N+1)}{2} \tag{2.3}$$

$$d_n = \frac{N-(n-1)}{SD}(VA-R) \tag{2.4}$$

$$VC_n = VC_{n-1} - d_n \tag{2.5}$$

where:

VA – Asset acquisition value
d_n – Annual depreciation rate
R – Residual asset value after N time periods
N – Timespan corresponding to R
VC_n – Asset value in a certain devauation period n

- Exponential Method - The asset devalues at a higher rate in the first years.

$$VC_n = VA(1-T)^n \tag{2.6}$$

$$T = 1 - N\sqrt{\frac{R}{VA}} \tag{2.7}$$

where:

VA – Asset acquisition value
T – Annual depreciation rate
VC_n – Cession value in year n
n – Analysis Year
R – Residual asset value after N time periods

Figure 2.7 illustrates the application of these models to a fictitious asset with an acquisition cost of 1 000 000€ and a residual value of 10 000€ in the timespan of 10 years.

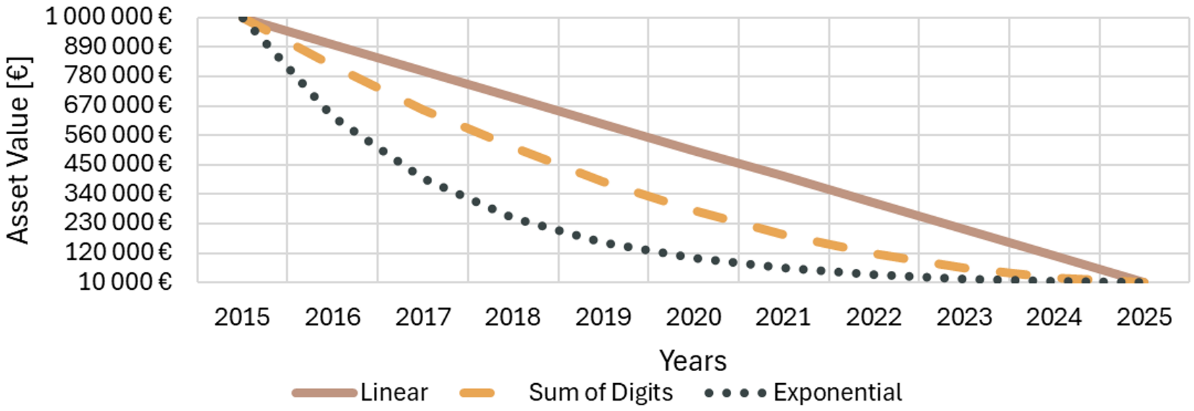


Figure 2.7: Example of depreciation methods

It is also important to note that the cession value is not the same as the residual value, although they may sometimes coincide. The cession value represents the potential value an asset could have in each year of analysis, while the residual value is defined as the minimum value the asset could be worth.

After data collection, these can be entered into various mathematical models for asset replacement, with the most common ones being described below [7]:

- Uniform Annual Income Method (UAIM) - Determines the time, in years, it takes for the asset to reach its lowest uniform annual cost, calculated with a recovery factor.
- Minimizing the Total Average Cost Method (MTACM) - Determines the lowest average cost of the asset that corresponds to the most rational optimal replacement time.
- MTACM with Reduction to the Present Value Method (MTACM-RPV) - Same theory of MTACM but it also considers the interest rate and inflation rate through an apparent rate.
- Useful Life - Determines the useful life of an asset in accordance with the CAPEX and OPEX.
- Life Cycle Investment Global Analysis - Considers not only expenses and rates, but also profits, allowing for an evaluation of the assets' profitability.

In order to reduce the money to the present value, an apparent rate can be used, which in turn can be calculated using Fisher's Equation, illustrated below. This rate makes use of the real interest rate and the inflation rate, but some authors introduce other variables in order to shape the formula with detail and improve the trustworthiness of their models. Farinha, *et al* do this [40], also taking the profit rate and the risk rate into account.

$$(1 + i_A) = (1 + i) \times (1 + f) \tag{2.8}$$

where:

i_A – Apparent rate
i – Interest rate
f – Inflation rate

These models can be shaped to incorporate variables that enhance the detail of the analysis, as exemplified by Farinha. With an extensive career in life cycle analysis and asset replacement, he is able to integrate maintenance indicators and various rates, such as profit and risk rates, to obtain more comprehensive results [7, 40].

Their adaptability is also demonstrated in multiple analyses ranging from cases where available data is quite limited, to situations involving large industries that provide a substantial amount of high-quality data, as illustrated by Figueiredo through analyses of public playgrounds and a major company in the paper industry [41].

2.4.1 Economic and Environmental Replacement Models Integration

The individual interpretation of different analyses is valuable for understanding how the subject of the study performs across various dimensions. However, decision-making may become challenging when multiple outcomes must be considered to reach a single conclusion. Therefore, it is essential to integrate the results of the various analyses in a coherent and structured manner to ensure that decisions are both clear and objective.

Integrating different perspective models can be used to compare, for example, the financial and environmental impact of single-use medical devices versus reusable devices. For example, Sherman [42] conducted an analysis of both disposable and reusable laryngoscopes, concluding that disposable devices have up to 16 times more emissions per use and up to 18 times more yearly associated costs than the reusable alternative.

The integration can be performed by taking into account a life-cycle framework that follows the product's value chain, acquiring data that can better support decision-making, potentially reducing costs, improving environmental and economic performance, and meeting sustainable development goals [43].

Bierer [44] argues that a stronger integration between the LCC and LCA should be pursued to avoid double work and inconsistent results. This is because, when done in parallel, these approaches differ in scopes, life cycle models, scenarios, and data bases. "A challenge of an integrated LCC & LCA system model is to align the modeling approaches."

In a practical case study, Calado [45] developed an integrated LCA with LCC model to choose the best configuration for a medium-size cargo aircraft elevator. The model is capable of calculating the environmental impact and the life cycle cost of aircraft structures, making it an effective decision-making tool for sustainable terms. The author concluded that the results of the tool could be analyzed even before the prototyping and testing, and found that with a balance between performance and optimum solution for maximum structural stiffness, it is possible to reduce the environmental and costs during the life cycle of the plane by 53% and 51%, respectively.

Eco-Efficiency Analysis

The growing emphasis on sustainability has prompted the introduction of decision-support tools designed to promote more sustainable development, including eco-efficiency analysis [46]. This tool can be seen as an evaluation of sustainable development parameters, aiming for the reduction of resource consumption while maintaining or improving the value of an asset [47]. It is considered an enhanced analysis due to the direct connection between environmental impacts and economic performance [48], through an integration of LCC and LCA [49].

The eco-efficiency analysis results in a graphic representation on a two-dimensional plane, economic and environmental, providing a direct interpretation of the comparison between various possible scenarios and the reference values [50].

The reference point is located at the origin $(0, 0)$, while the scenario results will be distributed on the plane, according to their relationship with the reference values. These points are represented by (x_s, y_s) values, in accordance with Formulas 2.9 and 2.10, which define their coordinates.

$$x_s = \frac{E_r - E_s}{E_r} \tag{2.9}$$

$$y_s = \frac{En_r - En_s}{En_r} \tag{2.10}$$

where:

E_r – Economic performance for the reference scenario
E_s – Economic performance for the alternative scenario
En_r – Environmental performance for the reference scenario
En_s – Environmental performance for the alternative scenario

The results obtained for each scenario could be distributed in one of the following quadrants of a Cartesian plane:

- Quadrant I $(+, +)$: The alternative scenario demonstrates a positive solution, outperforming the reference one in both the environmental and economic components.

- Quadrant II (–, +): In this situation, the alternative scenario is preferable from an environmental standpoint, but it is less economically viable than the reference scenario.
- Quadrant III (–, –): If the result of the alternative scenario falls into this quadrant, it indicates that transitioning from the reference scenario to this one is a disadvantageous solution in all aspects of the analysis.
- Quadrant IV (+, –): In contrast to Quadrant 2, this quadrant offers a more financially efficient scenario, though with less favorable environmental results than the reference value.

An example of the graphical output is provided in Figure 2.8. The scenarios are compared percentage-wise between five possible alternatives that are spread across the four quadrants of the Cartesian plane. This example shows that scenario 2 would have a worse financial and environmental performance. Scenario 5 reflects a better environmental result with a worse financial result, as opposed to scenario 6, which has a slight economic advantage but a major environmental disadvantage. Finally, scenarios 1, 3 and 4 are all located in the 1st quadrant, showcasing improvement in both aspects.

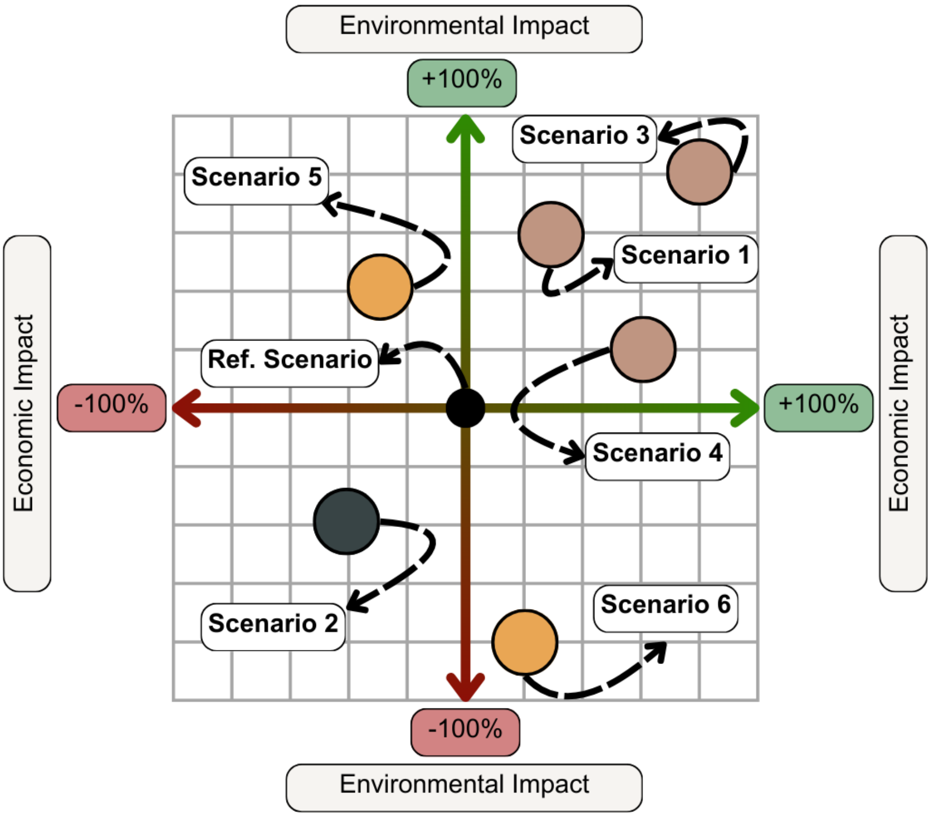


Figure 2.8: Eco-Efficiency analysis example

To enhance the eco-efficiency analysis, an index is utilized, calculated in accordance with Formulas 2.11 and 2.12, providing a numerical ranking to supplement the graphical result [50].

$$EEI_s = A * x_s + B * y_s \tag{2.11}$$

$$A + B = 1 \tag{2.12}$$

where:

EEI_s – Eco-Analysis Index for the alternative scenario
A – Weight factor for the economic performance
B – Weight factor for the environmental performance

The weight factors are subjective for each individual study, organization, or decision-makers, according to the relative importance or priority assigned to each aspect. The outcome is then determined accordingly.

2.4.2 Decision-Making Supported by Replacement Models

Asset replacement can be a strategic decision based on a variety of criteria, which may include the equipment itself or external factors affecting the asset. Such factors may include patient and operator safety, low performance or a high failure rate, technological development and obsolescence, technical support, standardization, regulation and associated legislation, economic benefits, among others.

Performing an asset replacement analysis through mathematical models can help organizations better understand the costs that result from a simple LCC. Moreover, it may allow for the consideration of several optimum replacement times that can be graded according to the organization's objectives. It is important to clarify that the results from the models cannot be blindly interpreted as the perfect solution. To ensure quality in the decisions, one must choose the most appropriate model for the study, understand the model, ensure the comprehensibility and quality of the input data, and analyze the outputs according to the Strategic Asset Management Plan (SAMP), acknowledging the limitations of the model.

In conclusion, any model should be employed as a decision-support tool, rather than as the only relevant indicator of the optimal point at which to replace equipment. There is a wealth of qualitative information that is not incorporated into the model, which can have a significant impact on the decision, such as the quality of patient care and its long-term implications.

In the context of effective medical equipment management, poor patient care linked to equipment failures or suboptimal performance can lead to substantial costs. When medical equipment isn't properly maintained or managed, it may malfunction or deliver inaccurate results, compromising the quality of care. This can result in misdiagnoses, ineffective treatments, or even patient harm, all of which may necessitate additional hospital visits, extended stays, or corrective procedures—each adding avoidable costs. Proper decision-making surrounding equipment management includes data from regular maintenance, timely replacements, compliance with regulatory standards, and life cycle monitoring. Investing in these areas minimizes the risk of breakdowns, ensures accurate diagnostics and treatments, and ultimately reduces both direct and indirect costs associated with patient readmissions and prolonged treatments. In this way, a proactive approach to medical equipment management directly supports both patient safety and financial efficiency in healthcare.

3 MONITORING OF ASSETS BETWEEN THE TIME OF PURCHASE AND REGISTRATION

This chapter outlines the development of a tool created as part of a project proposed by the host institution. The tool is designed to streamline the monitoring of assets, from their acquisition to their registration. It also enables the swift identification of discrepancies within this process, allowing for a quick resolution.

The effectiveness of asset management is contingent upon the quality and quantity of information available to facilitate an understanding of the entire asset environment. This understanding, in turn, allows for decisions to be adjusted in accordance with a Strategic Asset Management Plan (SAMP). The SAMP documents the relationship between organizational and asset management objectives, and provides a framework for achieving them [51]. Empirical studies indicate that the adoption of the right SAMP could help companies lower costs and risk, and boosting the performance of their assets [5]. In essence, effective asset management exerts influence over the process of decision-making in order to reduce costs and risk, and to pursue optimal performance.

As stated by Hastings [52], the success of asset management is dependent on the clear comprehension of the assets employed in the operational and sustaining functions of the business.

The asset portfolio provides the foundation for effective asset and organizational management. In essence, one can only manage that which currently exists, and thus, a complete and standardized asset database constitutes the key to gather optimal results from asset management. In regard to tangible assets, they must also be physically marked in order to confirm their location and distinguish them from other, identical assets.

In terms of hospital management, the asset portfolio should document all existing equipment, allowing the engineering department to carry out customized management concerning in-house and contracted maintenance, patient and user safety, and professional team management. Additionally, the information that can be retrieved from this database has a significant impact, supporting the development of budgets and the comprehension of investment needs, tracking operating costs, and facilitating associated risk analysis [6].

For the department that hosted the internship, FMS, there are three main areas of interest in the proper and complete inventorying of hospital assets. Firstly, it is part of the AMT remit to maintain accurate records and control of all hospital assets in order to provide accurate information to all other hospital services. For the Expenditure Sector, it is vital to be able to identify all hospital assets so that invoices can be analyzed. This allows any unpaid invoices to be easily identified and any non-compliance issues to be regulated, such as the return of an asset to the supplier. Lastly, due to legal obligations and the organization's financial control, the Accounting Sector uses the data from the asset portfolio to monitor the total value of the assets in the hospital's possession and calculate the respective depreciation, in line with fiscal responsibility.

Given the context, the ultimate aim of this work is to develop a dashboard that is simple to visualize, but which contains all relevant information. This dashboard should be used whenever necessary, in an easy and timely manner, to check the financial situation and verify key indicators, linking data from the three different platforms. A crucial element of this project is the ability to pinpoint discrepancies between the specified requirements, the payment schedule, and the inventory of assets.

3.1 Asset Acquisition Circuit

In accordance with the hospital's current operational procedures, in order for an item to be registered as an asset, it must be duly linked to a purchase order, a consequent invoice, and it needs to be effectively considered an asset, according to internal guidelines.

The initial stages of an asset's life cycle in ULS Coimbra are the demonstration of need or the decision about its acquisition, terms of reference, market consultation, acquisition, and commissioning, aligning exactly with what Farinha has stated previously [7]. These straightforward procedures typically require action from three distinct services: the Requesting Service, the Procurement Service, and the Financial Management Service. Additionally, three different platforms are necessary, being the *Sistema de Gestão Integrada do Circuito do Medicamento - Logística e Farmácia* (*SGICM-LF*), related to the PS, and the *Gestão Hospitalar do Armazém e Farmácia* (*GHAF*) and *Gestão Integrada Administrativa e Financeira*(*GIAF*).

Given the dimensions of the hospital, the acquisition of new assets for the organization is subject to a series of procedures that must be followed sequentially. Firstly, the Requesting Service identifies the need for acquisition and issues an internal investment request to the Procurement Service. The later, in turn, verifies if there is any available asset before moving on to the procurement process, according to internal guidelines and the Public Contracts Code. This process leads to a Purchase Order being issued on the *SGICM-LF* platform and sent to the supplier. Upon receipt of the asset, an evaluation takes place by the Facilities and Equipment Service to ensure its compliance. Ideally, at the same time, the asset file should be created on the asset management software, *GHAF*, along with the appropriate labeling. After the supplier delivers the respective invoice, it is registered in the accounting software, *GIAF*, to be checked and thereafter, paid.

As illustrated in Figure 3.1, a single purchase order can give rise to a multitude of subsequent invoices, each of which may in turn refer to a plurality of assets.

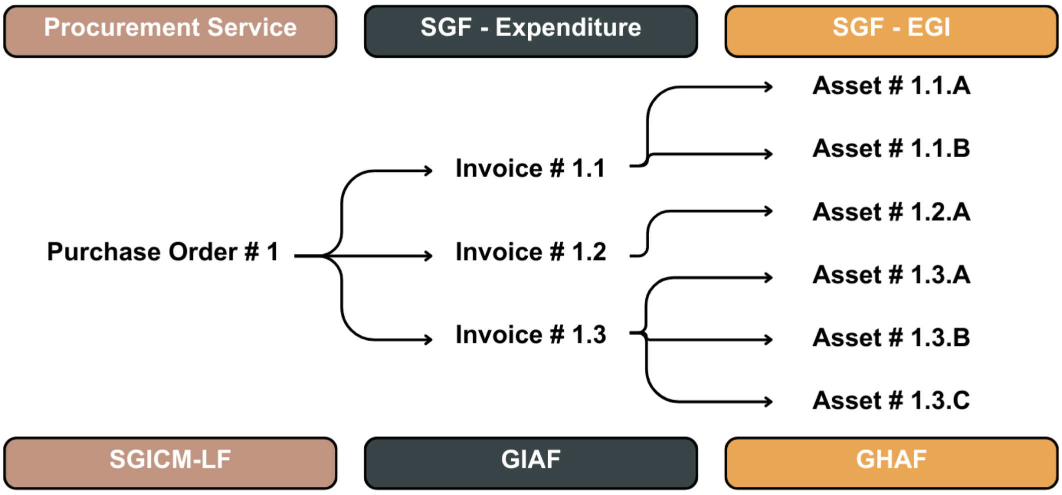


Figure 3.1: Example of a possible breakdown for a single Purchase Order, with departments and software of interest in each division

3.2 Data Analysis

The initial step in setting up a dashboard is to analyze data from different applications. This involves understanding the information that can be extracted from each database and defining the key or foreign keys with which the relationship between the tables is established.

For the proposed dashboard to function optimally, the foreign key linking the three databases should reference the asset itself, as this is the lowest possible data unit. The viability of this option is limited as the individual asset is only assigned a registration number at the end of the process, and the GIAF database does not contain any information about the assets, only the related invoices and purchase orders. This leaves only two other possible variables to assume the function of a foreign key, the PO and the invoice numbers, both featured across all databases.

In consideration of the minimum possible division of information, the invoice should be the chosen element. However, this solution is subject to a series of vulnerabilities, due to the fact that invoices are written in a way that is completely dependent on the supplier and not standardized, making them less suitable for this purpose. Additionally, there is a lack of uniformity in data entry practices and there is potential for human error. These factors all increase the likelihood that invoice numbers will differ across platforms.

Through an elimination process, the solution is to use the purchase order as the foreign key, thus establishing a relationship between the three databases.

As the PO can have multiple associated invoices and assets, the databases can contain several rows with the same PO number with different monetary values associated. To fill this gap, support databases are created by aggregating values by PO, connected to the original databases through the PO number, as seen in Figure 3.2. This functionality enables the comparison of total values per purchase order between databases, allowing for the identification of discrepancies in the results.

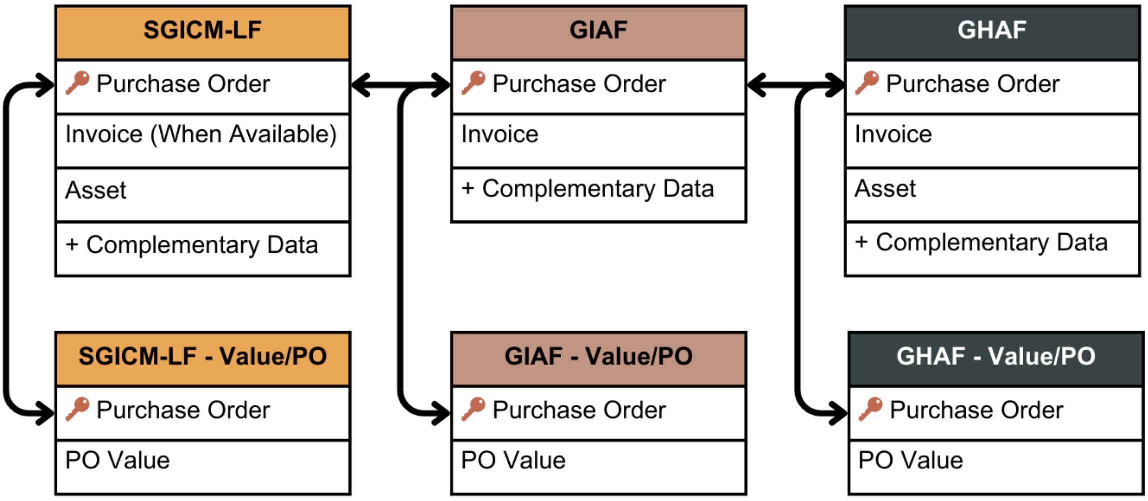


Figure 3.2: Data relationship diagram

It is crucial to have a straightforward visual component to understand the status of the asset registration. However, to facilitate the flow of information and explore events of interest, it is also necessary to be able to export the data to a simple spreadsheet. In this context, the PowerBI document automatically generates small tables dedicated to providing data resulting from the direct comparison between the platforms.

As illustrated in the Venn diagrams included in Figure 3.3, the document generates tables for all the POs that are in SGICM-LF but not in GIAF and all the POs that are in GIAF but not in GHAF. Additionally, in order to identify non-conformities in a reverse analysis, the document also generates tables with all the POs that are in GHAF but not in GIAF, and all the POs that are in GIAF but not in SGICM-LF.

It is important to note that according to internal procedures, assets that lack a PO cannot be invoiced and should not be recorded in the AMT software. This understanding allows us to conclude that, in accordance with the Portuguese Public Contracts Code, it is typical for goods to be received and registered in SGICM-LF but take a while to be documented in GIAF. This is mostly because suppliers have a specified number of days to send the corresponding invoice once the product has been delivered [53]. Similarly, it is also normal for some invoices to appear in GIAF without having yet been registered

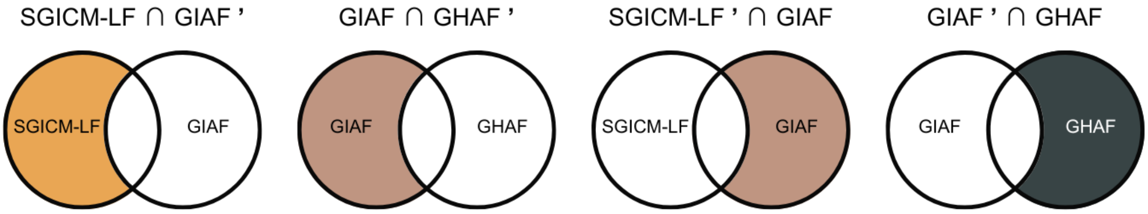


Figure 3.3: Venn diagrams depicting the intersections across the databases to create support tables

in GHAF. This is because an asset must have an associated paid invoice before it can be considered complete in the inventory process.

This indicates that any PO identified in a reverse analysis, originating from the asset (GHAF) to the invoice (GIAF) and then to the PO (SGICM-LF), represents nonconformities that should be investigated. These discrepancies could be the result of typing errors, offers from suppliers, or even the recording of acquired material from other years.

3.3 Dashboard

Given that one of the main objectives for this dashboard is to enable a quick and accessible analysis, the structure is designed in a way that prevents any need for changes to the databases. As a result, any data cleaning or transformations required to achieve the desired results can be carried out automatically. This allows for a comprehensive analysis to be completed in a relatively short period of time, being the time it takes for the databases to be obtained and entered into PowerBI.

The dashboard is split into six different sheets, ranging from an entire data overview up to the individual identification of each asset. Each sheet provides a succinct summary of the essential information pertinent to each software, either collectively or individually. These sheets can be seen in Appendix A.

The first page of the dashboard provides a high-level overview, comparing the total values recorded across each platform. These totals also allow for the calculation of three key indicators: the value of assets yet to be received, the amount still owed, and, from a perspective more aligned with the AMT, the number of assets that remain to be registered in GHAF.

Sheets 2, 3, and 4 of the dashboard provide a more detailed view of each associated platform: SGICM-LF, GIAF, and GHAF, respectively. These pages do not offer comparative data between platforms but allow for the analysis of various metrics, such as the value of assets linked to each financial classifier, the distribution of equipment reception throughout the year, the suppliers to whom the hospital owes the most, and the value of assets allocated to each cost center within the hospital.

The final two pages of the dashboard, 5 and 6, focus on identifying discrepancies between the platforms, highlighting what needs to be addressed to achieve consistent information across all platforms. Sheet 5 displays differences across four key indicators, with POs that can be directly accessed by clicking on them. Sheet 6 provides a clear view of asset invoices that have not yet been registered in the GHAF, along with the date these invoices were paid.

Given the volume of data involved in these analyses, it is clear that not everything can be visually represented on the dashboard. Therefore, an additional non-visual functionality has been included: the creation of tables listing all POs and their corresponding invoices that are inconsistent across the platforms. These tables can be easily exported to Excel for individual analysis.

3.4 Discussion

Effective asset management hinges on comprehensive identification and inventory of all assets. This requires collaboration with other services, including Procurement, Facilities and Equipment, and Financial Management. For optimal organizational performance, it is crucial that all stakeholders have access to accurate and comprehensive information concerning both medical and management aspects.

Given the size of the hospital, receiving on average 16 registrable assets daily, maintaining an up-to-date and accurate record of assets is a challenging task. This dashboard enables users to identify the number of pieces of equipment that are yet to be inventoried and are not included in the appropriate platform. It is not usual for this to occur, as the equipment should be registered as soon as possible after delivery. Typically, this happens as soon as the requesting department has given a positive statement on whether the equipment is in the expected condition.

The development of this dashboard has created a significant impact by enabling a standardized analysis with consistent indicators, simplifying the comparison of results across different time periods. It also provides data for all key indicators rather than limiting insights to a single table of discrepancies. Internally, it was estimated that the time required to obtain results has been reduced by approximately 30%, due to the automation of tasks that were previously predominantly manual.

It is important to clarify some limitations that were overcome in order to achieve the desired results:

- Different Databases for each software - Each software serves different purposes, focuses on specific data, and has limited access to the available databases. This needs to be overcome by pre-processing some of the files before importing them into PowerBI. As an example, one of the software does not include Value Added Tax (VAT) in the chosen database, so it must be supplemented with data from another list. Another database only contains data on material that has already been received, which restricts the scope of its analysis.

- The foreign key to identify non-conformities is the purchase order, not the invoice. This increases the effort needed to investigate irregular purchase orders. If the foreign key was the invoice number, less work would be necessary.
- The software utilized for this project is accessible only to a select group of employees. This makes it challenging to utilize the developed dashboard efficiently and among the stakeholders.
- The data set available for analysis is limited to the equipment that has been ordered and received. Due to this restriction, it was not feasible to conduct a comprehensive statistical analysis of all the material requested by the services that was not yet available on the hospital facilities.

One potential improvement to enhance the reliability of the dashboard data would be to develop a new foreign key by concatenating the invoice numbers with the supplier numbers to overcome the lack of standardization in the registration of the invoice, enabling fluid tracking of invoices across the platforms.

In view of the substantial number of assets held at ULS Coimbra, it would be prudent to consider whether it's necessary to undertake a full inventory of everything. The establishment of priority criteria focused on the most critical and frequently used equipment, to define the asset typology to be registered, would assist in a more efficient allocation of resources. In this context, it is crucial to distinguish between different types of assets, with particular emphasis on medical equipment. This distinction ensures that medical assets are managed with the appropriate level of detail, precision, and standardization. Given that medical equipment directly impacts patient health and requires ongoing maintenance, it is vital to keep a comprehensive record of all incidents and maintenance activities performed. This approach is markedly different from the management of non-critical assets, such as furniture or office supplies, which do not carry the same implications for health and safety.

This is supported by the World Health Organization, which emphasizes that equipment inclusion in an inventory should follow a risk-based analysis to ensure efficient use of time and resources while minimizing unnecessary tasks. Each healthcare facility is responsible for defining the level of detail in its inventory, tailoring it to its operational needs and capacities. Furthermore, the choice of inventory management system—whether paper-based or computer-based—depends on the facility's available resources and infrastructure [6].

Another way to leverage data more effectively for hospital management is through the use of KPIs. This doesn't necessarily mean creating new indicators, as maintaining uniformity for comparisons is crucial. Instead, it involves exploring existing KPIs using filters. These filters can be invaluable for identifying both cases of less efficient management and exemplary practices in asset management that can be adapted to less favorable scenarios. Filters might include parameters such as a specific time period, a hospital department, or even a type of medical equipment.

In this context, it is essential to emphasize the importance of introducing high-quality, consistent, and detailed data into the relevant platforms. This process directly determines the information that can be extracted and subsequently used for decision-making. As such, data should be as standardized as possible to avoid critical errors in analysis. This means minimizing free-text entries wherever possible and instead relying on predefined, normalized variables for categories such as equipment types, locations, or cost centers.

4 REPLACEMENT MODELS FOR MEDICAL EQUIPMENT

This chapter discusses a case study conducted at ULS Coimbra on the Life Cycle Analysis of a Medical Linear Accelerator, focusing on the application of data in traditional asset replacement models, such as MTACM and MTACM-RPV. It also introduces a dynamic model designed to integrate potential better performing assets to replace equipment currently in service.

4.1 Data and Assumptions

To utilize the replacement models presented in this chapter, it is essential to gather data that can yield clear and comprehensive results. As data from the past, present, and future is analyzed, one must distinguish between factual and estimated data. The former can be taken from historical records, while the latter represents forecasted future values and events.

The selection of the equipment to be studied emerged from a series of meetings with staff from the Financial Management Services and the Equipment and Installations Service. During these meetings, a radiotherapy equipment was identified for falling under the category of heavy medical equipment, boasting a large financial footprint after having been in service for 9 years (approaching the 10 useful life years indicated by the manufacturer).

This equipment is characterized as one of the most expensive assets in hospitals, with proportional energy consumption and maintenance costs. Hence, the optimization of its life cycle can potentially result in a significant cost reduction, improving the allocation of scarce resources in the healthcare sector.

The respective equipment is a Varian Trubeam, visible in Figure 4.1, acquired in 2015 through a public tender, avaiable on the of Procedure no. 70/2015, January 8th, in Diário da República, for the sum of 2 533 915.00€.

– Functioning Costs – Labor Costs

Functioning costs are the expenditures borne by the organization to make use of the asset, apart from maintenance costs, and are split into two main categories: labor costs and energy costs. The labor can be easily quantified by the number of personnel per role needed to keep the LINAC running (operational assistants, technical assistants,

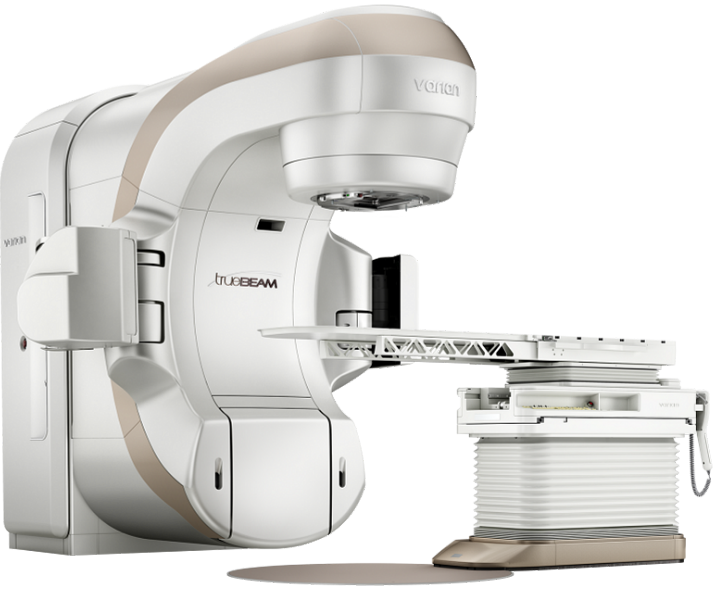


Figure 4.1: Varian Trubeam[1]

and medical physicists). This number is then multiplied by the annual cost per employee.

Due to confidentiality purposes, the number of workers associated with the LINAC and the direct labor costs are not disclosed. The results will be presented later, combining labor costs with energy expenses.

– Functioning Costs – Energy Costs

At the host institution, an electricity bill is structured as shown in Equation 4.1.

$$Electricity\ Bill = FT + PC + AP + RP \tag{4.1}$$

where:

FT – Fixed tariff
PC – Parcel of the bill corresponding to the power charges
AP – Parcel of the bill corresponding to the active energy consumed
RP – Parcel of the bill corresponding to the reactive energy consumed

For the purpose of this case study, the portion of the bill corresponding to reactive energy will not be considered because the hospital has already implemented a power factor compensation project, which has resulted in the energy cost for this portion to be effectively zero.

The FT is a result of the daily amount charged for the type of energy supply, which in

---

[1] Source: https://www.varian.com/pt-pt/products/radiotherapy/treatment-delivery/truebeam, accessed 10 Jul 2024

the hospital's case is medium voltage. Moreover, the PC relate to the costs associated with contracted power and peak hour power. In the present case study, neither of these factors is taken into consideration due to the small impact the LINAC has on these figures, representing less than 1% of the total electricity bill.

In light of the aforementioned details, the energy costs for this case study are calculated in a simplistic formula, being the product of the consumed energy with the energy price, which fits into the active energy fraction. This provides a not so rigorous solution but still yields acceptable results.

To determine the charges corresponding to the active energy consumed by the equipment, it is necessary to know the power consumed and the operating time in each time period, as well as the energy price per time period.

According to Energy Services Regulatory Authority (ERSE), the price of electricity is subject to fluctuations based on the time of day it is consumed. In accordance with the tariff applied to the hospital, there are four distinct periods throughout the day, each with a corresponding price per kWh consumed. Furthermore, they are also dependent on the time of year, with the time intervals varying depending on whether the period in question is summer or winter. As illustrated in Figure 4.2, these periods are designated as peak hours, mid-peak hours, off-peak hours, and super off-peak hours.

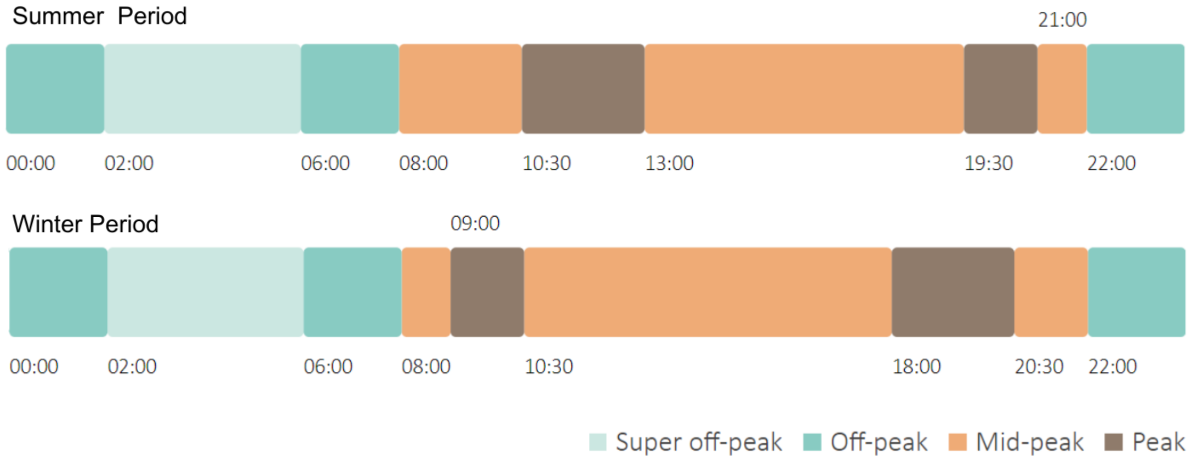


Figure 4.2: Time periods through the day on a three phase plan[2]

In order to determine the LINAC's power consumption and usage patterns, a Fluke 430 Series II three-phase power quality and energy analyzer was deployed on the equipment's power supply for a week, providing the results shown in Table 4.1 for Peak Hours (PH), Mid-Peak Hours (MPH), Off-Peak Hours (OPH)and Super Off-Peak Hours (SOPH).

---

[2] Adapted from: https://www.erse.pt/atividade/regulacao/tarifas-e-precos-eletricidade/#periodos-horarios, accessed 02 Feb 2024

Table 4.1: Active energy consumption over a week in February 2024

		Active Energy [kWh]				
Day	**Treatments**	**PH.**	**MPH.**	**OPH.**	**SOPH.**	**Total**
Friday	32	83.09	218.47	0.00	0.00	301.56
Saturday	30	0.00	112.36	212.81	26.15	351.32
Sunday	0	0.00	0.00	133.35	26.69	160.05
Monday	43	93.39	288.70	20.11	26.69	428.89
Tuesday	45	99.35	298.49	20.02	26.56	444.42
Wednesday	45	83.06	292.19	21.15	28.37	424.77
Thursday	45	86.51	312.50	19.89	26.48	445.38

To simulate the average LINAC consumption, the data from Monday to Thursday is used. The average of these days is used to simulate Friday. This is because the data available for Friday does not include information between 8:00 and 10:30. Saturday's data is also not taken into account because it represents an exception that had to be made to compensate for treatments that had not been carried out previously due to preventive maintenance.

In the end, the Functioning Costs, calculated by the sum of labor and energy costs, were estimated to be approximately 130 000.00€ for 2016, where the majority os costs are labor related. It is important to note that in the models with reduction to the present value, this number changes for subsequent years based on the inflation rate.

– Maintenance Costs

As previously discussed, maintenance costs and their evolution can have a significant impact on the models, so this data should be as accurate as possible.

In an attempt to have a realistic model, the data forecast should have a solid foundation in the form of a reliable and comprehensive database. Carlone, *et al* [54] showed that for the 16 Varian Trubeam LINACs under study, the parts costs seem to have a tendency to increase, with the costs of the oldest Trubeam (7.3 years old) being approximately 6 times higher than the Trubeam that was 1.4 years old, resulting in an average annual growth rate of approximately 35%. On a study more focused on equipment downtime, Kim, *et al* [55] worked with a dataset of 359 failure records on a LINAC, within a time period of 20 years. The study showed an almost linear increase in total equipment downtime, with an annual average of 63h ± 20.98, but it didn't disclose clear data about the evolution of downtime throughout the years.

To provide context for the equipment under study, it is important to clarify that, due to its high value, complexity, and specificity, the Varian Trubeam is covered by maintenance contracts. The relevant data is made available through reports provided by the maintenance service provider. Using this data, an individual analysis of each report was conducted to identify operational trends for this asset, as shown in Table 4.2.

Table 4.2: Evolution of maintenance on the LINAC under study

	2019	2020	2021	2022	2023
Maintenance Interventions	14	17	18	23	31
Downtime (h)	137.25	84.63	102.5	122.98	120.75
Downtime Variation	NA	-38.34%	21.11%	19.98%	-1.82%
Availability	95.42%	97.18%	96.58%	95.90%	95.97%

It is possible to notice an increase in the number of interventions greater than 100% in the timespan of 5 years. Although the total time to repair does not follow the rate of interventions, there is a clear positive slope that can result in an increase of equipment downtime.

The development of a maintenance cost prediction model can result in data that is either fairly accurate or has a large margin of uncertainty, depending on the methodology used to obtain it. As previously discussed, the bathtub curve provides a general representation of component life cycles, with each piece of equipment possibly exhibiting unique failure patterns compared to equivalent devices. Consequently, the optimal method for forecasting the maintenance costs associated with a given piece of equipment is to predict its failures based on its complete operational and maintenance history to date. However, this alternative is outside the scope of this report.

The LINAC under study is not maintained by the hospital, but by the manufacturer itself under a maintenance contract that covers all equipment failures and guarantees maintenance services for at least 10 years after the LINAC is purchased. Following this period, the option to continue maintenance contracts will depend on the manufacturer's acceptance and the hospital's financial capabilities, as the costs can get considerably higher. The initial annual maintenance contract was signed in 2018, with a value of 215 000€. This figure has remained relatively consistent with inflation, reaching approximately 230 000€ in 2023, as declared in the Public Contract Nº 367/99/2022.

The cost of maintaining equipment can naturally increase with inflation, or with the number and types of failures that occur. Thus, the modeling of equipment maintenance costs in this case study follows a simple mathematical rule as shown in equation 4.2. The equation accounts for two distinct rates depending on whether the equipment is within the first 10 years of its useful life or past them. For the first case, an annual increase of approximately 2% is applied in addition to the inflation rate, simulating the rising maintenance needs associated with equipment usage. In the second case, beyond the 10th year, an extra rate of 5% is applied on top of inflation. This higher rate reflects the challenges posed by the equipment's age, such as surpassing the manufacturer's recommended lifespan or the potential lack of guaranteed spare parts.

$$CM_j = \begin{cases} CM_{j-1} * f * 0.02, & \text{if } j \leq ak + 9 \\ CM_{j-1} * f * 0.05, & \text{if } j > ak + 9 \end{cases} \tag{4.2}$$

where:

CM_j – Maintenance costs in the year j
f – Inflation rate
ak – Acquisition year

It is also important to note that the models assume a two-year warranty period after the equipment is received in order to accurately represent the life cycle of the assets and their associated costs. Consequently, during this period, the maintenance costs are considered to be zero.

– Cession Value

In the models used to analyze the optimum asset replacement time point, the cession value represents the projected resale value of the equipment over the course of its useful life cycle. Ideally, this figure would be exactly equal to the market value, which is challenging to predict over a long time period. This is both due to the influence of internal factors, such as the condition of the equipment, its remaining useful life, its level of use, and external factors, such as technological obsolescence, markets, spare parts, or available resources, be them human, financial, or material.

After considering these factors, the methodology used to simulate the cession value involves the depreciation methods described in Chapter 2. In the case of the LINAC, the acquisition value of 2 533 915.00€ is used, with a residual value of 10 000.00€ over a period of 10 years, as represented in Figure 4.3. This residual value is considered from the perspective of a worst-case scenario for the hospital, given that the dismantling and transportation of the equipment entails a high cost for the institution due to its radiological nature. The 10 year period reflects the amount of time for which the manufacturer guarantees good maintenance conditions and the availability of spare parts.

It is always crucial to understand the dependency of models on the residual value and, consequently, to recognize the uncertainty associated with the values assigned. In the case of widely distributed equipment with numerous units and extensive data, such as cars, mobile phones, or electric motors, it is generally easier to determine the potential resale value and estimate future values. While some uncertainty remains, it is significantly lower compared to estimating cession values for rare equipment with limited distributed information, such as a LINAC.

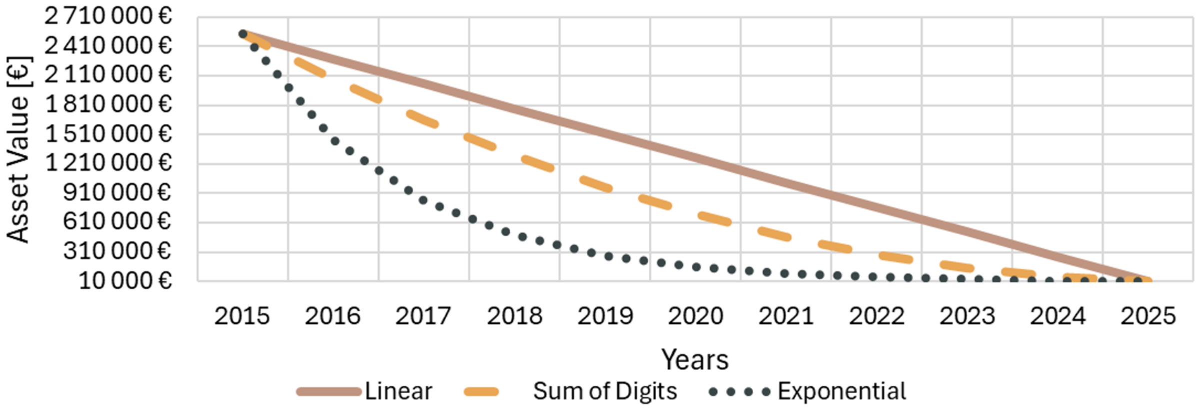


Figure 4.3: LINAC depreciation

4.2 Minimizing the Total Average Cost Model (MTACM)

As previously stated, the use of different models enables analysis from a variety of different perspectives. Some are focused on maximizing the return on an asset, while others are focused on minimizing the associated costs. In order to align the study with the hospital's strategic vision and objectives, the chosen model is Minimizing the Total Average Cost (MTACM). This model is straightforward and easy to comprehend, and sheds light on the impacts of considering the value of money, as demonstrated by its complementary Minimizing the Total Average Cost with Reduction to the Present Value (MTACM - RPV).

The MTACM presents the mean cost of ownership of the asset for each year. The calculation is as follows for each of the years under study:

$$C'_n = \frac{\sum_{j=1}^{n}(CM_j + CO_j)}{n} \tag{4.3}$$

$$C''_n = \frac{VA - VC_n}{n} \tag{4.4}$$

$$C_n = C'_n + C''_n \tag{4.5}$$

where:

C'_n – Exploration cost in year n
C''_n – Devaluation value per year n

C_n – Total average cost in year n
CM_j – Maintenance costs in the year j
CO_j – Operating costs in the year j
VA – Asset acquisition value
VC_n – Cession value in year n
n – Analysis year

Ultimately, the model allows for the identification of the point in time when the average cost of owning the equipment is minimal [39], as shown in Equation 4.6:

$$Minimum\ Cost = \min_{n \in \{1,2,\ldots,N\}} \frac{1}{n} \left(VA - VC_n + \sum_{j=1}^{n} (CM_j + CO_j) \right) \tag{4.6}$$

As previously mentioned, these models can be adapted and supplemented with additional parameters. An example of this is Albuquerque's application in the study of a Tomotherapy equipment, where the costs of non-production were considered in an asset replacement analysis [56].

The incorporation of the LINAC data into this model yields the following outcomes, illustrated in Figure 4.4 and Table 4.3.

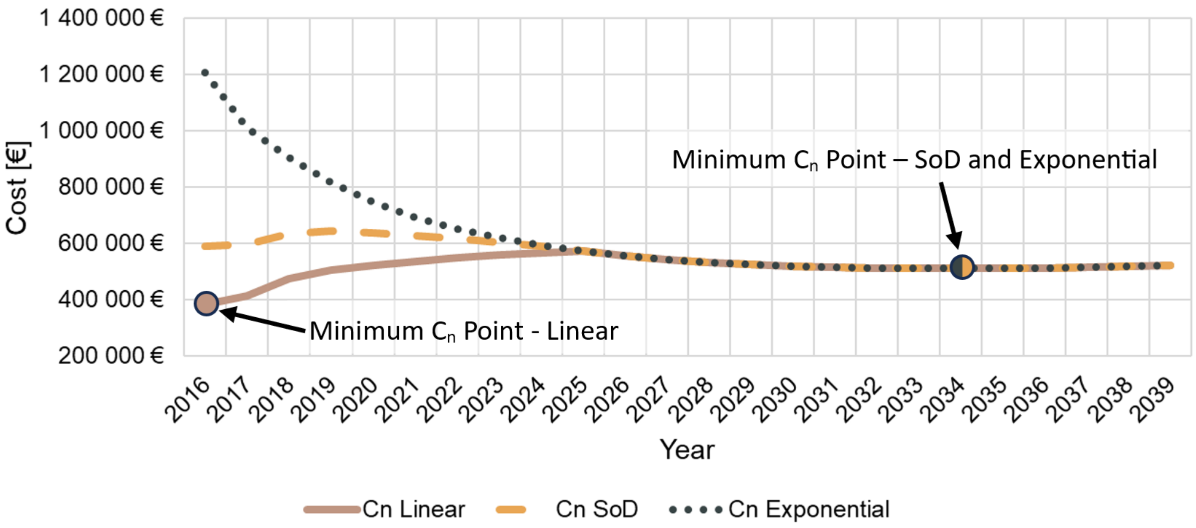
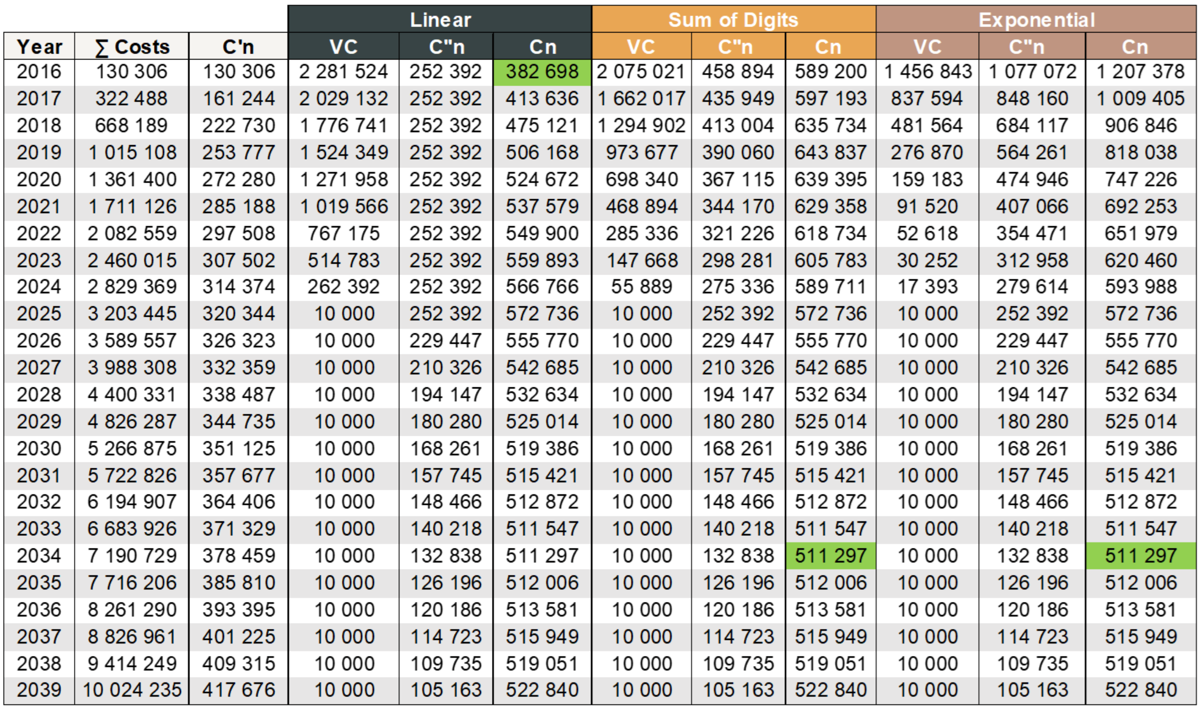


Figure 4.4: MTACM applied to the LINAC Results

The three distinct lines illustrated in the graph correspond to the values of the model when utilizing each of the specified depreciation methods: linear, sum of the digits, and exponential. The differentiation between the depreciation methods lies in the value attributed to the asset in a given year. Therefore, it can be concluded that the results of this MTACM model are highly dependent on the sale value of the equipment. It is evident that there is a discrepancy between the results of each method, which is then eliminated in year 10 when the value of the asset is equalized across all methods, with the cession value set to 10 000€.

Table 4.3: Data for MTACM applied to the LINAC



			Linear			Sum of Digits			Exponential		
Year	∑ Costs	C'n	VC	C"n	Cn	VC	C"n	Cn	VC	C"n	Cn
2016	130 306	130 306	2 281 524	252 392	382 698	2 075 021	458 894	589 200	1 456 843	1 077 072	1 207 378
2017	322 488	161 244	2 029 132	252 392	413 636	1 662 017	435 949	597 193	837 594	848 160	1 009 405
2018	668 189	222 730	1 776 741	252 392	475 121	1 294 902	413 004	635 734	481 564	684 117	906 846
2019	1 015 108	253 777	1 524 349	252 392	506 168	973 677	390 060	643 837	276 870	564 261	818 038
2020	1 361 400	272 280	1 271 958	252 392	524 672	698 340	367 115	639 395	159 183	474 946	747 226
2021	1 711 126	285 188	1 019 566	252 392	537 579	468 894	344 170	629 358	91 520	407 066	692 253
2022	2 082 559	297 508	767 175	252 392	549 900	285 336	321 226	618 734	52 618	354 471	651 979
2023	2 460 015	307 502	514 783	252 392	559 893	147 668	298 281	605 783	30 252	312 958	620 460
2024	2 829 369	314 374	262 392	252 392	566 766	55 889	275 336	589 711	17 393	279 614	593 988
2025	3 203 445	320 344	10 000	252 392	572 736	10 000	252 392	572 736	10 000	252 392	572 736
2026	3 589 557	326 323	10 000	229 447	555 770	10 000	229 447	555 770	10 000	229 447	555 770
2027	3 988 308	332 359	10 000	210 326	542 685	10 000	210 326	542 685	10 000	210 326	542 685
2028	4 400 331	338 487	10 000	194 147	532 634	10 000	194 147	532 634	10 000	194 147	532 634
2029	4 826 287	344 735	10 000	180 280	525 014	10 000	180 280	525 014	10 000	180 280	525 014
2030	5 266 875	351 125	10 000	168 261	519 386	10 000	168 261	519 386	10 000	168 261	519 386
2031	5 722 826	357 677	10 000	157 745	515 421	10 000	157 745	515 421	10 000	157 745	515 421
2032	6 194 907	364 406	10 000	148 466	512 872	10 000	148 466	512 872	10 000	148 466	512 872
2033	6 683 926	371 329	10 000	140 218	511 547	10 000	140 218	511 547	10 000	140 218	511 547
2034	7 190 729	378 459	10 000	132 838	511 297	10 000	132 838	511 297	10 000	132 838	511 297
2035	7 716 206	385 810	10 000	126 196	512 006	10 000	126 196	512 006	10 000	126 196	512 006
2036	8 261 290	393 395	10 000	120 186	513 581	10 000	120 186	513 581	10 000	120 186	513 581
2037	8 826 961	401 225	10 000	114 723	515 949	10 000	114 723	515 949	10 000	114 723	515 949
2038	9 414 249	409 315	10 000	109 735	519 051	10 000	109 735	519 051	10 000	109 735	519 051
2039	10 024 235	417 676	10 000	105 163	522 840	10 000	105 163	522 840	10 000	105 163	522 840

Regarding the interpretation of the results, the linear method suggests replacing the asset in the first year. This can be derived from two factors: zero maintenance costs due to the equipment still being under warranty on that time period, and the asset's low depreciation, which makes its sale value sufficiently high to justify selling in order to obtain the minimum cost point. While this appears to be a financially viable and advantageous strategy, there are some quantitative and qualitative factors that are not included in the model, which can have a significant impact on decision-making. The model is constructed in a way that does not consider business continuity. This is because the data entered does not account for the costs of purchasing new equipment to enable the business to continue operating.

In this context, the data also does not include any information on the costs or lost productivity associated with equipment replacement. This metric can be disregarded for small, ready-to-use equipment. However, in the case under study, large equipment requires time to remove the old and install the new assets, resulting in production losses.

The exponential and sum-of-the-digits methods yield identical results in terms of the point of minimum cost, despite the initial discrepancy in the cession values. This is due to the fact that it occurs after the 10th year of life, where the cession value is equal. Both methods indicate that the point of minimum average costs occurs in the year 2034, which is the equivalent of the 19th year of the equipment's life. This result appears to be a more favorable point for making the equipment profitable, since it will remain productive for several years, which is also more environmentally beneficial.

4.2.1 Cost per Treatment

One significant limitation of making a decision based on the outcomes of a traditional MTACM is that it neglects to consider factors such as production. This approach fails to demonstrate whether costs are justified from a production standpoint.

To address this, the analyst must have access to the production numbers from previous years. More specifically, the best indicator to understand the evolution of costs with production is the ratio between these two, leading to a new variable: Cost per Treatment.

For this purpose, it is necessary to take into account the average time per treatment, the annual availability of the machine, and the useful operational availability of the equipment.

Operational Availability is a Key Performance Indicator (KPI) relating to maintenance, defined in the Standard EN 15341 [57] as the total operating time divided by the total operating time plus time lost due to failures and preventive maintenance activities, as seen in Formula 4.7.

$$A_O = \frac{Total\ Available\ Time}{Total\ Available\ Time + Downtime} \tag{4.7}$$

This KPI can also be calculated as formulated by Farinha [7], through Formula 4.8.

$$A_O = \frac{MTBF}{MTBF + MTTR} \tag{4.8}$$

where:

A_O – Operational Availability
$MTBF$ – Mean Time Between Failures
$MTTR$ – Mean Time To Repair

Alternatively, a commonly used metric for production control is the Occupancy Rate, which directly compares the number of treatments performed in a given time period with the number of treatments that could potentially be carried out, given the equipment availability.

$$O_R = \frac{Total\ Usage\ Time}{Total\ Available\ Time} = \frac{T_r}{T_P * A_O} \tag{4.9}$$

where:

O_R – Occupancy Rate
T_r – Number of treatments performed in year j
T_P – Number of possible treatments
A_O – Operational Availability

The O_R is influenced by the A_O at the point where downtime, due to maintenance activities, results in a reduction of the total available time for the LINAC to perform treatments.

Ultimately, calculated as the product of the Operational Availability and Occupancy Rate, the Overall Efficiency aims to quantify the percentage of equipment utilization, directly comparing operational availability and uptime efficiency.

$$OE = A_O * O_R = \frac{Total\ Usage\ Time}{Total\ Available\ Time * Downtime} \tag{4.10}$$

The formula above is, in a sense, analogous to one of the most widely-known KPIs in asset management, Overall Equipment Effectiveness (OEE), which is calculated by multiplying performance, availability, and production quality. This would be an excellent indicator to leverage in asset replacement models. However, in a hospital setting and in regard to complementary diagnostic and therapeutic equipment, quality of treatments is somewhat subjective and challenging to quantify.

In this case study, the number of possible treatments (T_P) is calculated based on the average treatment time, the number of operating hours per day, and the number of operating days per year. This calculation assumes that the Overall Efficiency is 100%, which equates to 100% A_O and 100% O_R. The number of treatments performed (T_r) annually is the product of the multiplication of T_P by OE, which accounts for time losses.

$$T_P = \frac{N^{\underline{o}}\ Operating\ Hours\ per\ Day}{Average\ Treatment\ Time} * N^{\underline{o}}\ Operating\ Days\ per\ Year \tag{4.11}$$

$$T_r = T_P * OE \tag{4.12}$$

Having obtained the number of performed treatments, it is possible to formulate the cost per treatment variable. In general, this metric could be calculated by dividing the sum of the costs associated with the equipment by the sum of the treatments performed during each year of analysis. However, in order to follow the philosophy of averages in MTACM, a division is made where the numerator is the average minimum cost, while the denominator is the average of the treatments carried out up to the year of analysis. Thus, the Cost per Treatment (CT_n) is calculated as follows:

$$CT_n = \frac{C_n}{\frac{\sum_{j=1}^{n}(T_r)}{n}} \tag{4.13}$$

where:

C_n – Average cost of ownership for the year n
T_r – Number of treatments for year j
n – Analysis year

– Operational Availability and Occupancy Rate Calculations

The annual downtime for the LINAC was calculated through the sum of all the time to repair registered in the maintenance reports, as seen in Table 4.2 (page 37). The subsequent stage of the methodology requires the calculation of the total operating time of the equipment, or what would be the optimal time for the LINAC to be operational. In this instance, only working days throughout the year are considered, with the exclusion of public holidays in Portugal. For the purposes of this study, 250 days of annual operation are considered. The LINAC is assumed to operate daily with two shifts of six hours each, resulting in a total of 12 hours per day and 3 000 hours of annual operation.

In order to calculate the equipment occupancy rate, it is necessary to consider the total time the LINAC is available and the times when it is available but not in use. In the case of the equipment under study and the team allocated to it, within the 12-hour working day, there is always a 40-minute block of time allocated to Quality Assurance. Additionally, a process to guarantee the quality and safety of the use of the LINAC using simulations of treatments for each new patient or change in treatments, which can take up to 20 minutes. Furthermore, a brief interval of 10 to 15 minutes is allotted for the personnel to change shifts.
Therefore, as a guide value for this study, 75 minutes of non-operational time for the equipment are taken out of the 12 hours of daily operation, resulting in an occupancy rate of 89.58%, which is kept constant throughout the case study.

– Treatments

As previously stated, incorporating the number of treatments into the analysis provides valuable insight into the costs associated with the equipment. This is due to the fact that the number of treatments is a direct consequence of the operational availability and occupancy rate of the LINAC. Consequently, the longer the LINAC is under maintenance or not in operation, the fewer treatments can be carried out, while increasing maintenance costs.

Based on the hospital experience, type of treatments, and the characteristics of the equipment, 15-minute slots are reserved for each patient. The 15-minute period encompasses the patient's journey to the treatment room, the treatment itself, the patient's departure, and the requisite cleaning before starting another cycle.

In a utopian scenario where there are no production breaks or other time constraints. The LINAC would be able to carry out 48 daily treatments (one treatment every 15 minutes, for 12 hours) in each of the 250 working days. Accordingly, the reference value utilized in this study is 12 096 treatments per year with an Overall Efficiency rate of 100% for the equipment. However, to obtain the real number of treatments per year, it is necessary to multiply these utopian 12 096 treatments by the efficiency rate of the equipment, as shown in Equation 4.12 (page 12).

As previously discussed, the annual number of treatments is directly influenced by the equipment's operational availability and occupancy rate, collectively represented as Overall Efficiency. In this case study, downtime values were calculated for the period between 2019 and 2023. From 2024 onward, an annual reduction of 0.5% in availability is assumed, while the utilization rate is kept constant. This leads to a corresponding 0.5% annual decline in the number of treatments performed.

4.2.2 MTACM with Cost per Treatment Variable

After supplementing the analysis with the number of treatments to determine their average annual cost, the following results were obtained:

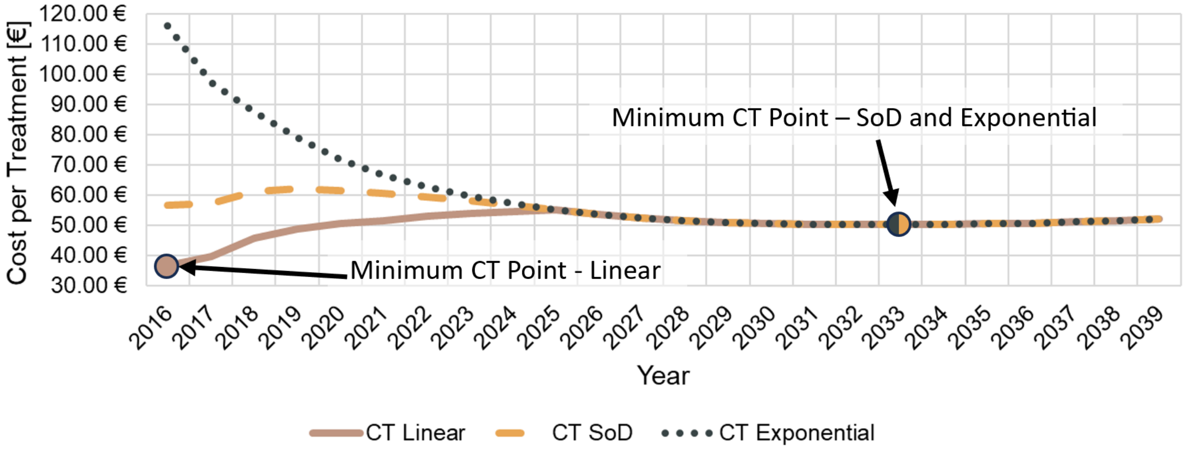


Figure 4.5: Average annual cost per treatment

As illustrated in the accompanying Figure 4.5, the average cost per treatment tendency is identical to the total average cost. Their direct relationship can be attributed to the way these costs are calculated. As illustrated in Table 4.4, in the event that the number of treatments shows a percentage change close to zero, the minimum points for both cases will be essentially identical (green highlighted cells). The analysis using the average treatment cost remains a more informed method, but it will stand out as much as changes in the number of treatments during the life cycle of the asset.

Table 4.4: Average annual cost per treatment data

					Linear		Sum of Digits		Exponential	
Year	**OE**	**∑ Treat.**	**∑ Costs [€]**	**C'n [€]**	**Cn [€]**	**CT [€]**	**Cn [€]**	**CT [€]**	**Cn [€]**	**CT [€]**
2016	86.0%	10 402	130 306	130 306	382 698	36.79	589 200	56.64	1 207 378	116.07
2017	85.7%	20 768	322 488	161 244	413 636	39.83	597 193	57.51	1 009 405	97.21
2018	85.4%	31 097	668 189	222 730	475 121	45.84	635 734	61.33	906 846	87.49
2019	85.0%	41 384	1 015 108	253 777	506 168	48.92	643 837	62.23	818 038	79.07
2020	86.8%	51 881	1 361 400	272 280	524 672	50.56	639 395	61.62	747 226	72.01
2021	86.2%	62 307	1 711 126	285 188	537 579	51.77	629 358	60.61	692 253	66.66
2022	85.5%	72 651	2 082 559	297 508	549 900	52.98	618 734	59.62	651 979	62.82
2023	85.6%	83 004	2 460 015	307 502	559 893	53.96	605 783	58.39	620 460	59.80
2024	85.1%	93 296	2 829 369	314 374	566 766	54.67	589 711	56.89	593 988	57.30
2025	84.6%	103 528	3 203 445	320 344	572 736	55.32	572 736	55.32	572 736	55.32
2026	84.1%	113 699	3 589 557	326 323	555 770	53.77	555 770	53.77	555 770	53.77
2027	83.6%	123 810	3 988 308	332 359	542 685	52.60	542 685	52.60	542 685	52.60
2028	83.1%	133 860	4 400 331	338 487	532 634	51.73	532 634	51.73	532 634	51.73
2029	82.6%	143 850	4 826 287	344 735	525 014	51.10	525 014	51.10	525 014	51.10
2030	82.1%	153 779	5 266 875	351 125	519 386	50.66	519 386	50.66	519 386	50.66
2031	81.6%	163 648	5 722 826	357 677	515 421	50.39	515 421	50.39	515 421	50.39
2032	81.1%	173 456	6 194 907	364 406	512 872	50.27	512 872	50.27	512 872	50.27
2033	80.6%	183 204	6 683 926	371 329	511 547	50.26	511 547	50.26	511 547	50.26
2034	80.1%	192 891	7 190 729	378 459	511 297	50.36	511 297	50.36	511 297	50.36
2035	79.6%	202 518	7 716 206	385 810	512 006	50.56	512 006	50.56	512 006	50.56
2036	79.1%	212 084	8 261 290	393 395	513 581	50.85	513 581	50.85	513 581	50.85
2037	78.6%	221 590	8 826 961	401 225	515 949	51.22	515 949	51.22	515 949	51.22
2038	78.1%	231 035	9 414 249	409 315	519 051	51.67	519 051	51.67	519 051	51.67
2039	77.6%	240 420	10 024 235	417 676	522 840	52.19	522 840	52.19	522 840	52.19

4.3 Minimizing the Total Average Cost Model with Reduction to Present Value (MTACM-RPV)

The simplified MTACM method evaluates the value of money based solely on known values at the time of analysis, without accounting for factors such as inflation, interest rates, risk, or other relevant considerations. In contrast, the MTACM-RPV methodology incorporates these factors by adjusting the value of money to its present value using rates outlined in Fisher's equation, such as inflation and interest rates. This approach provides a coherent with time and more accurate analysis.

Accordingly, the formulas for operating cost and depreciation value for the MTACM-RPV are modified by the inclusion of a denominator that reduces the necessary variables to a present value, as demonstrated in formulas 4.14, 4.15, 4.16 and 4.17.

$$C'_n = \frac{\dfrac{\sum_{j=1}^{n}(CM_j + CO_j)}{(1+i_A)^n}}{n} \tag{4.14}$$

$$C''_n = \frac{VA - \dfrac{VC_n}{(1+i_A)^n}}{n} \tag{4.15}$$

$$C_n = C'_n + C''_n \tag{4.16}$$

$$(1 + i_A) = (1 + i) \times (1 + f) \tag{4.17}$$

where:

C'_n – Exploration cost in year n
C''_n – Devaluation value per year n
C_n – Total average cost in year n
CM_j – Maintenance costs in the year j
CO_j – Operating costs in the year j
VA – Asset acquisition value
VC_n – Cession value in year n
n – Analysis year
i_A – Apparent rate
i – Interest rate
f – Inflation rate

After defining the formulas, the next step is selecting the rates and determining their values for the apparent rate. To keep the model straightforward and the results easier to analyze, only inflation and interest rates were included. However, since the interest rate is dependent on external factors, the apparent rates for years prior to the evaluation year, 2024, were based on the average Euribor rate for each respective year. Given that inflation rates are well-defined and available, the interest rate values can be calculated using the Fisher equation 4.18. The resulting rates applied to the years preceding 2024 are shown in Table 4.5.

$$i = \frac{(1 + i_A)}{(1 + f)} - 1 \tag{4.18}$$

For future years, starting from 2024, it is necessary to assume rate values for the model to reduce money to the present value. However, given the high subjectivity surrounding future rate predictions, an apparent rate of 2% was assumed. This value is based on an Autoregressive Integrated Moving Average (ARIMA) forecasting analysis which suggests a 2% future inflation rate along with a 0% interest rate. This forecast will be further explored through a sensitivity analysis later in the study.

With all data applied to the model, results can be extracted. Figure 4.6 shows a minimum cost point in 2016 in the case of linear depreciation, due to the more gradual devaluation. This means, in other words, that the asset retains much of its acquisition value after the first year. Selling the equipment at this point would yield a minimum

Table 4.5: Annual rates for Euribor, inflation, and real interest from 2016 to 2023

Year	**Euribor 12 Months Average Annual Rate**	**Inflation Average Annual Rate**	**Real Interest Average Annual Rate**
2016	0.0%	0.6%	-0.6%
2017	-0.1%	1.4%	-1.5%
2018	-0.2%	1.0%	-1.2%
2019	-0.2%	0.3%	-0.5%
2020	-0.3%	0.0%	-0.3%
2021	-0.5%	1.3%	-1.8%
2022	0.9%	7.8%	-6.4%
2023	3.8%	4.3%	-0.5%

total average cost. Alternatively, the model identifies a minimum cost point between 2033 and 2037, corresponding to the 18th to 22nd years of the asset's life cycle, respectively.

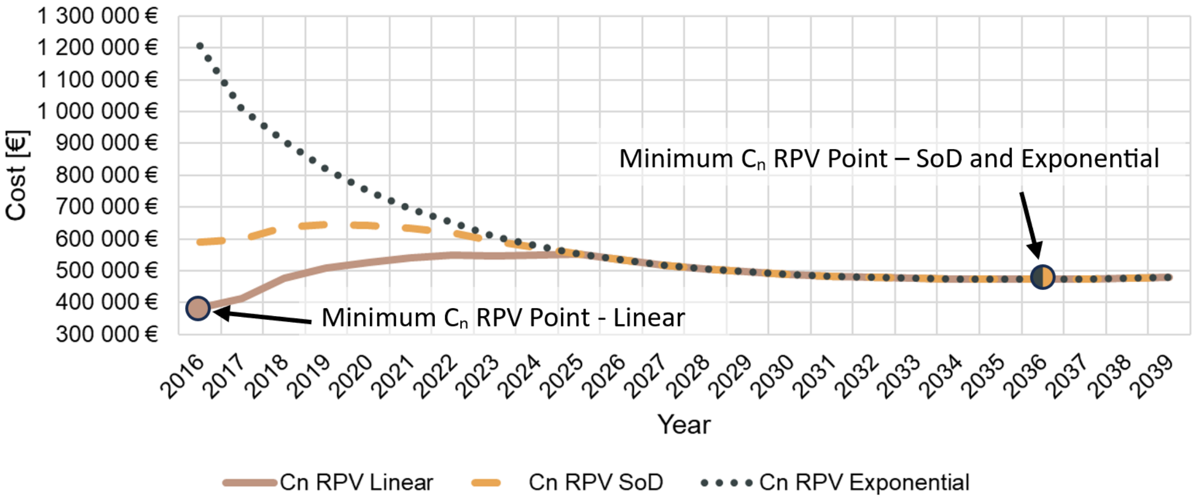


Figure 4.6: Total average annual cost results for the MTACM-RPV model

For treatment costs, the chart in Figure 4.7 shows a trend similar to that of the total average cost, suggesting replacement between 2032 and 2036, corresponding to the 17th to 21st years of the equipment's life. It is also worth noting that the recommended replacement years align with those in Figure 4.6, as the decline rate of Overall Efficiency is quite moderate. It is also important to clarify that from year 2025 onwards, the cession value is 10 000€ for each depreciation method, meaning that the results are equal for the three methods: Linear, Sum of Digits, and Exponential.

To assess the difference between MTACM and MTACM-RPV, their results were directly compared, as shown in Figures 4.8 and 4.9. It is important not to directly compare absolute values between them, as the value of money is not consistent across the results. Instead, the focus should be on understanding the impact of each analysis on the year

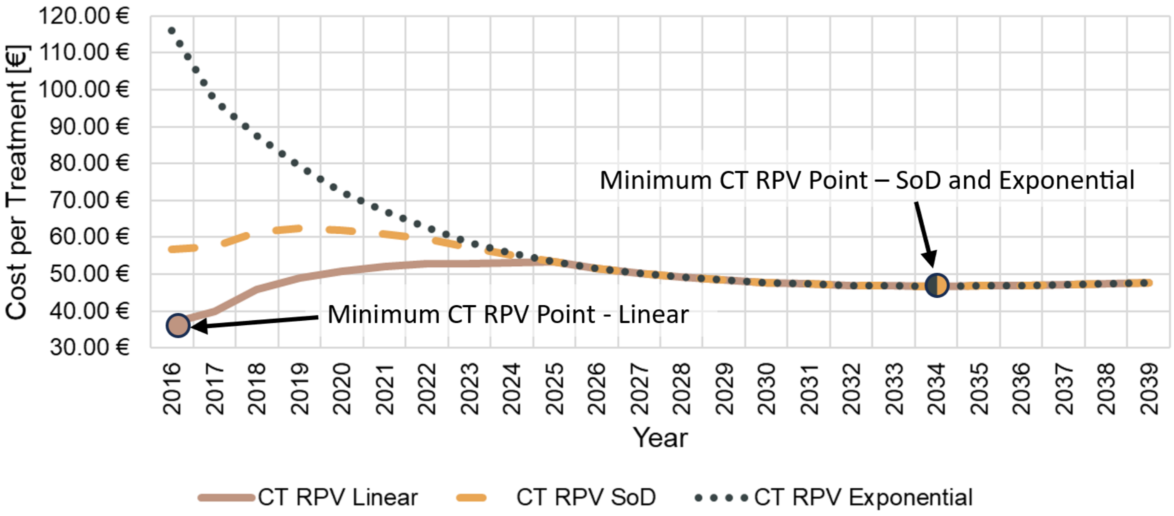


Figure 4.7: Average annual cost per treatment results for the MTACM-RPV model

of minimum cost points, which indicate a suggested year for asset replacement.

The direct comparison shows that the MTACM results suggest replacing the asset two years earlier than the timing proposed by the MTACM-RPV total average cost results.

Note: In order to keep the charts simple and clear, the results presented for the rest of the report are solely based on the sum-of-the-digits depreciation method, abbreviated as SoD.

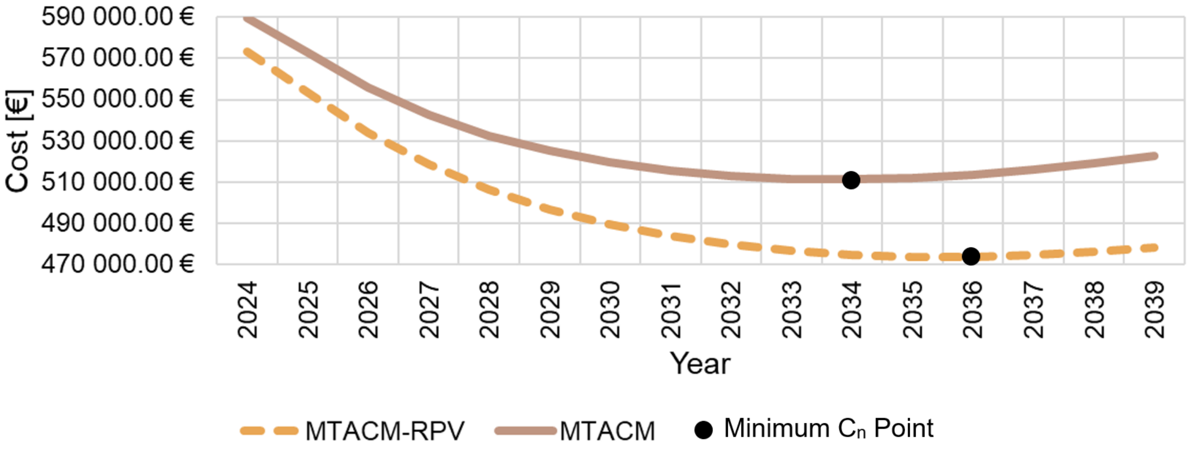


Figure 4.8: Average annual cost with MTACM and MTACM-RPV models

When the analysis shifts to the cost per treatment, it becomes clear that the method of discounting to present value still suggests a delay in asset replacement, although this delay is reduced to just one year.

4.3.1 Sensitivity Analyses

This sub-section aims to deepen understanding of the model MTACM-RPV and its behavior when certain key variables are adjusted. Specifically, this analysis examines the

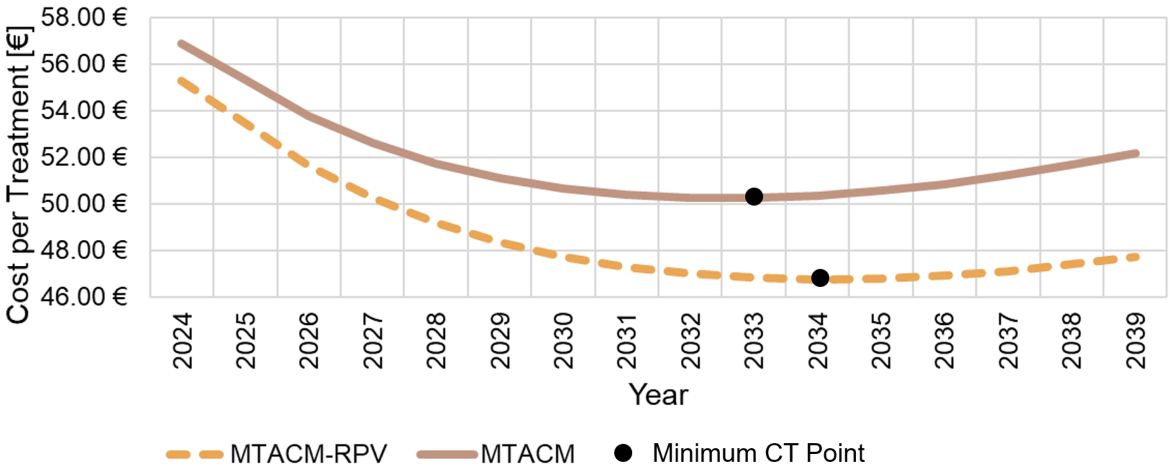


Figure 4.9: Average annual cost per treatment with MTACM and MTACM-RPV models

impact of the apparent rate, maintenance costs, and the equipment overall efficiency. This type of analysis ultimately helps to identify the most favorable scenarios for the organization, and highlights values that could lead to more critical or concerning outcomes.

The model's sensitivity caused by the apparent rate is represented in Figure 4.10. It analyzes the variations in the rate between -2% and 4%, assuming a constant inflation rate of 2%. Thus, this chart can be interpreted in two different ways. One approach is to consider a fixed inflation rate while varying the interest rate. Alternatively, both the inflation and interest rates can be fixed, while the risk rate remains variable. The risk used in these models can be highly dependent and tailored to each specific application. However, in general terms, risk can be interpreted as the uncertainty associated with future events.

The analysis of the chart in Figure 4.10 shows a clear trend: the lower the apparent rate, the earlier the tendency for replacement, while an increase in this rate indicates a tendency to delay asset replacement. These results are consistent with the relationship between investment, risk rates, and interest rates. This indicates that the higher the risk or interest rate, the more challenging and delayed the investment becomes.

The second variable to be analyzed relates to maintenance costs, as shown in Figure 4.11, where annual growth rates from 0% to 10% were applied in increments of 2.5%. Additionally, two progressive rates were considered, where the growth rate increases by 0.5% and 1% over the previous year's rate. It is important to note that, in addition to these applied rates, the model also accounts for a 2% annual growth due to inflation.

This graph reflects the true impact that maintenance can have on asset replacement. The results are logical, showing that a higher maintenance cost growth rate leads to an earlier asset replacement. On the other hand, if the growth rate is below just 2.5%, the asset may not reach a point of minimum costs at all.

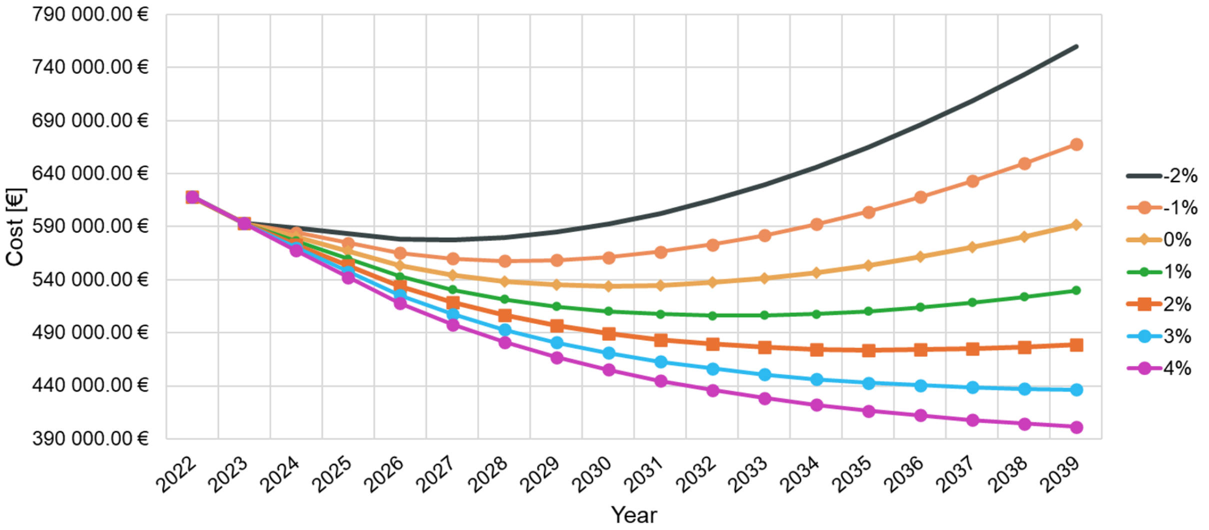


Figure 4.10: Sensitivity analysis to the apparent rate

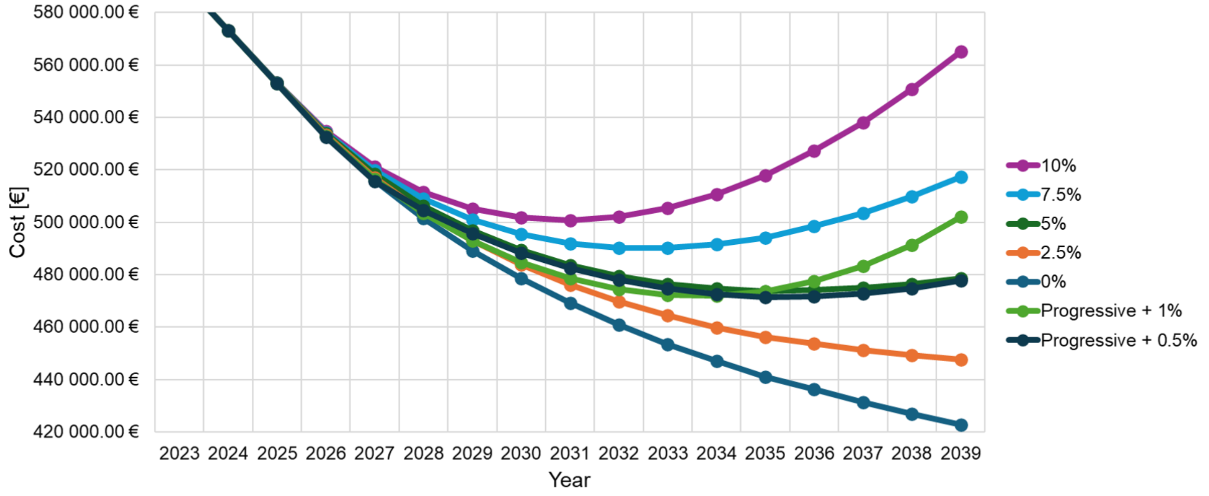


Figure 4.11: Sensitivity analysis to the maintenance costs

Lastly, the sensitivity of the model is analyzed for OE in Figure 4.12. This analysis, as previously explained, accounts for equipment O_R and A_O, and since this variable only impacts directly the number of treatments performed annually, the indicator analyzed will be the cost per treatment for each study year, rather than the total average cost. The annual decline rate in overall efficiency ranges from -0.5% to -3%, potentially resulting in a total difference of nearly 40 000 treatments by 2039.

The importance of complementary analyses such as cost per treatment is clearly highlighted by this graph. The results show that a simple variation of -2.5% in operational efficiency brings the replacement year forward by 4 to 5 years, while also having a direct impact on the individual treatment cost, increasing it by approximately 9%. This sensitivity analysis would not show any change if evaluated using the total average cost metric.

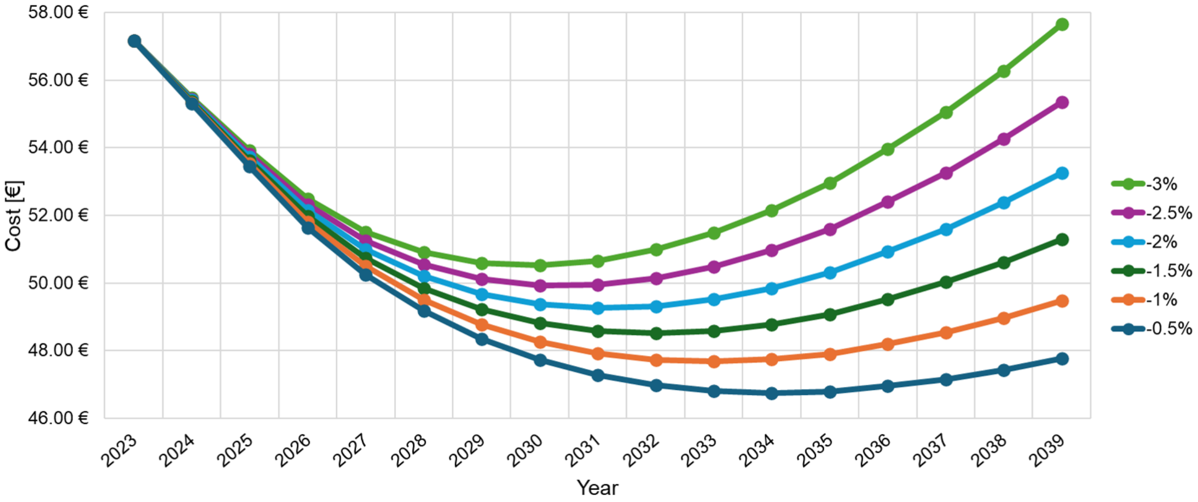


Figure 4.12: Sensitivity analysis to the cost per treatment by varying Overall Efficiency

In addition to highlighting scenarios that could either benefit or disadvantage the organization, these sensitivity analyses underscore the impact of input data on model outcomes. This reinforces the need to obtain data that is as accurate as possible, minimizing uncertainty to ensure reliable results. To prevent detrimental decision-making, and given that these models track equipment life cycle, an annual re-evaluation is recommended so that forecasted values are systematically replaced with factual data.

4.4 Dynamic Asset Replacement Model

Traditional asset replacement models are effective tools for managing assets but they often fall short in addressing key challenges. Overcoming this weakness could enhance these models to deliver greater strategic value.

One limitation of traditional models is their asset-centric perspective, which prioritizes the optimization of the asset's lifespan rather than aligning with the company's strategic goals. This narrow focus can overlook the need to ensure uninterrupted production or plan for the acquisition of new equipment.

Another challenge lies in technological advancements. As innovation drives the development of more efficient and productive equipment, traditional models often fail to incorporate these breakthroughs into their analyses, potentially leading to suboptimal replacement decisions.

To surpass these shortcomings, a dynamic approach has been developed. This method simulates the integration of improved assets available in the market, enabling a more precise and realistic assessment of the optimal replacement year. By taking into consideration the performance and the need to continue operation by the acquisition of a replacement asset, the dynamic approach offers a more comprehensive framework for informed decision-making.

The data is modeled for two assets, the one to be replaced and the replacement itself, or, as they have been referred to in the existing literature, the Defender and the Challenger [58]. It should be noted that the Defender represents the same equipment as the one in operation. For the purposes of this case study, the results of the Varian Trubeam are therefore compared to a Defender with the same characteristics and a Challenger with different characteristics.

In terms of calculations, this new approach is based in the MTACM-RPV model, which was presented before. The calculation of the operational costs (C'_n) and total average cost (C_n) remains the same as in Formulas 4.14 and 4.16 (page 46 and 47), respectively. The only change is in the calculation of the devaluation value (C''_n) where the Acquisition Value is replaced by the Total Investment, as presented in Formula 4.19.

$$C''_n = \frac{TI_n - \dfrac{VC_n}{(1+i_A)^n}}{n} \tag{4.19}$$

where:

TI_n – Total investment in year n
VC_n – Cession value in year n
n – Analysis year
i_A – Apparent rate

The Acquisition Value is replaced by Total Investment, as it is necessary to account for the acquisition cost of the Challenger and the resale value of the Defender, as represented in Formula 4.20. Simply put, the model considers only the value of the Defender (VA_D) up until the replacement year (k). After that, the acquisition cost of the Challenger (VA_C) is added, and the cession value of the old equipment (VCD_k) is subtracted.

$$TI_n = \begin{cases} VA_D, & \text{if } n \leq k \\ VA_D + VA_C - VCD_k, & \text{if } n > k \end{cases} \tag{4.20}$$

4.4.1 Model Explanation and Developed Code

The proposed methodology to address this issue is outlined in simplified flowcharts in Figures 4.13 and 4.14. Broadly, this dynamic model requires two assets: a Defender and a Challenger, each with the full set of data typically used in traditional replacement models. After setting up these inputs, the model iteratively combines the datasets of both assets over the desired period, generating new datasets that represent the hypothetical replacement years until the desired period or number of simulations has been reached.

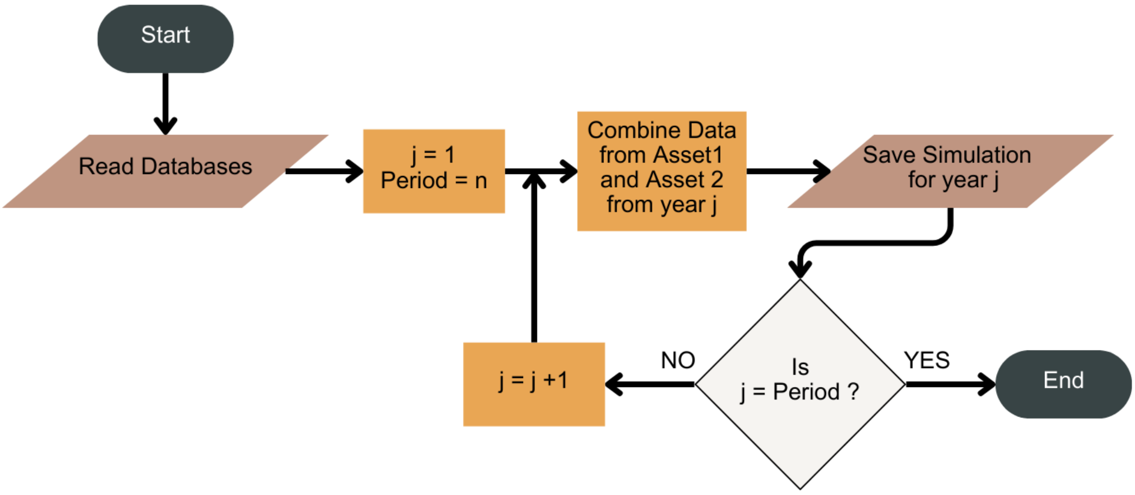


Figure 4.13: Simulation database flowchart

Once the databases have been created for each simulation, the results are analyzed and the minimum costs are identified in each database, as well as the respective year in which this minimum occurs. Ultimately, to identify the optimal replacement year, the minimum results of each simulation are compared to determine the overall minimum, as illustrated in Figure 4.14.

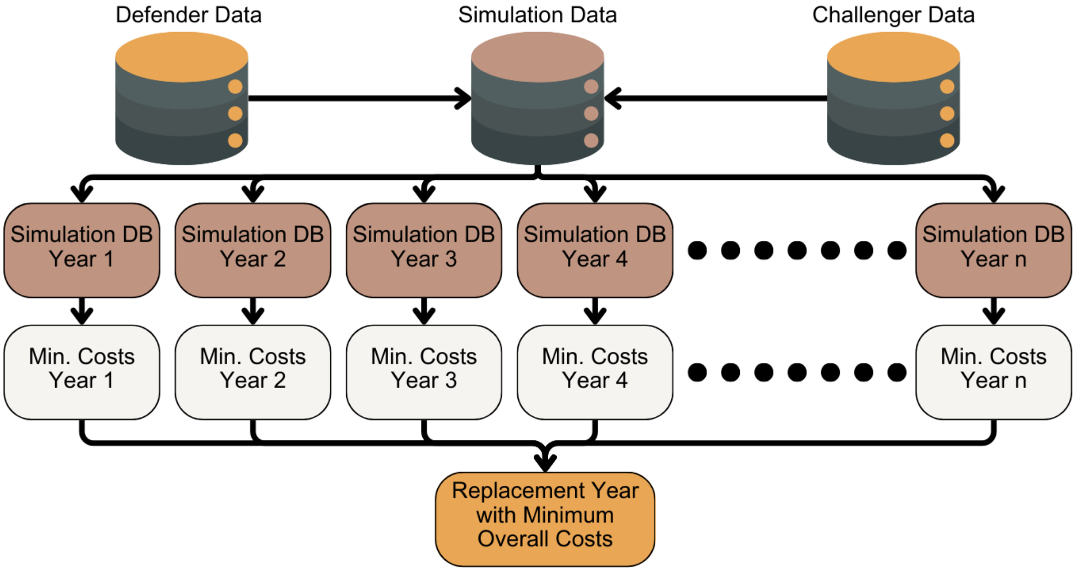


Figure 4.14: Determining the replacement year that will result in the overall minimization of costs

For example, if a replacement simulation by a Challenger asset is needed within the first 10 years of the Defender asset's life, 10 datasets are created. The first assumes replacement after the first year of the Defender's operation, the second after the second year, and so on until the tenth where the simulation assumes replacement.

Figure 4.15 illustrates the data obtained in each of the simulations conducted to emulate a different year of asset replacement. Simplistically, the graph represents the same information as that derived from the traditional MTACM-RPV model, with the added complexity of incorporating a mid-analysis asset replacement. The results of the presented graph correspond to the 10th simulation, meaning that in this example, the replacement occurs in the 11th year of the analysis, following 10 years of the Defender's operation. It is important to note that it was arbitrated that all simulations evaluate 24 years of the replacement asset's life cycle, regardless of the replacement year. Much like in traditional cost models, each simulation has a minimum cost point, marked with a green triangle in the figure. These green points across all simulations form the basis for the dynamic model's result graphs. Similarly, the 10th year following the replacement is also highlighted for comparative analysis, marked with a red square. The accumulation of these red-square values across simulations contributes to the post-replacement 10-year analysis graphs, which will be presented later in the study.

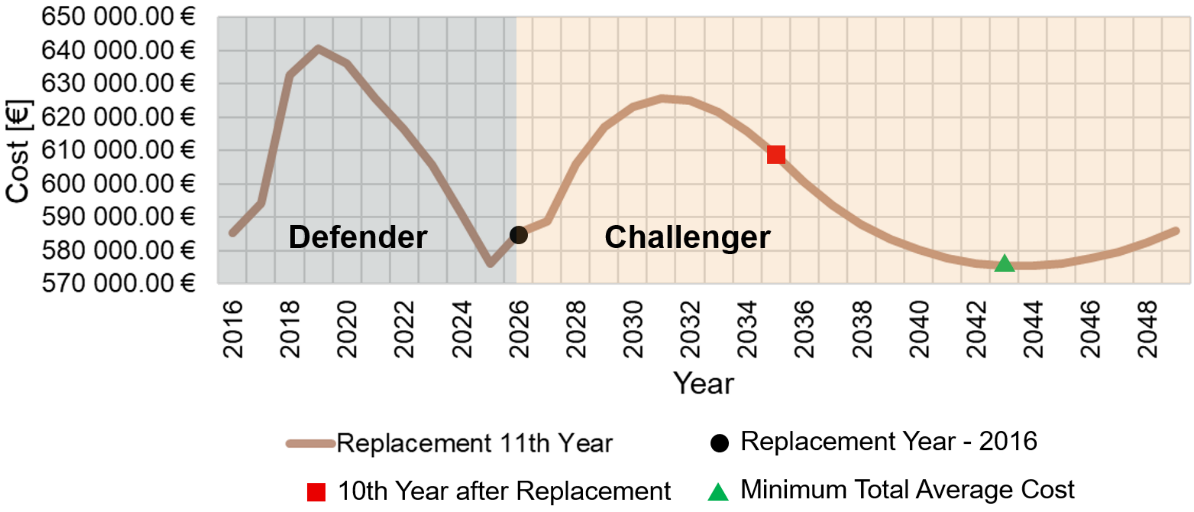


Figure 4.15: Example of results for the simulations conducted, specifically the 10th simulation

– Explanatory Pseudocode

Define the Function `Minimum Cost`

- **Input:** Data from both assets, number of simulations
- **Initialize Variables:**
  - `Minimum_Cost_per_Treatment` and `Minimum_Average_Cost`: Arrays of zeros with size equal to the number of simulations;
  - Lists to store all minimum average cost values, minimum cost per treatment values, values 10 years post-replacement, and years with minimum costs.

- **For each replacement year from 0 to (Number of Simulations - 1):**
    - Concatenate the data of both assets up to the current year;
    - Calculate accumulated costs by calling `Calculate Accumulated Costs`;
    - Obtain the total average cost and cost per treatment for each year in each simulation;
    - Store the minimum treatment and total average costs from the DataFrame;
    - Identify the years corresponding to the minimum costs.
- **Calculate the Overall Minimum Costs:**
    - Find the global minimum cost per treatment and total average cost;
    - Return the values and the corresponding years.

Define the Function `Calculate Accumulated Costs`

- **Input:** Concatenated Dataframe, replacement year
- **Copy and Adjust Data:**
    - Add index, update years, and total costs;
    - Update values based on relative time (for present value calculation);
    - Calculate accumulated costs and indicators operating costs, depreciation value, and total average cost.
- **Output:** Updated DataFrame with all calculated costs

Prepare Data for Final Analysis

- **Initialize Lists and Variables:**
    - `tables`: To store the cost DataFrames;
    - `results`: To store the simulation results.
- **Run Loop for Simulations:**
    - Concatenate the data, calculate costs, and store the results;
    - Add a column indicating the simulation and store in the `tables` list.

Determine the Overall Minimum Costs

- Initialize variables for global minimum costs and corresponding years/simulations;
- **For each simulation, analyze each year:**
    - Update the global minimum cost per treatment, if necessary;
    - Update the global minimum total average cost, if necessary.

Display Results

- Print a table of minimum costs per replacement year;
- Print the overall minimum costs per treatment and total average cost.

Export Data to CSV

- Create a dictionary with the results;
- Transform the dictionary into a DataFrame;
- Export the DataFrame to a CSV file.

In a simplified way, the code functions as follows:

- **Accumulated Cost Calculation:** The function `Calculate Accumulated Costs` is responsible for computing all relevant costs, adjusting values based on years and inflation.
- **Identification of Minimum Costs:** The `Minimum Cost` function loops through each simulation year, calculating and storing minimum costs and the years in which they occur.
- **Result Consolidation:** Global minimum costs are determined and displayed, with all important data exported for further analysis.

The purpose of the code is to make the dynamic analysis process faster, enhancing its appeal and optimizing the user's time. This, in turn, enhances decision-making as the saved time can be used for additional analyses or for clearly and transparently interpreting the results obtained. In this specific case, the time required to obtain results was reduced to less than a third of the original time when aggregating initial data, from 50 minutes to 15 minutes. Furthermore, the time required to obtain results was reduced tenfold when only updates to existing databases were necessary(for example, when conducting sensitivity analysis), reducing the time from 40 minutes to just 4. In addition to this time optimization, the code also minimizes human errors in data processing, ensuring more reliable outcomes.

4.4.2 Data and Assumptions

As previously mentioned, this new approach to replacement models incorporates data on two assets. The Defender's dataset utilizes the data previously provided for the MTACM application.

Ideally, the data utilized for the Challenger asset should be derived from actual, commercially available equipment. However, obtaining this type of information is difficult due to the specific, expensive, and restricted nature of the heavy medical equipment market. For the purposes of this project, data was estimated to simulate equipment that is very similar to a Varian Trubeam but with slightly improved quantitative performance, namely the time per treatment and the energetic consumption.

It is crucial to highlight that the presented data is hypothetical and solely intended to illustrate the capabilities of this dynamic model. The actual data is entered by the organization, which reserves the right to the confidentiality of the results.

– Initial Investment

For the Challenger, an initial investment value of 3 000 000 € has been arbitrated. This value was assumed to represent a similar but better performing equipment which generally entails a higher acquisition cost.

– Treatments - Challenger

For the Defender, the number of treatments was set at 12 096, based on the 15-minute slot for each patient, and assuming full equipment availability.

The Challenger was simulated with enhanced performance, and in this variable of the time needed per treatment, it was estimated that this new equipment would be able to reduce the slot time from 15 to 12 minutes.

So, according to the calculations formerly employed, the Challenger has the capacity of 60 slots for treatment, which, for 250 working days, would result in 15 120 treatments per year at an rate of 100% availability.

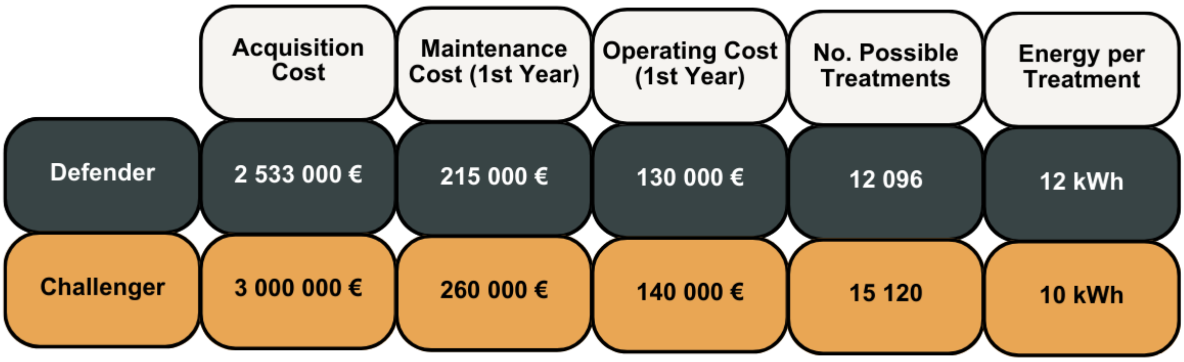
– Operational Costs - Challenger

The overall operational costs will vary in value according to the specific energy consumption and labor variables involved.

Although the Challenger can perform a greater number of treatments, the simulation of more energy-efficient equipment leads to a reduction in energy consumption per treatment.

In addition, labor costs were increased by simulating the need for an additional employee to operate the new equipment. This demonstrates the model's adaptability to any quantifiable data, allowing for comparisons across various aspects of the different replacement asset options.

In summary, for ease of understanding, Figure 4.16 illustrates the key points that distinguish the two assets considered. Despite their differences, they remain quite similar, which leads to the conclusion that the results obtained from the analyses are not significantly different.



	Acquisition Cost	Maintenance Cost (1st Year)	Operating Cost (1st Year)	No. Possible Treatments	Energy per Treatment
Defender	2 533 000 €	215 000 €	130 000 €	12 096	12 kWh
Challenger	3 000 000 €	260 000 €	140 000 €	15 120	10 kWh

Figure 4.16: Key cost and performance indicators that distinguish the two assets simulated in the dynamic model of this case study

4.4.3 Results and Interpretation

To facilitate the interpretation of the results, it is recommended to review the next graphs alongside the table provided in Appendix B (page 100).

According to the flowchart and the objectives of the dynamic model, the most intuitive graphical representation would be the aggregation of the minimum values obtained in each simulation, which in a way could be assimilated to the graphs obtained via traditional replacement models.

In light of that, Figure 4.17 illustrates the total average minimum cost on the vertical axis, while the horizontal axis represents the different simulations performed in the study. The first simulation considers asset replacement in 2017, the second in 2018, and so forth, up to the 23rd simulation, which models replacement in 2039. Two lines are depicted: the yellow line corresponds to simulations where the Varian Trubeam was replaced with a Challenger, representing a new, higher-performing piece of equipment. The gray line represents simulations where the Varian Trubeam was replaced with a Defender, maintaining the same characteristics as the original asset. Each line identifies the year in which the lowest average cost occurred for each simulation.

As an example of how to read the graph, it can be observed that for simulation 9, where the asset is replaced in 2026, the Challenger reaches a minimum value of approximately 575 000€ in 2043, while the Defender reaches a minimum of approximately 495 000€ in 2047.

Therefore, the graph shows that the absolute minimum point occurs in the year of replacement 2038, which corresponds to simulation 22. This minimum is reached with the replacement by a Defender, with a total average cost of approximately 455 000€ in 2061. In the same simulation, replacing the asset with a Challenger only reaches a minimum of approximately 510 000€ annually in 2058.
These graphs should be read in order to understand which substitution year would be the most beneficial for the organization, but attention should be paid to the year when

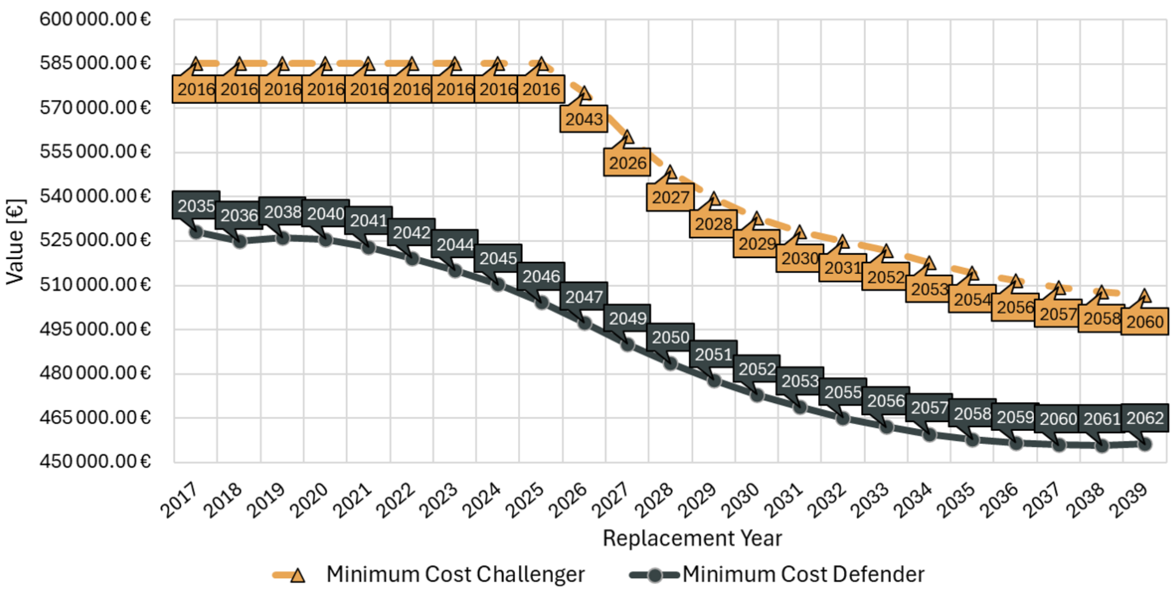


Figure 4.17: Minimum total average cost for each simulation

this minimum point occurs.

Table 4.6 presents an example of the output data used in Figure 4.17. Since the dynamic model runs 23 simulations for each replacement asset, there are numerous tables containing all the detailed data, which can be reviewed as needed. However, due to the large volume of data and the focus of this report, this table is provided as the sole example of how data can be compiled.

The table demonstrates that the average cost of replacing an asset with a Challenger is higher throughout the simulations, due to the elevated costs of acquisition, as well as ongoing maintenance and overall functioning costs. However, the discrepancy in values between replacing with a Challenger and a Defender tend to decrease and eventually stabilize due to the model formulations, where the replacement with a Challenger can reduce the difference up to only 11.04% higher than the Defender.

Moreover, Figure 4.18 demonstrates the significance of aligning cost data with production metrics. As previously mentioned, the first representation shows only the total ownership costs of the equipment, while the second representation demonstrates the direct impact of the performance differences between new and existing equipment. Despite the high acquisition and maintenance costs, the greater production capacity is reflected in the significant difference in costs per treatment for the Challenger, which is evident from the first simulation, reaching a difference of up to 2.3% in cost per treatment for the last simulation performed.

Figures 4.17 and 4.18 provide valuable insight into the minimum values found via simulation. However, they do not allow for a direct, fair, or accurate comparison between the analysis of replacement with a new asset and an equal asset due to the fact that the minimum cost points are not at the same moment in time. To overcome this, it is

Table 4.6: Output table for Figure 4.17 results

		Minimum Cn Year Data						
Replacement Year	Replacement Asset	Year	Sum Costs [€]	Sum Treatments	C′n [€]	C″n [€]	Cn [€]	CTn [€]
2017	Challenger	2016	127 314	10 402	127 314	457 979	585 292	56.27
	Defender	2035	7 584 795	203 299	379 240	149 049	528 289	51.97
2018	Challenger	2016	127 314	10 402	127 314	457 979	585 292	56.27
	Defender	2036	7 628 889	213 665	363 280	161 618	524 899	51.59
2019	Challenger	2016	127 314	10 402	127 314	457 979	585 292	56.27
	Defender	2038	8 342 357	233 622	362 711	163 526	526 237	51.81
2020	Challenger	2016	127 314	10 402	127 314	457 979	585 292	56.27
	Defender	2040	9 057 965	253 475	362 319	163 293	525 612	51.84
2021	Challenger	2016	127 314	10 402	127 314	457 979	585 292	56.27
	Defender	2041	9 242 180	263 972	355 468	167 602	523 071	51.52
2022	Challenger	2016	127 314	10 402	127 314	457 979	585 292	56.27
	Defender	2042	9 431 957	274 398	349 332	169 893	519 225	51.09
2023	Challenger	2016	127 314	10 402	127 314	457 979	585 292	56.27
	Defender	2044	10 169 659	294 249	350 678	164 506	515 184	50.77
2024	Challenger	2016	127 314	10 402	127 314	457 979	585 292	56.27
	Defender	2045	10 402 813	304 601	346 760	163 611	510 372	50.27
2025	Challenger	2016	127 314	10 402	127 314	457 979	585 292	56.27
	Defender	2046	10 632 814	314 894	342 994	161 294	504 288	49.65
2026	Challenger	2043	10 596 039	336 894	378 430	196 893	575 323	47.82
	Defender	2047	10 871 916	325 126	339 747	157 688	497 435	48.96
2027	Challenger	2026	3 643 029	113 695	331 184	229 364	560 548	54.23
	Defender	2049	11 616 929	344 743	341 674	148 412	490 086	48.33
2028	Challenger	2027	4 061 179	123 806	338 432	210 250	548 682	53.18
	Defender	2050	11 878 727	354 854	339 392	144 171	483 564	47.69
2029	Challenger	2028	4 492 742	133 856	345 596	194 077	539 672	52.41
	Defender	2051	12 157 006	364 905	337 695	140 167	477 861	47.14
2030	Challenger	2029	4 938 391	143 846	352 742	180 214	532 957	51.87
	Defender	2052	12 452 375	374 895	336 551	136 378	472 929	46.68
2031	Challenger	2030	5 398 830	153 775	359 922	168 200	528 122	51.52
	Defender	2053	12 765 480	384 825	335 934	132 789	468 723	46.28
2032	Challenger	2031	5 874 797	163 644	367 175	157 688	524 862	51.32
	Defender	2055	13 557 140	404 079	338 929	126 150	465 079	46.04
2033	Challenger	2052	13 795 196	431 240	372 843	149 000	521 843	44.77
	Defender	2056	13 898 779	413 888	338 995	123 073	462 068	45.77
2034	Challenger	2053	14 158 940	440 988	372 604	145 079	517 683	44.61
	Defender	2057	14 260 492	423 636	339 536	120 143	459 678	45.57
2035	Challenger	2054	14 543 516	450 675	372 911	141 359	514 270	44.50
	Defender	2058	14 643 077	433 323	340 537	117 349	457 886	45.44
2036	Challenger	2056	15 459 510	472 398	377 061	134 463	511 525	44.40
	Defender	2059	15 047 376	442 951	341 986	114 682	456 668	45.36
2037	Challenger	2057	15 878 331	481 964	378 056	131 262	509 317	44.38
	Defender	2060	15 474 279	452 517	343 873	112 133	456 006	45.35
2038	Challenger	2058	16 320 850	491 470	379 555	128 209	507 764	44.43
	Defender	2061	15 924 720	462 024	346 190	109 696	455 885	45.39
2039	Challenger	2060	17 287 167	512 935	384 159	122 511	506 670	44.45
	Defender	2062	16 399 687	471 469	348 930	107 362	456 291	45.49

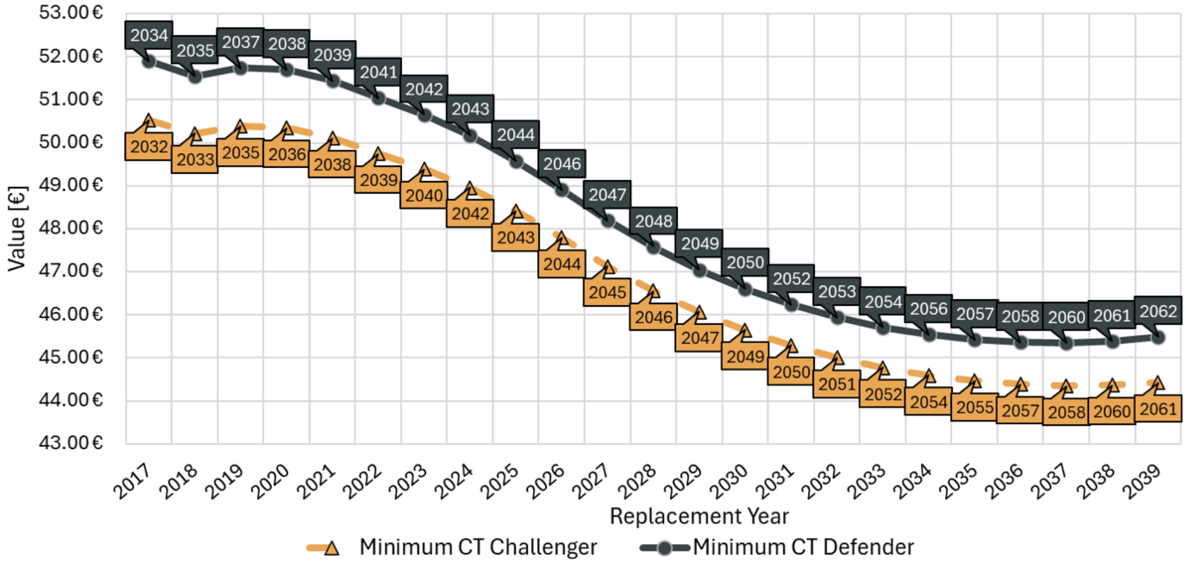


Figure 4.18: Minimum average cost per treatment for each Simulation

necessary to define a common point in time so that the analysis is more accurate and can serve as a complement to informed decision-making.
In this study, the time point has been established, corresponding to 10 years of estimated useful life, as provided by the manufacturer. Accordingly, for each simulation, the results for the 10th year after equipment replacement are selected.
By way of illustration, simulation 4 represents the replacement of the asset in the 5th year, with the selected outcomes corresponding to the 14th year. This is because the 5th year already contributes to the lifespan of the replacement equipment.

Following this, Figures 4.19 and 4.20 show the same data as the previous figures, but directly comparable in time between the replacement with a Defender and a Challenger.

Upon initial observation, it is evident that the absolute values depicted in these images are significantly higher than those reflected in the minimum cost graphs. However, the data obtained with the filter from the 10th year after replacement can be considered to have a lower risk factor. This is due to the fact that the time frame of the results is also considerably shorter than that of the minimum cost analysis, which typically occurs between the 17th and 23rd year after replacement. In this context, risk can be defined as the uncertainty of predicting future data, hence, as the number of years to be predicted increases, so does the uncertainty associated with the results.

The individual analysis of Figure 4.19 yields similar results to those shown in Figure 4.17 , indicating that the Challenger incurs higher costs due to the aforementioned factors. However, the difference between the two assets is at its lowest point, of 5.5%, in the last simulation, which models the replacement of the assets in the 24th year.

The analysis of costs per treatment in Figure 4.20 clearly demonstrates the advantage of the best-performing asset. Additionally, an inversion in the cost curve is visible, indi-

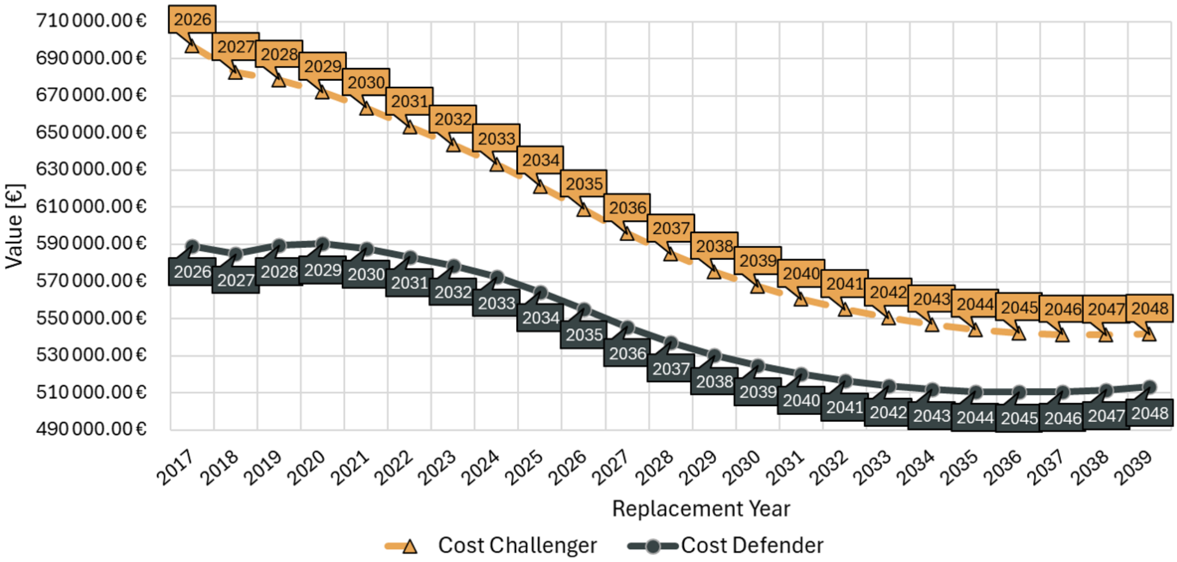


Figure 4.19: Total average cost after 10 years of replacement, for each simulation

cating that equipment should be replaced between 2034 and 2038. It is also important to note that the Defender reaches a minimum of 49.97€ per treatment in 2044, while the Challenger reaches a minimum of 48.48€ per Treatment in 2043, one year earlier for the suggested replacement date.

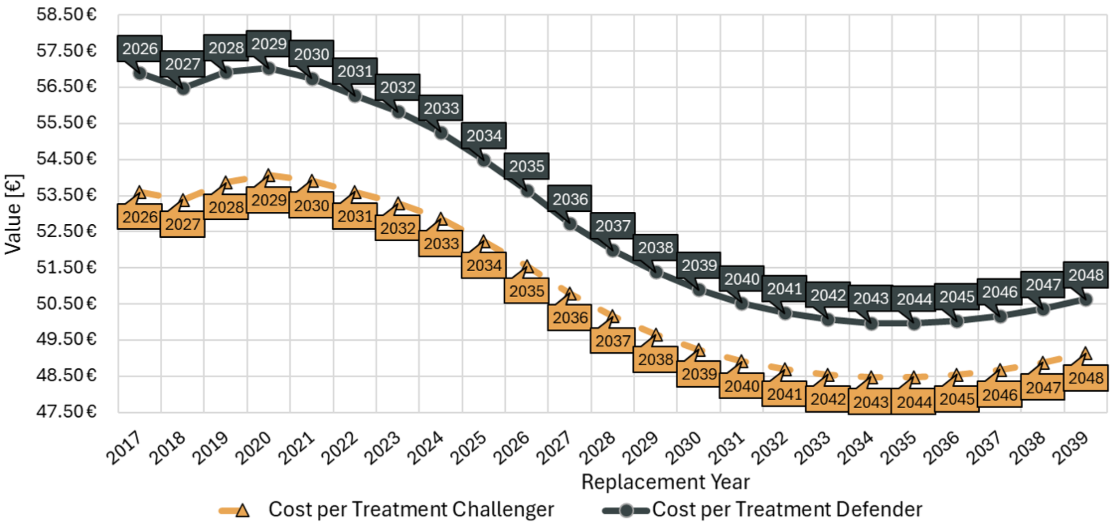


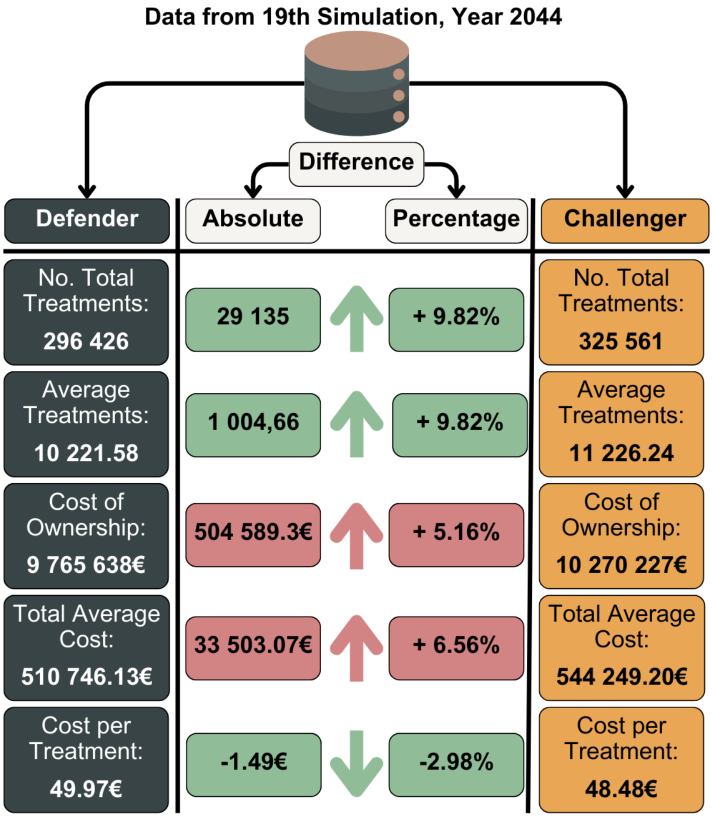
Figure 4.20: average cost per treatment after 10 years of replacement, for each simulation

4.4.4 Impact of the Consideration of New Assets

To account for the influence of new technologies available in the market for asset replacement, it is essential to establish a benchmark for comparison and assess the viability of new assets. To generate genuine outcomes, the selection of reference values is based on a bias towards optimism. This assumes the most favorable scenario of replacement with the Defender will take the place as reference values.

To provide a conservative benchmark, the reference values for comparisons throughout the remainder of the report were based on the most favorable outcomes for the Defender. These results were found in the replacement years of 2035 and 2044, with a Total Average Cost of €510,746.13 and a Cost per Treatment of €49.97. These values were used as the reference for subsequent comparisons in Figure 4.21 and for all following analyses in the report.

To facilitate comprehension and provide a robust foundation for decision-making, five key performance indicators were identified for comparative financial analysis. These include the total number of treatments, the average number of treatments, the total cost of equipment ownership during the analysis period, the total average cost, and the cost per treatment.



Data from 19th Simulation, Year 2044

	Difference			
Defender	Absolute		Percentage	Challenger
No. Total Treatments: 296 426	29 135	↑	+ 9.82%	No. Total Treatments: 325 561
Average Treatments: 10 221.58	1 004,66	↑	+ 9.82%	Average Treatments: 11 226.24
Cost of Ownership: 9 765 638€	504 589.3€	↑	+ 5.16%	Cost of Ownership: 10 270 227€
Total Average Cost: 510 746.13€	33 503.07€	↑	+ 6.56%	Total Average Cost: 544 249.20€
Cost per Treatment: 49.97€	-1.49€	↓	-2.98%	Cost per Treatment: 48.48€

Figure 4.21: Result comparison between data from the replacement with a Defender and with a Challenger, both on year 2044 of the 19th simulation

The Figure 4.21 illustrates the substantial impact of considering a Challenger-type asset. Here, we can directly compare the costs associated with owning the equipment and the average total cost, where the figures are 5.16% and 6.56%, respectively, with the Challenger bearing the higher cost. However, a comprehensive analysis of the results indicates a notable reduction of approximately 3% in costs per treatment, attributed to the significant increase in production capacity. One particular note is the increase in the number of treatments, which has grown by nearly 10%, leading to an absolute increase of 29,135 treatments. This growth has a significant social impact given the high demand for this type of treatment that far surpasses the current supply.

4.4.5 Sensitivity Analysis

This subchapter presents a sensitivity analysis in a similar way to the section 4.3.1, but adapted to the dynamic model.

As previously outlined, this analysis incorporates a range of potential rates, between -2% and 4%, with the reference results aligning with the simulations with an apparent rate of 2%, as illustrated in Figure 4.22.

Since the variations in the apparent rate are being discussed, each line in the charts represents a different perception of the value of money. Therefore, the charts should not be interpreted based on absolute values. Instead, focus should be placed on the years with minimum costs for each rate, representing the optimal years for replacement.

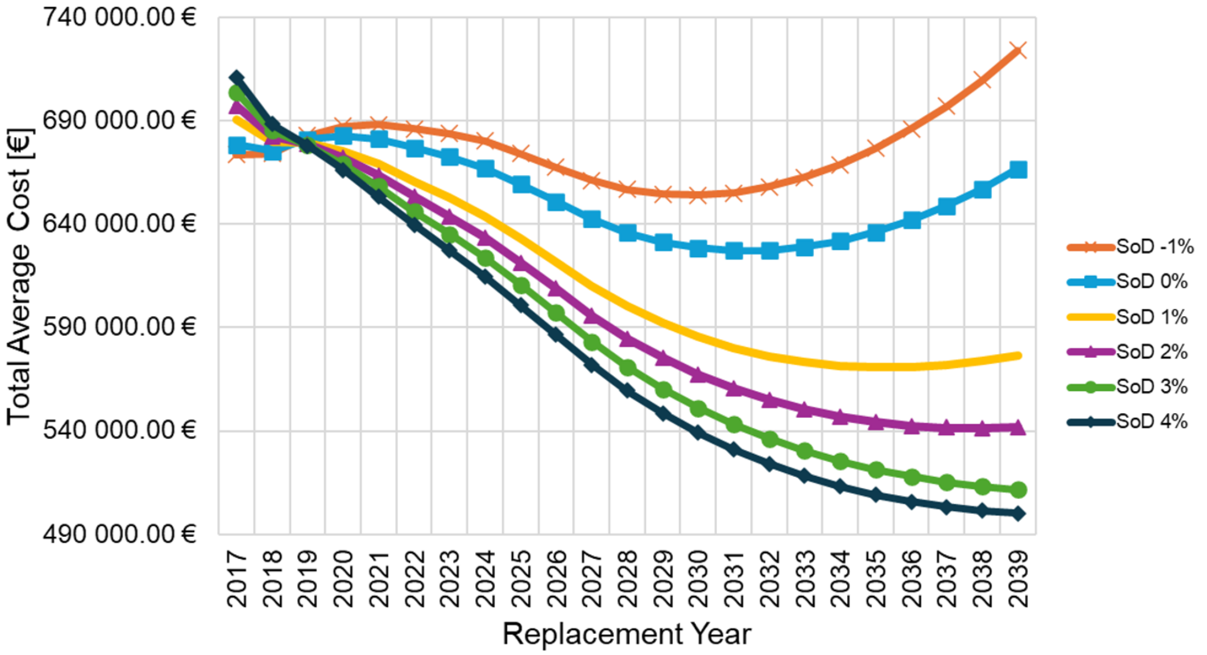


Figure 4.22: Sensitivity analysis to the dynamic replacement model with a Challenger, emphasizing data from the 10th year after replacement

The results align with the trends observed in the earlier sensitivity analysis for MTACM-RPV. They indicate that with apparent rates above 3%, the model may fail to reach a minimum point, whereas assuming a rate below -1% could suggest replacement before 2028, resulting in a life cycle for the Varian TrueBeam of less than 11 years.

Given the discrepancies in values, this sensitivity analysis highlights the importance of regularly updating the model's real data to reduce the uncertainty associated with the results.

4.5 Discussion

The objective of this chapter was to identify the optimal time for replacing one of the linear accelerators at ULS Coimbra. To this end, all the data necessary for the analysis was collected, including the acquisition cost, maintenance costs, energy costs, operating costs, and the disposal value which was estimated using depreciation methods. The data was then applied to asset replacement models, including MTACM and MTACM-RPV with the introduction of a new analysis variable, cost per treatment, which was developed and subjected to a sensitivity analysis of the apparent rate and maintenance costs.

While these results provide a solid foundation for decision-making, there are several constraints that prevent them from reaching their full potential. One such limitation is the inability to integrate factors such as technological development and the optimization of the asset itself, rather than the operation of the organization. To address this issue, a dynamic model was developed based on the MTACM-RPV. This new approach predicts the operational performance of an organization after replacing an asset and considers the potential impact of alternative equipment.

These developments enable the quantification of the economic advantages or disadvantages of replacing the existing asset with one that offers a different level of performance.

These differences mentioned above are evident across all models and metrics applied. The first model analyzed was the basic MTACM, which initially suggested replacement in 2034 but shifted to 2033 when the cost-per-treatment metric was considered. Introducing the concept of reduction of money to the present value further delayed the replacement timeline by one year for each metric.

With the introduction of the dynamic model, which theoretically provides more comprehensive results, the optimal replacement years with minimal costs fall between 2034 and 2039. However, the differences in outcomes within this range are relatively marginal.

Despite the promising results, there are still some limitations in the dynamic replacement model that need to be acknowledged to understand them more thoroughly and subsequently address these weaknesses:

- The model lacks qualitative information, which has a significant impact on equipment selection but is usually challenging to quantify. In the healthcare sector, this factor is of particular importance, as a minor enhancement in image quality or the capacity to undertake a distinct treatment can significantly impact the ultimate outcome for patients;

- This model assesses the life cycle of equipment to identify the optimal time for replacing assets without a defined time interval for the analyses. As a complementary measure, a similar model should be developed to conduct analysis for a previously defined period;
- The proposed model is developed on the basis of MTACM, which is based on costs. This leaves the analysis open-ended because it is not possible to directly quantify the income that organizations would benefit from. Consequently, it is not possible to make decisions based on the point of maximum return or maximum ROI. To address this challenge, a comparable dynamic model could be developed, anchored in the Global LCI, which already incorporates income generated by asset production;
- Another significant drawback is the presentation of future maintenance costs, which is not a direct limitation of the dynamic model but rather a consequence of the data used to populate the models. The cost of maintenance can vary significantly depending on the type of equipment in question and a number of other factors. It would be highly beneficial to apply data from predictive maintenance simulators to this type of asset replacement model. Doing so would allow us to associate the data with the respective costs and reduce the uncertainty associated with the models developed;
- Another factor not included in these models is the concept of the system. The models do not account for the auxiliary equipment needed for the asset to operate at its optimal level. This can include items such as air treatment units, air compressors, and air conditioning systems;
- The replacement of equipment may result in changes to the workflow and operation, as well as introduce new challenges. It is essential to study these changes in order to ensure the effective operation of new assets. This concept initially affects the efficiency with which the equipment is used, and is known as the learning curve. The impact of this curve on overall effectiveness rates can be significant, particularly in the case of certain types of equipment. However, this is not directly quantifiable in the model.

The cost per treatment is largely dependent on the number of treatments carried out, which in turn is contingent on the availability of the necessary equipment and its occupancy rate. One possible solution is to implement the Single Minute Exchange Die (SMED) methodology, which streamlines the logistical processes involved in treatment, eliminating waste and maximizing production capacity. It is highly recommended to use this tool consistently and review it periodically to ensure the most efficient utilization of the equipment installed within the organization. With respect to the hospital linear accelerator, the treatment slots are 15 minutes, as previously stated. Thus, a simple reduction of one minute would equate to a percentage increase of 6.25%, corresponding to an additional 756 annual treatments.

The feasibility of increasing costs in exchange for delivering more treatments should also be evaluated, particularly in the context of critical equipment within healthcare institutions. This approach involves assessing whether the additional investment required to enhance treatment capacity is justified by the resulting benefits, such as serving a greater number of patients or improving the quality of care provided. In public healthcare systems, where the primary goal is community well-being, this analysis can validate higher expenditures if they lead to significant and measurable positive outcomes.

It is important to note that these models are not a decision-making method, rather, they are a decision-support method. The equipment manager or decision-maker should not simply accept the recommendations presented by these asset replacement models uncritically. All acquired data must be supplemented with further information and discussed with multidisciplinary teams, who must ascertain their interests and explain their points of view in order to arrive at a favorable solution for the organization in question.

When analyzing maintenance costs, it would be insightful to compare the expenses and implications of two approaches: maintaining equipment under a service contract versus opting for a pay-as-you-go model, paying only when the equipment breaks down. A service contract typically offers predictable costs and ensures regular maintenance, potentially reducing the likelihood of unexpected failures and extending the equipment's lifespan. On the other hand, a pay-as-you-go approach might initially seem more cost-effective but could lead to higher costs over time due to unplanned downtime, urgent repairs, and potential loss of productivity during equipment failures. Comparing these models could reveal which approach is more cost-efficient and reliable, especially for critical, high-value assets in healthcare.

In evaluating these asset replacement models and the potential benefits they offer, it is essential to conduct a thorough comparison with the specific type of equipment which the old assets can be replaced by. It is also important to consider the potential for major repairs or retrofits of more obsolete equipment. Such cases can also be itemized and modeled in the replacement models and directly compared with the purchase of new equipment.

The dynamic model proves to be a highly valuable tool for public procurement processes, as it enables organizations to quantitatively compare the proposals received, guiding them toward more informed and favorable decision-making.

5 LIFE CYCLE ASSESSMENT

This chapter presents the work carried out to gather data on the environmental impacts of assets, specifically regarding climate change, through an LCA. It also explores how this data is applied within a dynamic asset replacement model to determine, from an environmental perspective, the optimal replacement point.

When it comes to environmental analysis, different products can have very distinct life cycle assessments. In some cases, the biggest impact lies on the production phase of an asset, such as in civil construction, but in others, especially in assets with higher energy consumption, the use phase of the product can amount to more than 90% of the environmental impacts [59]. The energetic consumption and material use and consequent emissions during the use phase are directly influenced by the users' behavior [60]. Thus, the importance of improving the models of consumer choice and behavior for more accurate LCA results is clear [61].

The goal of this study is to quantify and evaluate the environmental impacts of the Linear Accelerator during its use phase, identifying the optimum replacement year. The results of this study will be presented to everyone interested within the organization, with no intention of using the results for public comparisons due to the specific context.

Since this study is conducted from a customer perspective, it focuses solely on the usage phase, leaving out the analysis of other stages. Consequently, the impacts associated with raw material extraction, manufacturing, processing, and end-of-life disposal of the equipment are not assessed. Therefore, as illustrated in Figure 5.1, a system boundary is defined in the use phase of the equipment, which is assessed while excluding other factors, such as the impact of patient travel, which is highly dependent on the patient, the impact of consumables which are rarely used, and the maintenance due to the lack of data.

In light of the information presented above, this study has opted to employ a simplified LCA methodology, calculating the emissions that derive from the operating energetic consumption and identifying the emissions associated with the production of the LINAC. It is important to emphasize that the production emission values of the LINAC are not studied in detail, but rather estimated, whereas the decomissioning emissions are not even considered.

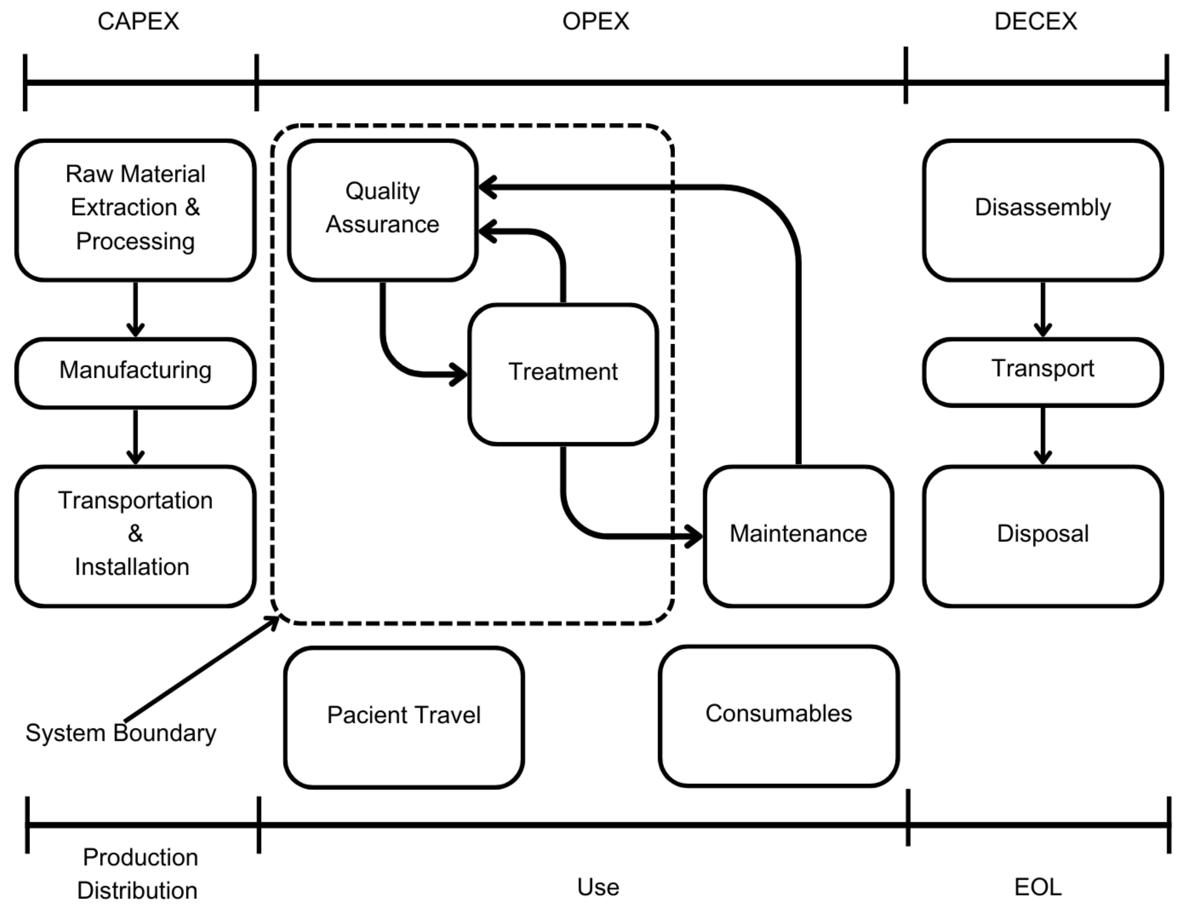


Figure 5.1: LCA boundary system for the present case study

5.1 LCA Replacement Model Adaptation

In order to integrate environmental results with economic outcomes, it is crucial to ensure that the data used in both areas is consistent. This means that for the economic model of asset replacement, data collected from a standard LCC analysis is used and adapted to the MTACM to express annual average cost results, aiming to identify the optimal replacement point. Similarly, in the environmental perspective, data from a simplified LCA is introduced and subsequently integrated into an annual average emission model adapted from the MTACM, ensuring consistency and alignment between the two.

However, given the specificities and intricacies involved in the LCA process, as previously described, no cession values are considered for emissions. This modifies the model's formulation, where instead of having two components - the operating cost (C'_n) and the asset's depreciation value (C''_n) - we transition to a single component, Total Average Emissions (E_n). This E_n represents the average of the sum of the emissions generated during the development of the asset and all operational emissions up to year n, as shown in formula 5.1.

$$E_n = \frac{EA + \sum_{j=1}^{n}(EO_j)}{n} \tag{5.1}$$

where:

E_n – Total average emissions in year n
EO_j – Operating emissions in the year j
EA – Acquisition emissions
n – Analysis year

Similarly to the economic analysis, it is necessary to define the emissions per treatment metric. In this case, instead of having an economic indicator (C_n) in the numerator, an environmental indicator is used, as illustrated by Equation 5.2.

$$ET_n = \frac{E_n}{\frac{\sum_{j=1}^{n}(T_r)}{n}} \tag{5.2}$$

where:

ET_n – Average emissions per treatment in year n
E_n – Total average emissions in year n
T_r – Number of treatments for year j
n – Analysis year

With these two metrics, the models yield consistent results that reflect the average costs and emissions for each year, allowing for a complementary and accurate analysis of both dimensions.

5.1.1 Data and Assumptions

As with economic replacement models, it is necessary to collect data and make assumptions about future values, for both the Defender and the Challenger.

– Acquisition or Development Emissions

To obtain concrete values for an LCA focused on the production of equipment, factors such as raw material extraction and processing, manufacturing, installation, and all transportation requirements throughout these stages are taken into account. However, accessing and tracing this information is highly challenging, as the only entity with reliable data on all these steps is the product manufacturer. This complexity makes conducting a full LCA particularly intricate.

Since this is not the primary focus of the current study, the production and distribution emissions for the equipment are estimated using average values available for similar equipment.

Based on the clarifications provided above, the emissions associated with the acquisition of the Defender were defined as 80 000 $kgCO_2eq$, while those resulting from the purchase of a Challenger were set at 90 000 $kgCO_2eq$.

– Energy Consumption

In the specific case of the Defender, the calculation of the annual energy consumption follows what was described in the chapter on asset replacement models, based on the data collected by the data logger over a one-week period. This is made through the sum of the average energy used in a regular business day (436 kWh) for 250 days, with the energy spent by the equipment on standby mode (158 kWh) for the remaining 115 days of the year. This amounts to an average of 127 170 kWh per year.

Based on the hypothetical capacity of 10 353 treatments in 2023 (the year the data logger was installed), the average energy consumption is calculated at approximately 12 kWh per treatment. This figure serves as the benchmark for the Defender analysis.

For the Challenger, given that one of the objectives of this study was to model equipment with superior performance and greater efficiency compared to its predecessor, it was determined that this new asset would have an energy consumption of 10 kWh per treatment, approximately 16% lower than that of the Defender.

Based on this data, it is also possible to understand that, in an ideal scenario where the equipment operates at 100% Overall Efficiency, with 15,120 treatments performed annually, the Challenger would consume approximately 151,200 kWh per year. This means that, despite the individual energy consumption being lower, when considering the larger number of potential treatments, it can be concluded that the total energy costs and the corresponding total emissions will be higher for the Challenger.

In conclusion, it is clear that for future values, the assumed energy consumption will depend solely on the number of treatments performed annually, which, in turn, is determined by the overall efficiency of the equipment.

– Emissions

With the aim of estimating the environmental impact for the usage phase of LINAC-based external beam radiation therapy in the four most common cancers (Prostate, Lung, Breast and, Rectal), Shenker [62] considered that the emissions could vary between an average of 2.18 and 17.34 $kgCO_2eq$ per modality course, resulting in an average of between 0.436 and 1 kg CO_2eq per treatment.

In this case study, o calculate the emissions associated with electricity production, the Portuguese Environment Agency provides a document on the greenhouse gas emission factor of electricity produced in Portugal [63], which aggregates data for the country, mainland Portugal and the autonomous regions of the Azores and Madeira. This information is presented in Table 5.1.

Table 5.1: Electricity emission factor, adapted from [63]

Region	Unit	2015	2016	2017	2018	2019	2020	2021
Continent	tCO2 eq./MWh	0.328	0.267	0.338	0.282	0.224	0.175	0.151
Madeira	tCO2 eq./MWh	0.507	0.491	0.506	0.493	0.524	0.505	0.465
Azores	tCO2 eq./MWh	0.470	0.471	0.455	0.448	0.450	0.435	0.462
Portugal	tCO2 eq./MWh	0.334	0.273	0.342	0.287	0.233	0.184	0.162

The data above only contains values up to 2021, which are used for the respective years. In line with LCA recommendations, a reference value of 0.15 $tCO_2eq./MWh$, or 0.15 $kgCO_2eq./kWh$, has been estimated for future years, with no decay assumed over time.

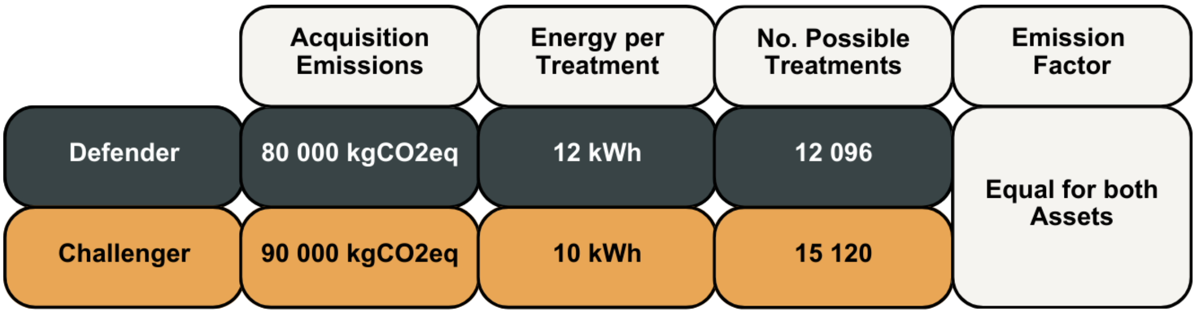
Based on this data, considering the estimate of 12 kWh per treatment for the Defender and assuming emissions of 0.15 $kgCO_2eq./kWh$ for 2023, approximately 1.8 $kgCO_2eq.$ would be generated per treatment.

This value is 80% higher than the highest estimate from Shenker[62]. However, this discrepancy can be explained by the fact that, in this particular case study, the emissions per treatment metric does not solely account for the emissions directly related to each treatment. Instead, it includes the total energy consumption of the LINAC over an entire year of operation, which also factors in the 12 hours of standby time, during which no treatments are performed, but the equipment still consumes energy.

– Data Summary

To facilitate the understanding of the differences between potential replacement assets, a simple summary is available in Table 5.2, which can be reviewed alongside the results for better interpretation.

Table 5.2: LCA data specification comparison between the defender and the challenger



	Acquisition Emissions	Energy per Treatment	No. Possible Treatments	Emission Factor
Defender	80 000 kgCO2eq	12 kWh	12 096	Equal for both Assets
Challenger	90 000 kgCO2eq	10 kWh	15 120	

5.2 Results and Interpretation

The results can first be presented as a simple minimization of the total average emissions method, similar to the MTACM, where only the individual data of the Varian Trubeam LINAC is modeled. This involves the direct application of the Formulas 5.1 and 5.2 (page 71), described earlier. These results are illustrated in Figure 5.2.

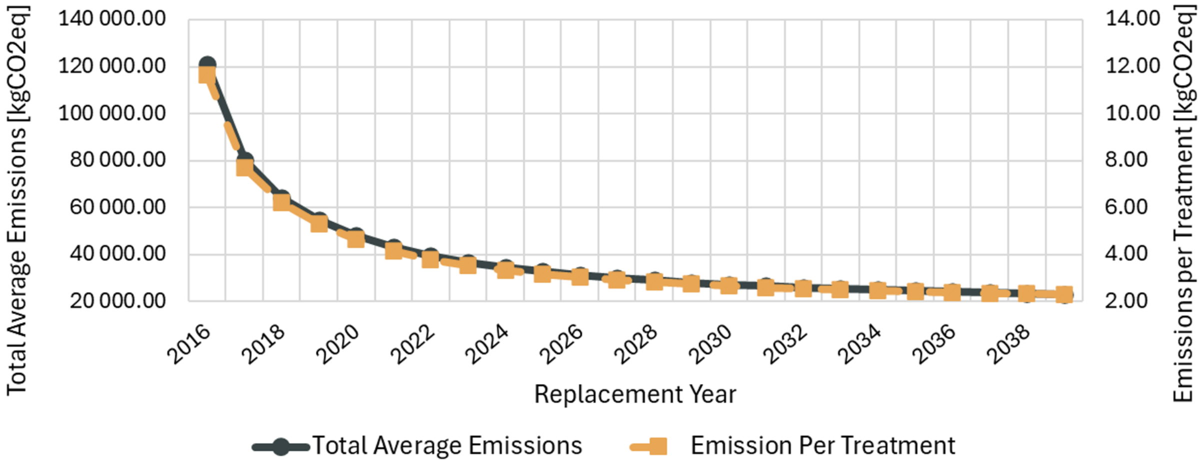


Figure 5.2: Minimum total average emissions model, applied only to the Varian Trubeam LINAC data

The Figure provides a logical and expected representation of the outcomes from the developed model, which excludes the residual value variable. As this is an average minimization model focused on environmental impact, and given the absence of any projected increase in electricity emission factors, the results reveal a predictable downward trend across both metrics analyzed. The minimization of the total average emissions and emissions per treatment metrics yield similar results, largely due to the calculation method applied to the average number of treatments, which totals approximately 10 000 treatments annually.

Following this, the results obtained from applying the data to the dynamic model are expected to maintain the same downward trend.

To facilitate the interpretation of the results, it is recommended to review the next graphs alongside the table provided in Appendix B (page 100).

The analysis focuses on the environmental impact of the equipment under study. Since there are no apparent rates that would increase the energy consumption of the equipment, and annual production can never exceed the maximum production capacity, it is natural for the models to show continuously decreasing results. This is also due to the averaging formulation used in the model. This is represented in Figure 5.3, which also illustrates that the point of minimum average emissions always occurs in the final year of each simulation.

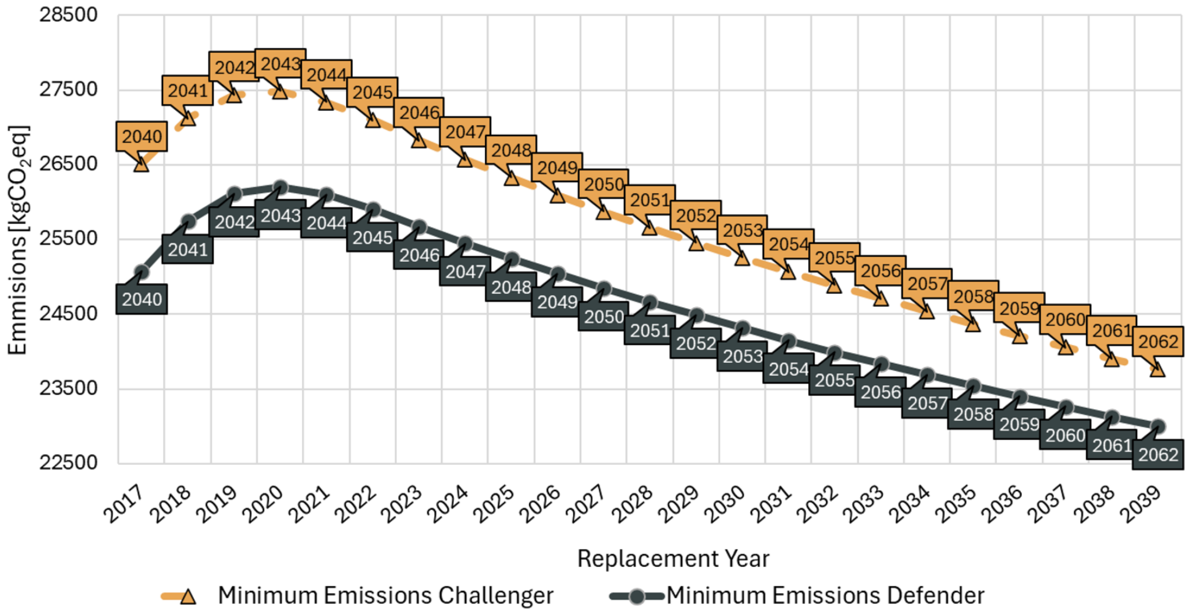


Figure 5.3: Minimum total average emissions for each simulation

It is important to explain why environmental impact charts consistently show an increase in emissions during the initial simulations. This occurs because, as previously mentioned, the early simulations analyze the replacement of the asset within its initial years of use. Since the emissions associated with the production of the equipment are also included, the models interpret this as the combined emissions from the production of two pieces of equipment within a short time frame, in addition to the emissions generated during their usage. As a result, the average annual emissions are higher in the first few simulations.

On the other hand, Figure 5.4 highlights the importance of conducting analyses using more than one indicator. Figure 5.3, which depicts total average emissions, illustrates that, from an overall environmental impact standpoint, choosing a replacement with a Defender would be less harmful, as it results in lower total equivalent carbon emissions. However, when the analysis considers emissions per treatment, a role reversal is observed (similarly to what occurred in the economic analysis), making the replacement with a Challenger the most environmentally viable option.

Following the demonstration of the results above, the issue of comparing outcomes at the same point in time persists, which is essential for conducting a fair analysis. Therefore, a filter was once again applied to the results to ensure that only the values corresponding to the 10th year after the replacement are graphically presented for each simulation.

In this sequence, Figure 5.5 shows that the total average emissions present a very small difference when comparing a Defender versus a Challenger. This can be explained by the difference in energy consumption per treatment and the number of treatments per-

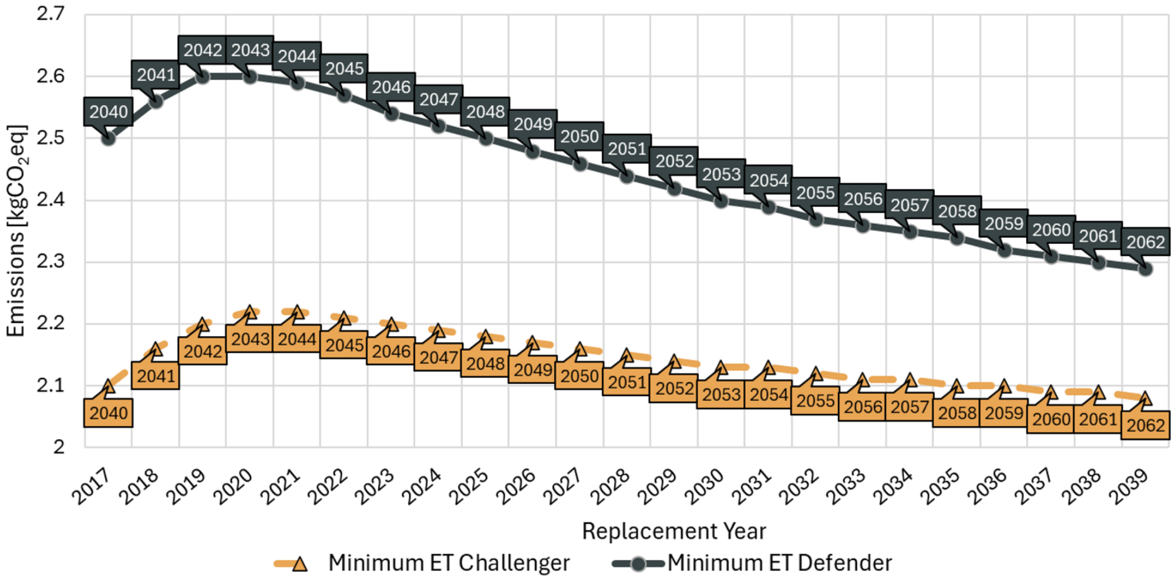


Figure 5.4: Minimum total average emissions per treatment for each simulation

formed, where the Challenger consumes 16.66% less energy and performs 25% more treatments than the Defender. Over 10 years of use, these variables result in the total emissions difference being minimal.

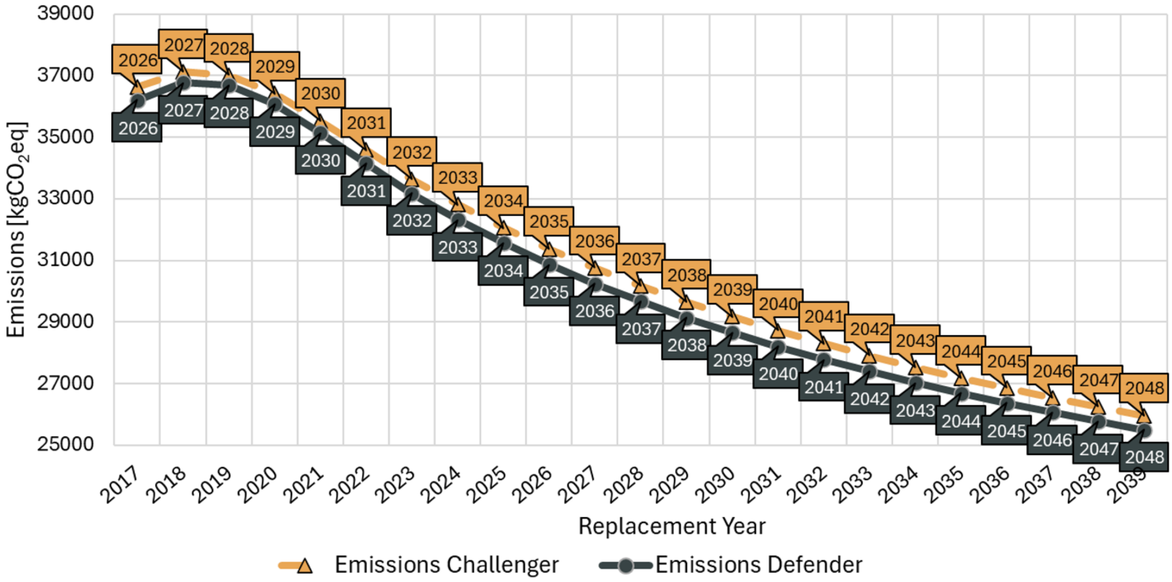


Figure 5.5: Total average emissions concerning to the 10th year post-replacement, for each simulation

In the case of emissions per treatment after 10 years of replacement, as shown in Figure 5.6, it remains evident that, on a unitary basis, replacement with a Challenger would yield more favorable results for mitigating climate change.

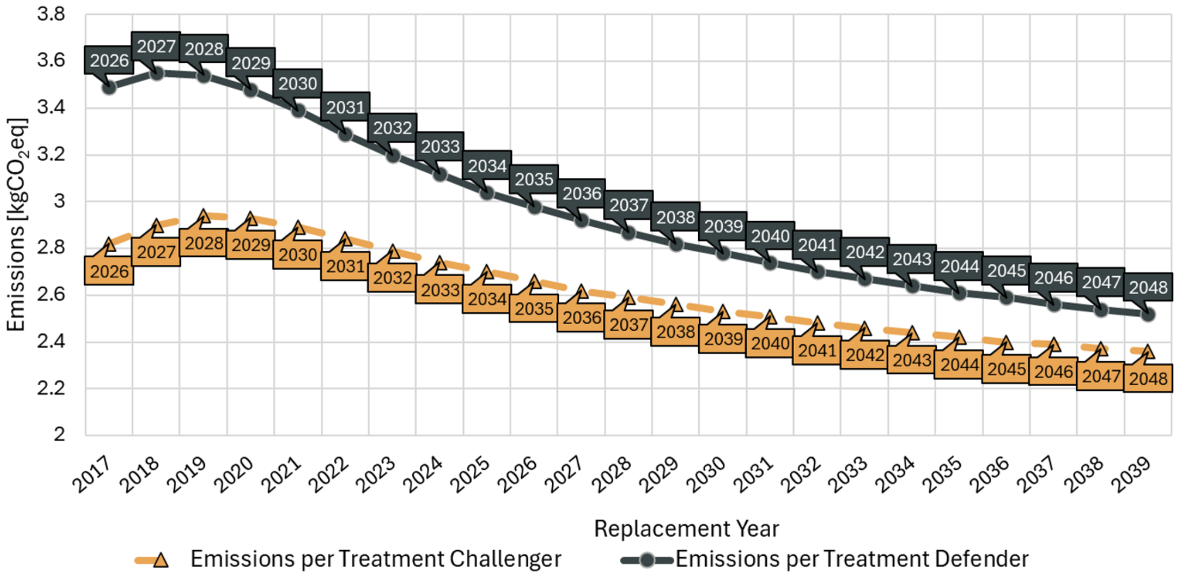


Figure 5.6: Total average emissions per treatment concerning to the 10th year post-replacement, for each simulation

5.3 Discussion

The quantification of the environmental impact caused by organizational equipment is an increasingly popular topic, amidst concerns about climate change. To support such analyses, asset data on environmental impacts should be as accessible as financial data. In this case study, we propose a methodology to identify the optimal environmental point for asset replacement, leveraging existing models designed for financial indicators. This approach advocates for manufacturers to disclose emission data related to the production of equipment, just as they do for acquisition costs. This alignment ensures greater transparency and facilitates informed decision-making in sustainability efforts.

When analyzing the results from an environmental perspective, a key observation emerges that encapsulates the general application of the models: the longer the equipment remains in operation, and the further the analysis extends over time, the lower the average environmental impacts associated with the assets tend to be.

Despite this conclusion, the primary objective of the analysis was to compare the environmental impacts between the two potential replacement assets. It becomes evident that, in terms of total emissions, the Defender consistently holds an advantage due to its lower annual treatment count. However, this ranking shifts when the focus turns to emissions per treatment, mirroring the results observed in the economic models.

Although the models provide consistent results, the depth of the environmental analysis could be further enhanced if the study of emissions was expanded to fully capture all potential emission sources throughout the asset's entire life cycle. This level of detail was not pursued in the current study due to the complexity and technical rigor required for a comprehensive LCA.

It would still be interesting to explore potential residual values, similar to those in the economic analysis, simply to understand the impact of not bearing the full production emissions of the equipment. For instance, this could involve selling the equipment to a third party, with the emissions of this acquisition being significantly lower than those of a new asset.

Another factor that could have a significant impact on the model results is the integration of on-site energy sources, such as the hospital's solar panel array. In this case, there would be a direct reduction in the electricity emissions factor, as the energy would come from a fully renewable source. However, it would be necessary to account for the emissions associated with the production of the solar panels themselves.

6 ECONOMIC AND ENVIRONMENTAL REPLACEMENT MODELS INTEGRATION

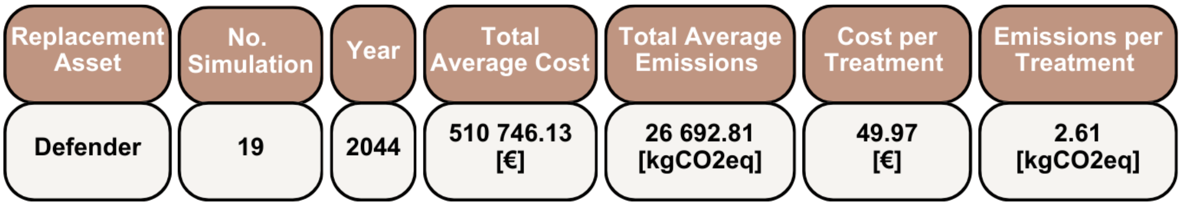
Performing an individual interpretation for each analysis can help the organization select the optimum time to replace the asset, from both a financial and environmental perspective, separately. This can lead to a false sense of optimization that may not reflect the desired results.

To address this ambiguity in decision-making, it is essential to integrate the results of the analyzed aspects and determine the relative importance assigned by the organization to each variable. In this case, said variables are the financial and the environmental, where the Eco-Efficiency Analysis (EEA) was selected to integrate the results. This method offers an easy-to-use, straightforward approach with clear solutions.

6.1 Eco-Efficiency Analysis

The objective of this Eco-Efficiency Analysis is to compare the results of all the possible alternative scenarios with a defined reference scenario.

In this study, as previously established, the reference point was set to the results from the year 2044 of the 19th simulation involving replacement with a Defender, represented in Figure 6.1. These results were identified as the optimal benchmark for replacing an asset with one identical to the one in operation.



Replacement Asset	No. Simulation	Year	Total Average Cost	Total Average Emissions	Cost per Treatment	Emissions per Treatment
Defender	19	2044	510 746.13 [€]	26 692.81 [kgCO2eq]	49.97 [€]	2.61 [kgCO2eq]

Figure 6.1: Reference values, defined by the results of the replacement with a Defender, on the 19th simulation and year 2044

The EEA was conducted from two perspectives: Total Average Impact, which includes the metrics of Total Average Cost and Total Average Emissions, and Impact per Treatment, encompassing the metrics of Cost per Treatment and Emissions per Treatment.

6.1.1 Results and Interpretation

To facilitate the interpretation of the results, it is recommended to review the graphs alongside the table provided in Appendix B (page 100).

Figure 6.2 presents a comparison of the best outcomes after 10 years of replacing the asset with a Challenger, for each simulation, against the reference values previously defined. When analyzing the Total Average Impact, a new perspective emerges on earlier conclusions. In terms of environmental impact, replacing the asset with a Challenger results, at best, in a minimum of approximately 6% higher emissions compared to the optimal Defender scenario. Moreover, the total costs only become economically advantageous starting from the 21st simulation, which corresponds to a replacement in 2037.

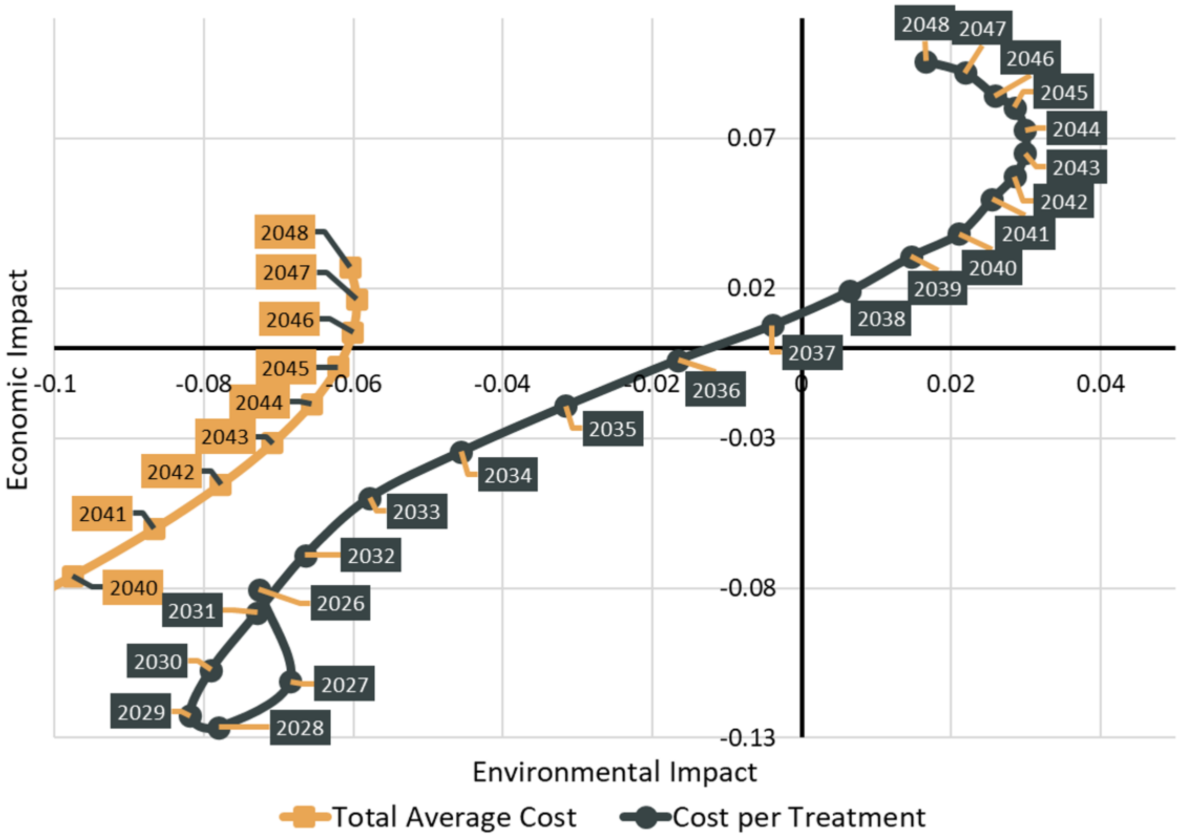


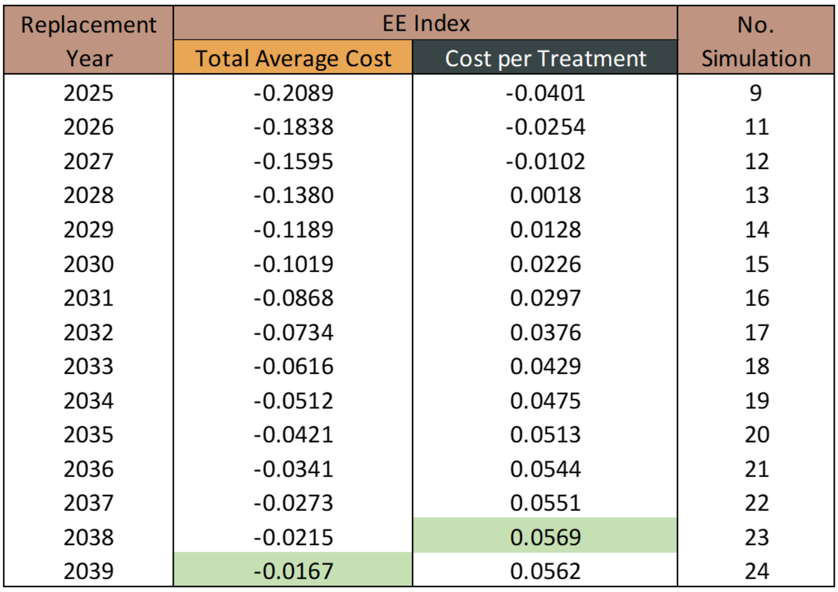
Figure 6.2: Eco-Efficiency graph

On the other hand, when examining the Impact per Treatment, it becomes evident that replacing the asset with a new one yields negative outcomes until 2036/2037, corresponding to the replacement years 2025 and 2026, respectively. However, this does not negate the fact that the replacement with a Challenger delivers better results than replacing with a Defender. This is because the EEA uses the 19th simulation in 2044 as the reference point for the Defender, meaning the temporal comparison point differs. Nevertheless, the results for replacing with a Challenger become positive in both economic and environmental aspects starting in 2038, which corresponds to the 13th simulation, with replacement occurring in 2029.

The interpretation of the previous graph suggests that, to achieve the most favorable economic performance, the optimal replacement moment would be in 2039 (23rd simulation), with the minimum costs after 10 years of replacement, in 2048. Alternatively, if the goal is to minimize the impact of replacing the asset with a new one, the best point would be in 2035 (19th simulation), with the optimal results in 2044 . However, the organization may wish to assign varying importance, or weight, to each factor, allowing for flexibility between 100% focus on the economic aspect and 100% focus on the environmental aspect.

In the presented case study, an equal weighing of 50% was assigned to both the economic and environmental aspects. These weights were incorporated into the formulas to determine the most advantageous scenario from this point of view. The resulting values are displayed in Table 6.1, illustrating how the assignment of weights can influence the information which will influence decision-making.

Table 6.1: Eco-Efficiency Index results



Replacement Year	EE Index		No. Simulation
	Total Average Cost	Cost per Treatment	
2025	-0.2089	-0.0401	9
2026	-0.1838	-0.0254	11
2027	-0.1595	-0.0102	12
2028	-0.1380	0.0018	13
2029	-0.1189	0.0128	14
2030	-0.1019	0.0226	15
2031	-0.0868	0.0297	16
2032	-0.0734	0.0376	17
2033	-0.0616	0.0429	18
2034	-0.0512	0.0475	19
2035	-0.0421	0.0513	20
2036	-0.0341	0.0544	21
2037	-0.0273	0.0551	22
2038	-0.0215	0.0569	23
2039	-0.0167	0.0562	24

In this instance, it was determined that the balance, considering equal weighing of economic and environmental factors, lies between the years 2047 and 2048. These correspond to simulations 22 and 23, and replacement in the years 2038 and 2039, respectively.

6.2 Discussion

Conducting individual analyses from economic and environmental perspectives can be extremely useful to understand the data within each domain, assessing asset performance, and identifying optimal solutions for replacement. Nonetheless, if the organization seeks concrete decision-support data, it is essential to integrate these analyses to produce a single, unified result instead of two separate outcomes with differing units.

One of the major advantages of using an EEA is that it enables a direct, global comparison of the benefits of having a new asset versus an older one, all within a single graph, providing a clear decision-making indicator. While such comparisons can also be made in independent analyses, the EEA offers a more holistic view, allowing for the simultaneous evaluation of both economic and environmental perspectives.

As with all the analysis methods used in this work, the limitations and details should be identified and understood for each. In the case of the EEA, it is essential to clearly understand the impact being analyzed, how it could shape the future, and how monetary value can be related to emissions. When assigning a weight of 50%, it implies that a 1% variation in costs is considered equivalent to a 1% variation in emissions. However, this assumption may not be entirely accurate. This is because we are working with percentage-based comparisons, meaning variations relative to a baseline value. For instance, if the baseline financial value is €1 million and the alternative scenario is €1.1 million, there is a 10% increase. Similarly, if the environmental baseline is 1 kg CO2eq and the alternative scenario is 1.1 kg CO2eq, there is also a 10% increase. In such a hypothetical case, it would suggest that €100,000 holds the same significance for the organization as 100 grams of CO2eq emissions. Depending on the organization's priorities and objectives, this might not represent a fully balanced or meaningful analysis.

7 CONCLUSIONS & FURTHER RESEARCH

This report begins with a brief introduction to the internship, including its motivation, an overview of the host institution, and the research questions. This is followed by a literature review focusing on asset and medical equipment management, maintenance concepts, and concluding with the state of the art in replacement models, which played a central role in the work carried out.

During the internship, several tasks were carried out in support of the FMS, including:

- Reviewing invoices for newly acquired assets to ensure compliance;
- Proposing new listings for management support platforms;
- Conducting visits to all hospital units within CHUC;
- Providing daily support to the AMT, which included registering over 600 assets worth nearly 2 000 000€ and resolving inventory discrepancies;
- Analyzing various internal procedure manuals;
- Supporting internal audits.

In addition to these daily tasks, two major projects were undertaken. The first focused on developing a monitoring tool to track the status of new assets, from acquisition and reception to their registration on the designated platform. The second involved studying the life cycle of a Medical Linear Accelerator to determine the optimal replacement point.

The first project focuses on improving the asset portfolio management. In large institutions, maintaining strict control over newly acquired assets can be challenging due to the high volume of daily acquisitions and the lack of integration between different software systems. These issues are particularly evident in the case of ULS Coimbra.

The proposed solution involves creating a Power BI dashboard that integrates data from the three different management platforms used for asset acquisition, payment, and registration. It provides standardized indicators for tracking and comparing asset statuses over time and, additionally, it allows users to generate tables highlighting discrepancies between the platforms, enabling the completion or correction of missing or inaccurate information.

This project demonstrates the feasibility of developing rapid monitoring tools to track assets effectively. Moreover, by automating data processing tasks, the solution achieved a reduction of approximately 30% in the time required to generate results, which was previously reliant on manual data treatment.

In addition to monitoring newly acquired assets, it is important to emphasize three key aspects that can enhance data quality and optimize the resources dedicated to asset portfolio management. The first involves identifying which assets truly need to be inventoried and registered. In large institutions, it may not be worthwhile to allocate human resources to record low-value assets, allowing the focus to remain on more critical items.
The second aspect focuses on the quality and relevance of the data entered into asset management platforms. As an example, a clear distinction should be made between medical equipment and administrative assets. The effort required to input detailed information for administrative assets may not be justifiable, whereas ensuring the accuracy and completeness of data for medical equipment is essential.
The third aspect pertains to the disposal of obsolete or unnecessary equipment, where monitoring decommissioned assets is as important as tracking new acquisitions, ensuring that resources are not wasted on assets that are no longer operational or needed.
By addressing these aspects comprehensively, institutions can significantly improve the efficiency and reliability of their asset management processes.

The second project focused on determining the optimal time frame for replacing a Medical Linear Accelerator using cost-minimization models. Initially, data is introduced in traditional models, MTACM and MTACM-RPV, incorporating a new cost per treatment metric to evaluate whether production costs are justified by the production.
Subsequently, these models are adapted into a dynamic replacement model to overcome the limitations of traditional approaches, such as ignoring the need for the organizations to continue operating and the introduction of new assets in the market with varying performance levels.
Additionally, an environmental replacement analysis is conducted using data from a simplified LCA, where the base unit shifts from euros to $kgCO_2eq$.
To integrate the economic and environmental perspectives, an eco-efficiency analysis is performed, combining the two indicators into a single index. This comprehensive approach provides a balanced evaluation of both cost and environmental impact in asset replacement decisions.

Among all the models applied, the replacement of the LINAC is suggested within a timespan between 2034 and 2039. The years from 2034 to 2036 are indicated by the traditional MTACM and MTACM-RPV models, while the minimum cost points from 2037 to 2039 are associated with the dynamic model and the accompanying eco-efficiency analysis.
Therefore, in the presented case study, selecting the dynamic model over traditional models results in a difference in the optimal replacement point ranging from a minimum of 1 year to a maximum of 5 years. While choosing this developed broader model

may not guarantee better future outcomes, it does ensure a more informed decision-making process, potentially with reduced uncertainties.
The minimum results obtained for each replacement model can be analyzed in Appendix C.

The study concludes that replacement models demonstrated significant adaptability to the specific needs of an organization and its specific objectives. They not only support the analysis of total costs but can also be tailored to accommodate new indicators, such as the cost per treatment metric introduced in this study. This flexibility is particularly valuable since organizations often operate with distinct metrics and KPIs. By leveraging quantitative data and effectively integrating and interpreting relevant metrics, these models enable the development of new indicators that align with diverse organizational priorities.
Additionally, the models showcased their versatility by extending beyond purely financial applications. In the presented case study, the MTACM model was adapted to analyze environmental impacts, measuring emissions in kgCO_2eq. rather than euros. This adjustment highlights the capacity of these models to incorporate sustainability considerations, broadening their scope and relevance.
In conclusion, this study goes beyond determining the optimal time frame for asset replacement to minimize costs. It demonstrates that even when comparing two assets with very similar performance levels, there can be a significant impact on the replacement year, as well as on overall costs and production outcomes. The dynamic replacement model developed here not only proves to be a practical tool but also surpasses traditional models in its ability to provide a more complete and informed framework for decision-making.

As a final remark, when studying the optimum asset replacement point, it is essential to pay close attention to two key factors that can significantly impact decision-making. The first point relates to the quality and veracity of the data input, which should be updated to real values whenever possible. In the case of future value inputs, it is important to recognize any uncertainty associated with the data. The second key factor is the need to recognize that these models are merely mathematical models. They do not possess the ability to comprehend the source of the data, nor do they have the capacity to reason. Furthermore, they do not consider qualitative factors to supplement the analysis, unless they are clearly translated and attributed in a quantitative manner. The efficient and effective use of these models, therefore, depend on a clear understanding of the data, its source, the filters applied, and the impact of any changes. It is also essential to understand the qualitative limitations of the models in order to make well-informed, transparent, and conscious decisions.

7.1 Answers to the Research Questions

This subsection is solely intended to directly address the research questions proposed during the curricular internship.

RQ1 – What is the optimum replacement point for the studied medical linear accelerator?

The optimal timeframe for replacing a LINAC ultimately depends on the organization's strategic decision-making framework. However, based on the applied models, the period with the lowest costs typically falls between 2034 and 2038 when focusing exclusively on economic factors. When incorporating environmental considerations into the analysis, the ideal replacement window shifts to between 2038 and 2039.

It is important to emphasize that this result is derived from the data input into the models, making it highly dependent on the projections made for the future. Therefore, one of the most critical steps in using these models is the systematic updating of estimated data with real data, gradually reducing the uncertainty associated with the results.

RQ2 – How does technological evolution impact the optimum decisions for asset management and replacement?

The consideration of technologically advanced equipment with superior performance directly impacts the timing of replacement and the absolute cost implications for the organization. In the presented case study, which compares replacing an asset with an identical model versus a slightly more advanced one, findings reveal that opting for the newer asset incurs approximately 6% higher total ownership costs. However, this decision leads to a nearly 10% exponential increase in the number of treatments performed, and a corresponding 3% reduction in cost per treatment. From a temporal perspective, considering the Challenger could either bring the replacement forward by up to 2 years or delay it by the same amount, depending on the metric used for decision-making.

Incorporating new assets into replacement decisions allows for more informed and strategic decision-making for the organization.

RQ3 – How does sustainable management impact the life cycle of equipment and the decision for replacement?

Integrating environmental impacts into investment analyses tends to delay the timing of asset replacement, as one of the most effective ways to reduce emissions is to halt consumption. This is directly reflected in the individual life cycle analysis of equipment, where average emissions consistently follow a downward trajectory. The critical insight here is determining which replacement asset will be the most environmentally sustainable. In the case study presented, incorporating environmental considerations could postpone the replacement year by up to five years. While this approach logically increases total emissions, it simultaneously reduces annual averages, striking a balance between environmental responsibility and operational needs.

7.2 Appended Papers and Articles

During the internship and the period dedicated to developing this report, the following papers and articles were produced:

- L. M. D. Neves, J. M. T. Farinha, J. L. F. Martinho, "O Impacto de Novas Tecnologias na Substituição de Ativos", Coimbra: ENEGI, 12th-13th September 2024. – Paper published in the proceedings of ENEGI 2024.
- L. M. D. Neves, R. M. F. Albuquerque, "KPI na gestão de equipamentos e infraestruturas hospitalares", TecnoHospital, no. 125, pp. 20-23, September/October, 2024.

Additionally, a paper based on this internship report and the developed methodology is currently being prepared for publication in an international indexed journal.

7.3 Future Research

During this internship, a life cycle analysis was conducted on a linear accelerator, one of the most expensive pieces of heavy medical equipment in a hospital, in order to identify the point of minimum costs and the lowest environmental impact associated with its replacement. Additionally, this analysis aimed to understand how the organization would be affected by the replacement at various stages. Similarly, it would be beneficial to conduct a comparative analysis of numerous smaller medical devices, which collectively represent a value equal to or greater than that of a single large-scale medical equipment item. In this framework, it might be worthwhile to establish a fixed time interval to determine how often replacements would be necessary over a given period.

The healthcare sector benefits not only from the number of treatments performed, but also from the quality of those treatments. It would, therefore, be valuable to develop a method for incorporating qualitative factors into replacement models. This could enable quantitative comparisons between equipment, such as those with differing image resolutions, offering a more comprehensive basis for decision-making.

The development of the dynamic model in this work involved adapting the MTACM, which focuses solely on costs. To conduct analyses with greater precision, it was necessary to establish cost per production metrics. Adapting the dynamic model to replacement models that incorporate revenue metrics, such as the Global Life Cycle Investment approach, could significantly enhance the objectivity of determining the optimal replacement year for organizations aiming to maximize profitability.

BIBLIOGRAPHY

[1] "Decreto-lei n.º 30/2011, de 2 de março." [Online]. Available: https://diariodarepublica.pt/dr/detalhe/portaria/76-b-2014-680834

[2] E. CENTRO HOSPITALAR E UNIVERSITÁRIO DE COIMBRA, "Relatório e contas," 2022. [Online]. Available: https://www.chuc.min-saude.pt/wpcontent/uploads/sites/43/2023/09/PDE_2020_22_1.pdf

[3] "Orçamento do estado para 2023 - lei n.º 24-d/2022." [Online]. Available: https://diariodarepublica.pt/dr/legislacao-consolidada/lei/2022-205695052

[4] "Asset management - overview, principles and terminology," International Organization for Standardization, Geneva, CH, Standard ISO 55000:2014, 2014. [Online]. Available: https://www.iso.org/standard/55088.html

[5] D. Maletič, M. Maletič, B. Al-Najjar, and B. Gomišček, "Development of a model linking physical asset management to sustainability performance: An empirical research," *Sustainability*, vol. 10, no. 12, p. 4759, dec 2018. [Online]. Available: http://www.mdpi.com/2071-1050/10/12/4759

[6] W. H. Organization, "Introduction to medical equipment inventory management," *Introduction à la gestion du parc des équipements médicaux*, 2011. [Online]. Available: https://iris.who.int/handle/10665/44561

[7] J. M. T. Farinha, *Asset maintenance engineering methodologies*. Boca Raton: CRC Press/Taylor and Francis Group, 2018.

[8] J. Torres Farinha, H. Nogueira Raposo, and D. Galar, "Life cycle cost versus life cycle investment – a new approach," *WSEAS TRANSACTIONS ON SYSTEMS AND CONTROL*, vol. 15, p. 743–753, dec 2020. [Online]. Available: https://wseas.com/journals/sac/2020/b505103-966.pdf

[9] D. G. Woodward, "Life cycle costing—theory, information acquisition and application," *International Journal of Project Management*, vol. 15, no. 6, p. 335–344, dec 1997. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0263786396000890

[10] K. El-Akruti, R. Dwight, T. Zhang, and M. Al-Marsumi, *The Role of Life Cycle Cost in Engineering Asset Management*. Cham: Springer International Publishing, 2015, p. 173–188. [Online]. Available: https://link.springer.com/10.1007/978-3-319-09507-3_17

[11] "Environmental management - life cycle assessment - principles and framework," International Organization for Standardization, Standard ISO 14040:2006, 2006. [Online]. Available: https://www.iso.org/standard/37456.html

[12] H. K. Jeswani, A. Azapagic, P. Schepelmann, and M. Ritthoff, "Options for broadening and deepening the lca approaches," *Journal of Cleaner Production*, vol. 18, no. 2, p. 120–127, jan 2010. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0959652609003229

[13] B. De Jonge and P. A. Scarf, "A review on maintenance optimization," *European Journal of Operational Research*, vol. 285, no. 3, p. 805–824, sep 2020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0377221719308045

[14] "Manutenção - terminologia de manutenção," Instituto Português da Qualidade, Standard NP EN 13306:2021, 2021.

[15] C. Stenström, P. Norrbin, A. Parida, and U. Kumar, "Preventive and corrective maintenance – cost comparison and cost–benefit analysis," *Structure and Infrastructure Engineering*, vol. 12, no. 5, p. 603–617, may 2016. [Online]. Available: http://www.tandfonline.com/doi/full/10.1080/15732479.2015.1032983

[16] I. Alsyouf, "The role of maintenance in improving companies' productivity and profitability," *International Journal of Production Economics*, vol. 105, no. 1, p. 70–78, jan 2007. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S092552730600065X

[17] D. S. Thomas and B. Weiss, "Maintenance costs and advanced maintenance techniques: Survey and analysis," *International Journal of Prognostics and Health Management*, vol. 12, no. 1, apr 2021. [Online]. Available: https://papers.phmsociety.org/index.php/ijphm/article/view/2883

[18] M. Gerdes, D. Scholz, and D. Galar, "Effects of condition-based maintenance on costs caused by unscheduled maintenance of aircraft," *Journal of Quality in Maintenance Engineering*, vol. 22, no. 4, p. 394–417, oct 2016. [Online]. Available: https://www.emerald.com/insight/content/doi/10.1108/jqme-12-2015-0062/full/html

[19] P. D. T. O'Connor and A. Kleyner, *Practical Reliability Engineering*, 1st ed. Wiley, dec 2011. [Online]. Available: https://onlinelibrary.wiley.com/doi/book/10.1002/9781119961260

[20] G. Klutke, P. Kiessler, and M. Wortman, "A critical look at the bathtub curve," *IEEE Transactions on Reliability*, vol. 52, no. 1, p. 125–129, mar 2003. [Online]. Available: http://ieeexplore.ieee.org/document/1179819/

[21] M. Aghaei, A. Fairbrother, A. Gok, S. Ahmad, S. Kazim, K. Lobato, G. Oreski, A. Reinders, J. Schmitz, M. Theelen, P. Yilmaz, and J. Kettle, "Review of degradation and failure phenomena in photovoltaic modules," *Renewable and*

Sustainable Energy Reviews, vol. 159, p. 112160, may 2022. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S1364032122000880

[22] D. J. Smith, *Reliability, maintainability and risk: Practical methods for engineers including reliability centred maintenance and safety-related systems*, 8th ed. Oxford, England: Butterworth-Heinemann, 2011.

[23] W. Nelson, *Applied life data analysis*, ser. Wiley series in probability and mathematical statistics. Hoboken, N.J: Wiley-Interscience, 2004.

[24] D. Kececioglu and F.-b. Sun, *Environmental stress screening: its quantification, optimization and management*. Upper Saddle River, N.J: Prentice Hall, 1995.

[25] A. Gaonkar, R. B. Patil, S. Kyeong, D. Das, and M. G. Pecht, "An assessment of validity of the bathtub model hazard rate trends in electronics," *IEEE Access*, vol. 9, p. 10282–10290, 2021. [Online]. Available: https://ieeexplore.ieee.org/document/9319134/

[26] Medtronic, "Medtronic, Annual Report Fiscal Year 2022," https://investorrelations.medtronic.com/annual-meeting-reports, October 2022.

[27] OECD and E. Union, *Health at a Glance: Europe 2022: State of Health in the EU Cycle*, ser. Health at a Glance: Europe. OECD, dec 2022. [Online]. Available: https://www.oecd-ilibrary.org/social-issues-migration-health/health-at-a-glance-europe-2022_507433b0-en

[28] "Regulation (EU) 2017/745 of the european parliament and of the council," 2017, https://eur-lex.europa.eu/legalcontent/EN/TXT/uri=CELEX:02017R0745-20230320.

[29] K. Willson, K. Ison, and S. Tabakov, *Medical equipment management*, ser. Series in medical physics and biomedical engineering. Boca Raton: Taylor and Francis, 2014.

[30] W. H. Organization, "Medical equipment maintenance programme overview," *Programme de maintenance des équipements médicaux: présentation générale*, p. 92, 2011. [Online]. Available: https://iris.who.int/handle/10665/44587

[31] R. Bahreini, L. Doshmangir, and A. Imani, "Influential factors on medical equipment maintenance management: In search of a framework," *Journal of Quality in Maintenance Engineering*, vol. 25, no. 1, p. 128–143, mar 2019. [Online]. Available: https://www.emerald.com/insight/content/doi/10.1108/JQME-11-2017-0082/full/html

[32] M. B. Moyimane, S. F. Matlala, and M. P. Kekana, "Experiences of nurses on the critical shortage of medical equipment at a rural district hospital in south africa: a qualitative study," *Pan African Medical Journal*, vol. 28, 2017. [Online]. Available: http://www.panafrican-med-journal.com/content/article/28/100/full/

[33] M. Hillebrecht, C. Schmidt, B. P. Saptoka, J. Riha, M. Nachtnebel, and T. Bärnighausen, "Maintenance versus replacement of medical equipment: a cost-minimization analysis among district hospitals in nepal," *BMC Health Services Research*, vol. 22, no. 1, p. 1023, aug 2022. [Online]. Available: https://bmchealthservres.biomedcentral.com/articles/10.1186/s12913-022-08392-6

[34] E. Iadanza, V. Gonnelli, F. Satta, and M. Gherardelli, "Evidence-based medical equipment management: a convenient implementation," *Medical & Biological Engineering & Computing*, vol. 57, no. 10, p. 2215–2230, oct 2019. [Online]. Available: http://link.springer.com/10.1007/s11517-019-02021-x

[35] S. Eze, W. Ijomah, and T. Wong, "Remanufacturing: a potential sustainable solution for increasing medical equipment availability," *Journal of Remanufacturing*, vol. 10, no. 2, p. 141–159, jul 2020. [Online]. Available: https://link.springer.com/10.1007/s13243-020-00080-0

[36] C. Mendes, H. Raposo, R. Ferraz, and J. T. Farinha, "The economic management of physical assets: The practical case of an urban passenger transport company in portugal," *Sustainability*, vol. 15, no. 15, p. 11492, jul 2023. [Online]. Available: https://www.mdpi.com/2071-1050/15/15/11492

[37] R. K. Perrin, "Asset replacement principles," *American Journal of Agricultural Economics*, vol. 54, no. 1, p. 60–67, feb 1972. [Online]. Available: https://onlinelibrary.wiley.com/doi/10.2307/1237734

[38] A. Ioannou, A. Angus, and F. Brennan, "Parametric capex, opex, and lcoe expressions for offshore wind farms based on global deployment parameters," *Energy Sources, Part B: Economics, Planning, and Policy*, vol. 13, no. 5, p. 281–290, may 2018. [Online]. Available: https://www.tandfonline.com/doi/full/10.1080/15567249.2018.1461150

[39] H. Raposo, J. T. Farinha, L. Ferreira, and D. Galar, "An integrated econometric model for bus replacement and determination of reserve fleet size based on predictive maintenance," *Eksploatacja i Niezawodnosc - Maintenance and Reliability*, vol. 19, no. 3, p. 358–368, jun 2017. [Online]. Available: https://archive.ein.org.pl/sites/default/files/2017-03-06.pdf

[40] J. T. Farinha, H. D. N. Raposo, J. E. de-Almeida-e Pais, and M. Mendes, "Physical asset life cycle evaluation models—a comparative analysis towards sustainability," *Sustainability*, vol. 15, no. 22, p. 15754, nov 2023. [Online]. Available: https://www.mdpi.com/2071-1050/15/22/15754

[41] P. Figueiredo, "Life cycle analysis – a global approach," Master's thesis, Instituto Superior de Engenharia de Coimbra, 2024.

[42] J. D. Sherman, L. A. Raibley, and M. J. Eckelman, "Life cycle assessment and

costing methods for device procurement: Comparing reusable and single-use disposable laryngoscopes," *Anesthesia & Analgesia*, vol. 127, no. 2, p. 434–443, aug 2018. [Online]. Available: https://journals.lww.com/00000539-201808000-00022

[43] N. G. Atia, M. A. Bassily, and A. A. Elamer, "Do life-cycle costing and assessment integration support decision-making towards sustainable development?" *Journal of Cleaner Production*, vol. 267, p. 122056, sep 2020. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S095965262032103X

[44] A. Bierer, U. Götze, L. Meynerts, and R. Sygulla, "Integrating life cycle costing and life cycle assessment using extended material flow cost accounting," *Journal of Cleaner Production*, vol. 108, p. 1289–1301, dec 2015. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0959652614008592

[45] E. A. Calado, M. Leite, and A. Silva, "Integrating life cycle assessment (lca) and life cycle costing (lcc) in the early phases of aircraft structural design: an elevator case study," *The International Journal of Life Cycle Assessment*, vol. 24, no. 12, p. 2091–2110, dec 2019. [Online]. Available: http://link.springer.com/10.1007/s11367-019-01632-8

[46] R. G. G. Caiado, R. De Freitas Dias, L. V. Mattos, O. L. G. Quelhas, and W. Leal Filho, "Towards sustainable development through the perspective of eco-efficiency - a systematic literature review," *Journal of Cleaner Production*, vol. 165, p. 890–904, nov 2017. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0959652617316128

[47] D. Maxime, M. Marcotte, and Y. Arcand, "Development of eco-efficiency indicators for the canadian food and beverage industry," *Journal of Cleaner Production*, vol. 14, no. 6–7, p. 636–648, jan 2006. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0959652605001812

[48] K. Müller, A. Holmes, M. Deurer, and B. E. Clothier, "Eco-efficiency as a sustainability measure for kiwifruit production in new zealand," *Journal of Cleaner Production*, vol. 106, p. 333–342, nov 2015. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0959652614007665

[49] R. Heijungs, "Ratio, sum, or weighted sum? the curious case of basf's eco-efficiency analysis," *ACS Sustainable Chemistry & Engineering*, vol. 10, no. 27, p. 8754–8762, jul 2022. [Online]. Available: https://pubs.acs.org/doi/10.1021/acssuschemeng.2c01073

[50] M. Wu, J. Sadhukhan, R. Murphy, U. Bharadwaj, and X. Cui, "A novel life cycle assessment and life cycle costing framework for carbon fibre-reinforced composite materials in the aviation industry," *The International Journal of Life Cycle Assessment*, vol. 28, no. 5, p. 566–589, may 2023. [Online]. Available: https://link.springer.com/10.1007/s11367-023-02164-y

[51] "Asset management - management systems — guidelines for the application of iso 55001," International Organization for Standardization, Geneva, CH, Standard ISO 55002:2018, 2018. [Online]. Available: https://www.iso.org/standard/70402.html

[52] N. A. J. Hastings, *Physical Asset Management: With an Introduction to the ISO 55000 Series of Standards*. Cham: Springer International Publishing, 2021. [Online]. Available: http://link.springer.com/10.1007/978-3-030-62836-9

[53] "Código dos contratos públicos - ccp - decreto-lei n.º 18/2008." [Online]. Available: https://diariodarepublica.pt/dr/legislacao-consolidada/decreto-lei/2008-34455475

[54] M. Carlone, W. Beckham, C. Duzenli, K. Kohli, and S. Tyldesley, "Linear accelerator maintenance cost analysis," *Journal of Applied Clinical Medical Physics*, vol. 25, no. 2, p. e14246, feb 2024. [Online]. Available: https://aapm.onlinelibrary.wiley.com/doi/10.1002/acm2.14246

[55] K. H. Kim, M.-J. Sohn, S. Lee, H.-W. Koo, S.-W. Yoon, and A. K. Madadi, "Descriptive time series analysis for downtime prediction using the maintenance data of a medical linear accelerator," *Applied Sciences*, vol. 12, no. 11, p. 5431, May 2022. [Online]. Available: https://www.mdpi.com/2076-3417/12/11/5431

[56] R. Albuquerque, "Reorganization of physical assets and maintenance in a portuguese hospital," Master's thesis, Instituto Superior de Engenharia de Coimbra, 2024.

[57] "Maintenance. maintenance key performance indicators," British Standards Institution, London, Standard EN 15341:2019, 2019.

[58] W. Al-Talabi, "Optimization of medical equipment replacement strategies," Ph.D. dissertation, Cairo University, 2020.

[59] O. Jørgen Hanssen, "Environmental impacts of product systems in a life cycle perspective," *Journal of Cleaner Production*, vol. 6, no. 3–4, p. 299–311, sep 1998. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0959652698000316

[60] K. Peattie, "Green consumption: Behavior and norms," *Annual Review of Environment and Resources*, vol. 35, no. 1, p. 195–228, nov 2010. [Online]. Available: https://www.annualreviews.org/doi/10.1146/annurev-environ-032609-094328

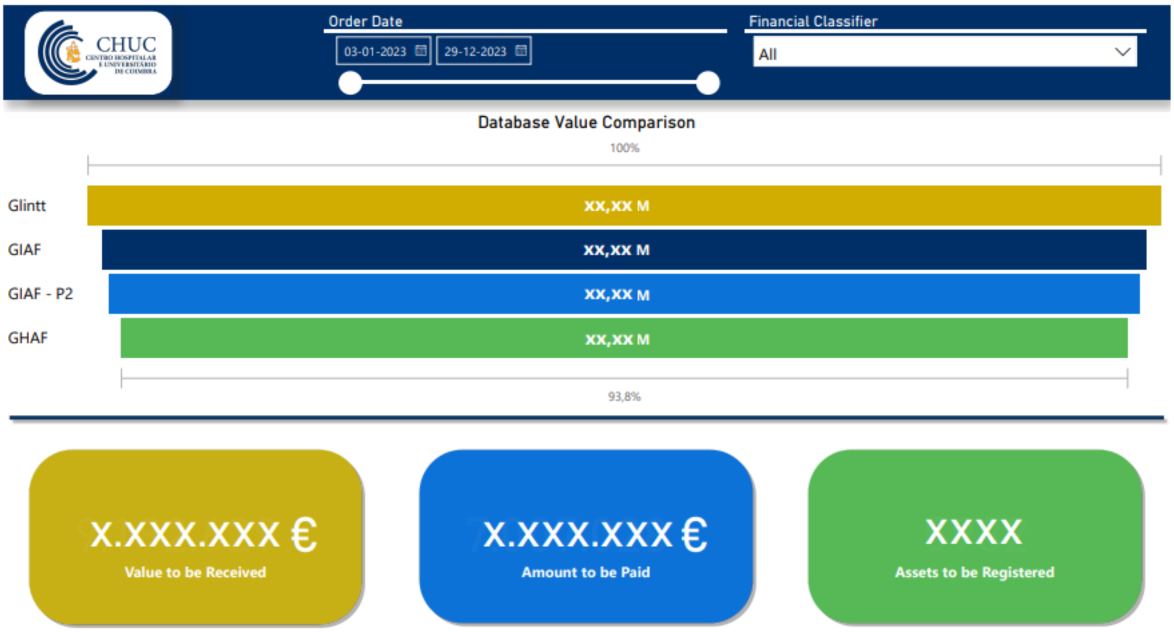
[61] E. Polizzi Di Sorrentino, E. Woelbert, and S. Sala, "Consumers and their behavior: state of the art in behavioral science supporting use phase modeling in lca and ecodesign," *The International Journal of Life Cycle Assessment*, vol. 21, no. 2, p. 237–251, feb 2016. [Online]. Available: http://link.springer.com/10.1007/s11367-015-1016-2

[62] R. F. Shenker, T. L. Johnson, M. Ribeiro, A. Rodrigues, and J. Chino, "Estimating carbon dioxide emissions and direct power consumption of linear accelerator–based external beam radiation therapy," *Advances in Radiation Oncology*, vol. 8, no. 3, p. 101170, may 2023. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S2452109422002755

[63] A. P. do Ambiente, "Fator de emissão da eletricidade 2023 portugal." [Online]. Available: https://apambiente.pt/clima/fator-de-emissao-de-gases-de-efeito-de-estufa-para-eletricidade-produzida-em-portugal

APPENDIXES

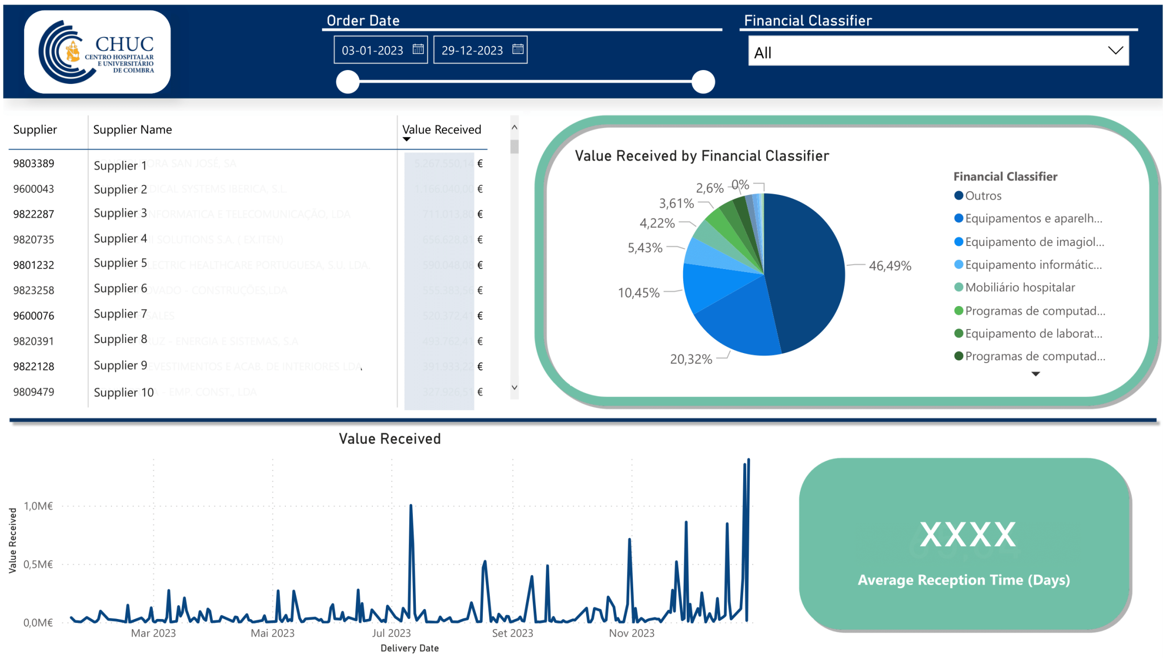
Appendix A - Dashboard Sheets



Order Date: 03-01-2023 – 29-12-2023

Financial Classifier: All

Figure A1: Dashboard sheet 1

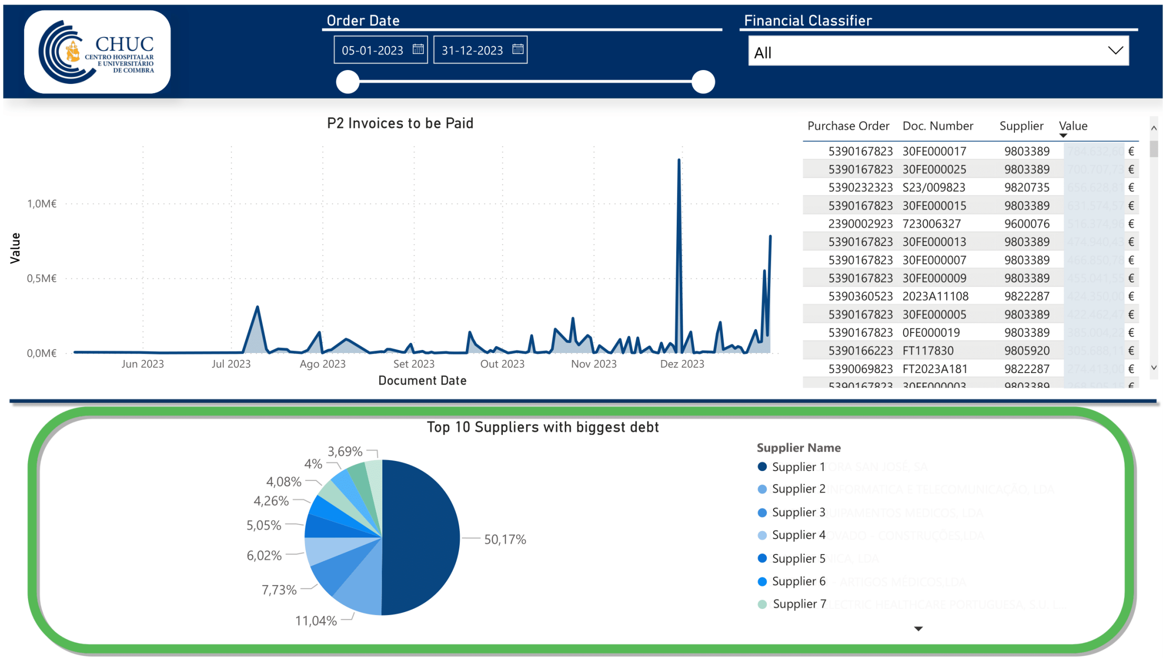


Order Date: 03-01-2023 – 29-12-2023

Financial Classifier: All

Supplier	Supplier Name	Value Received
9803389	Supplier 1	[redacted] €
9600043	Supplier 2	[redacted] €
9822287	Supplier 3	[redacted] €
9820735	Supplier 4	[redacted] €
9801232	Supplier 5	[redacted] €
9823258	Supplier 6	[redacted] €
9600076	Supplier 7	[redacted] €
9820391	Supplier 8	[redacted] €
9822128	Supplier 9	[redacted] €
9809479	Supplier 10	[redacted] €

Figure A2: Dashboard sheet 2



Purchase Order	Doc. Number	Supplier	Value
5390167823	30FE000017	9803389	[redacted] €
5390167823	30FE000025	9803389	[redacted] €
5390232323	S23/009823	9820735	[redacted] €
5390167823	30FE000015	9803389	[redacted] €
2390002923	723006327	9600076	[redacted] €
5390167823	30FE000013	9803389	[redacted] €
5390167823	30FE000007	9803389	[redacted] €
5390167823	30FE000009	9803389	[redacted] €
5390360523	2023A11108	9822287	[redacted] €
5390167823	30FE000005	9803389	[redacted] €
5390167823	0FE000019	9803389	[redacted] €
5390166223	FT117830	9805920	[redacted] €
5390069823	FT2023A181	9822287	[redacted] €
5390167823	30FE000003	9803389	[redacted] €

Figure A3: Dashboard sheet 3

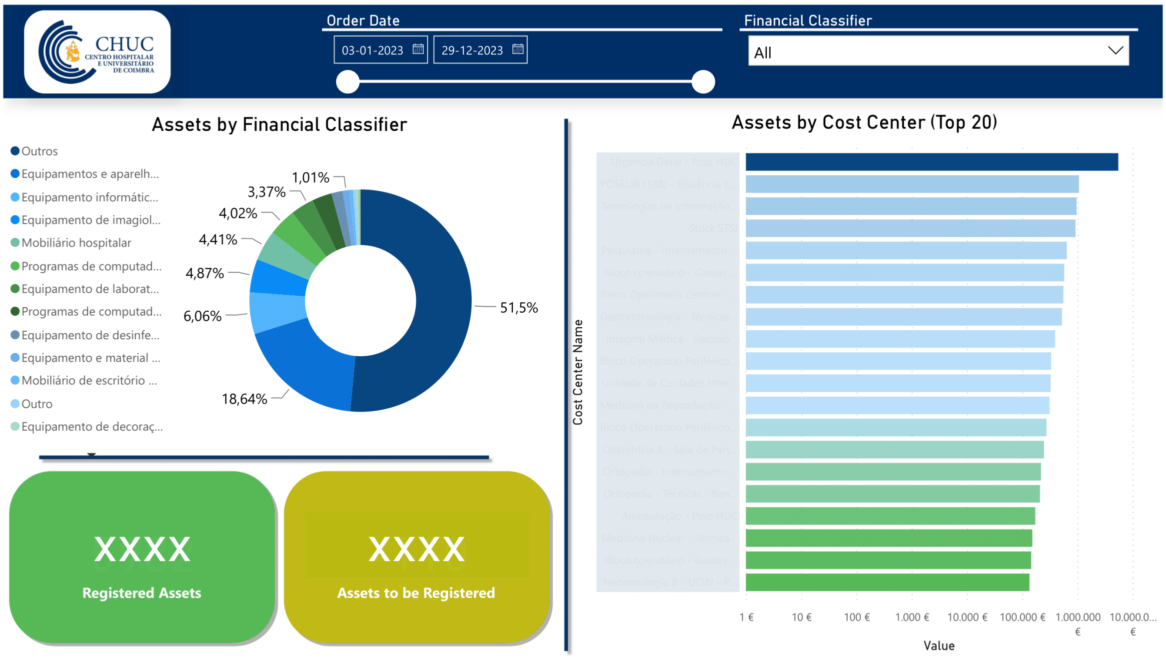
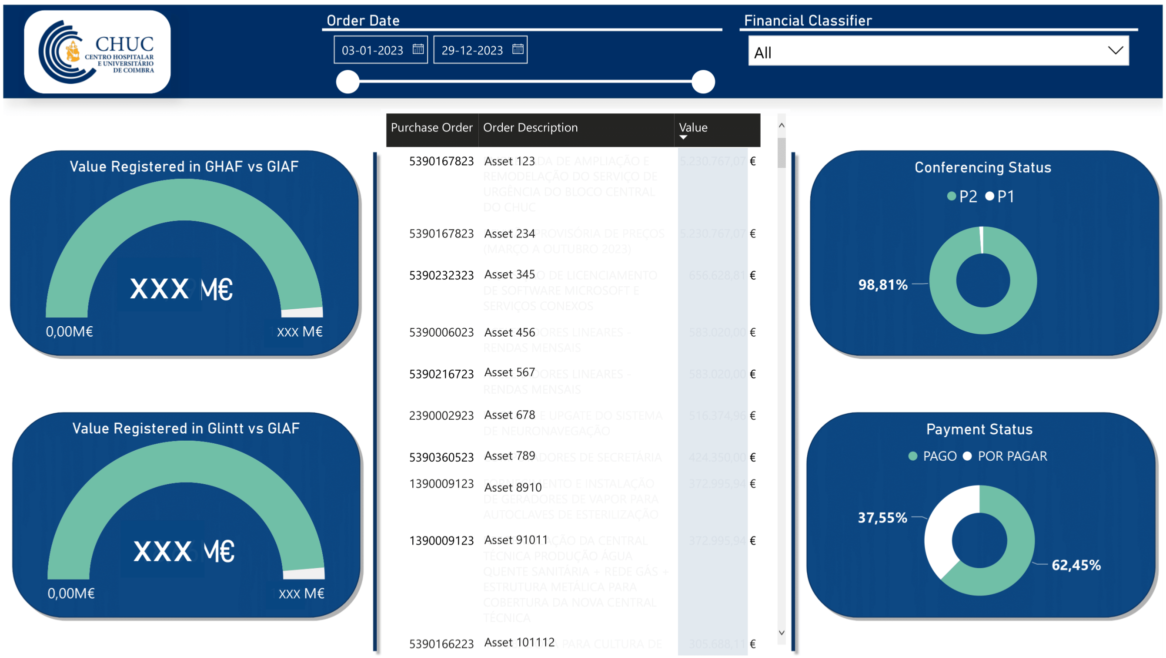
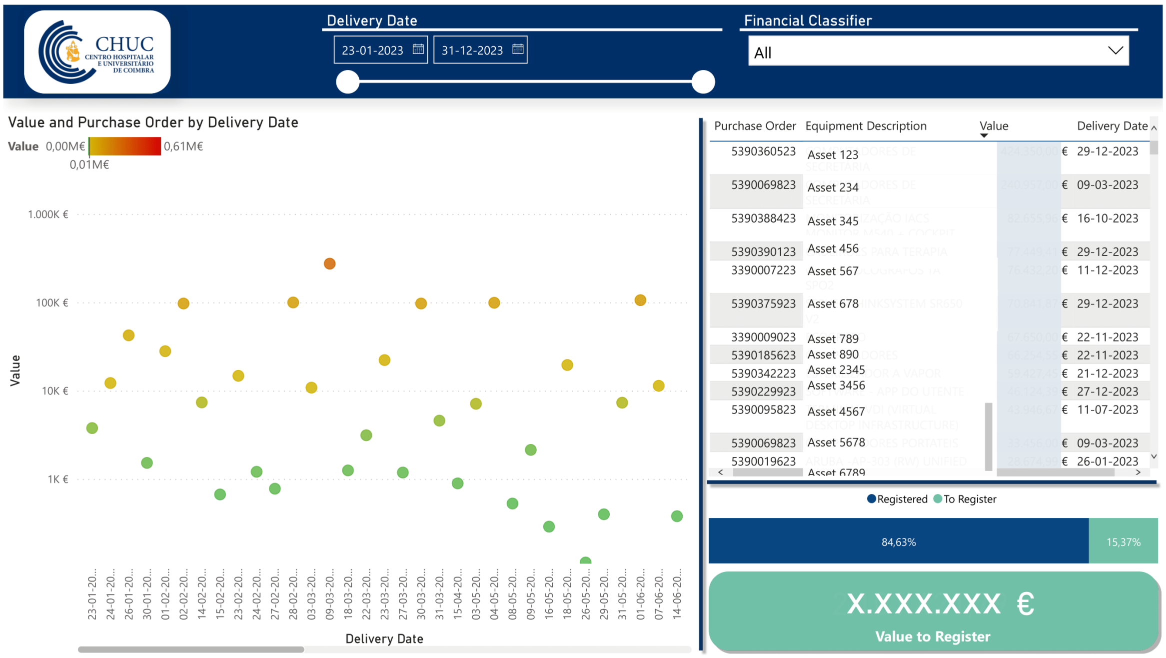


Figure A4: Dashboard sheet 4



Purchase Order	Order Description	Value
5390167823	Asset 123 [redacted]	[redacted] €
5390167823	Asset 234 [redacted]	[redacted] €
5390232323	Asset 345 [redacted]	[redacted] €
5390006023	Asset 456 [redacted]	[redacted] €
5390216723	Asset 567 [redacted]	[redacted] €
2390002923	Asset 678 [redacted]	[redacted] €
5390360523	Asset 789 [redacted]	[redacted] €
1390009123	Asset 8910 [redacted]	[redacted] €
1390009123	Asset 91011 [redacted]	[redacted] €
5390166223	Asset 101112 [redacted]	[redacted] €

Figure A5: Dashboard sheet 5



Purchase Order	Equipment Description	Value	Delivery Date
5390360523	Asset 123 [redacted]	[redacted] €	29-12-2023
5390069823	Asset 234 [redacted]	[redacted] €	09-03-2023
5390388423	Asset 345 [redacted]	[redacted] €	16-10-2023
5390390123	Asset 456 [redacted]	[redacted] €	29-12-2023
3390007223	Asset 567 [redacted]	[redacted] €	11-12-2023
5390375923	Asset 678 [redacted]	[redacted] €	29-12-2023
3390009023	Asset 789 [redacted]	[redacted] €	22-11-2023
5390185623	Asset 890 [redacted]	[redacted] €	22-11-2023
5390342223	Asset 2345 [redacted]	[redacted] €	21-12-2023
5390229923	Asset 3456 [redacted]	[redacted] €	27-12-2023
5390095823	Asset 4567 [redacted]	[redacted] €	11-07-2023
5390069823	Asset 5678 [redacted]	[redacted] €	09-03-2023
5390019623	Asset 6789 [redacted]	[redacted] €	26-01-2023

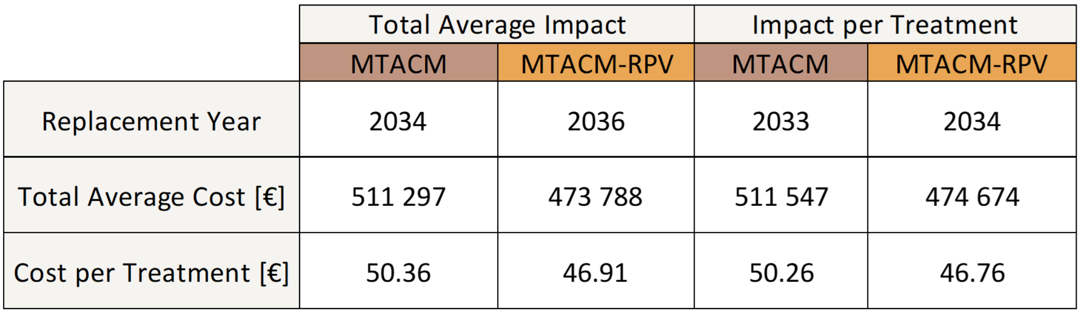
Figure A6: Dashboard sheet 6

Appendix B - Interpretation Support Table

Nº Simulation	Defender Useful Life	Replacement Year	10th Year after Replacement
1	1	2017	2026
2	2	2018	2027
3	3	2019	2028
4	4	2020	2029
5	5	2021	2030
6	6	2022	2031
7	7	2023	2032
8	8	2024	2033
9	9	2025	2034
10	10	2026	2035
11	11	2027	2036
12	12	2028	2037
13	13	2029	2038
14	14	2030	2039
15	15	2031	2040
16	16	2032	2041
17	17	2033	2042
18	18	2034	2043
19	19	2035	2044
20	20	2036	2045
21	21	2037	2046
22	22	2038	2047
23	23	2039	2048

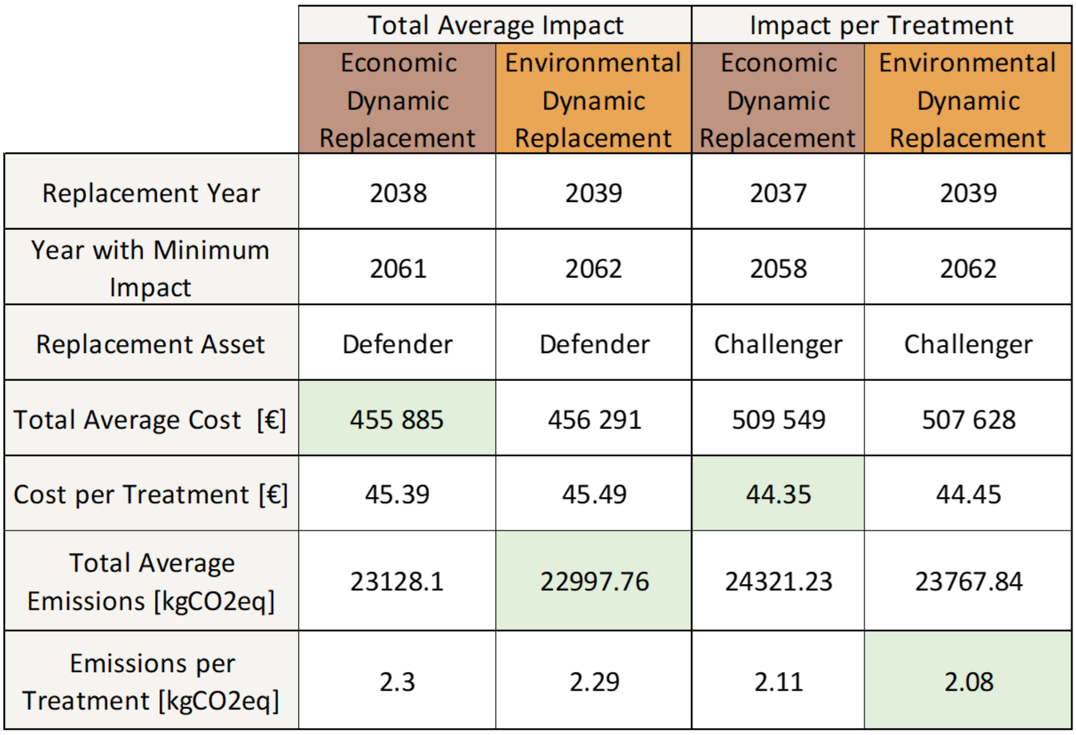
Figure B1: Results interpretation support table

Appendix C - Replacement Models Results



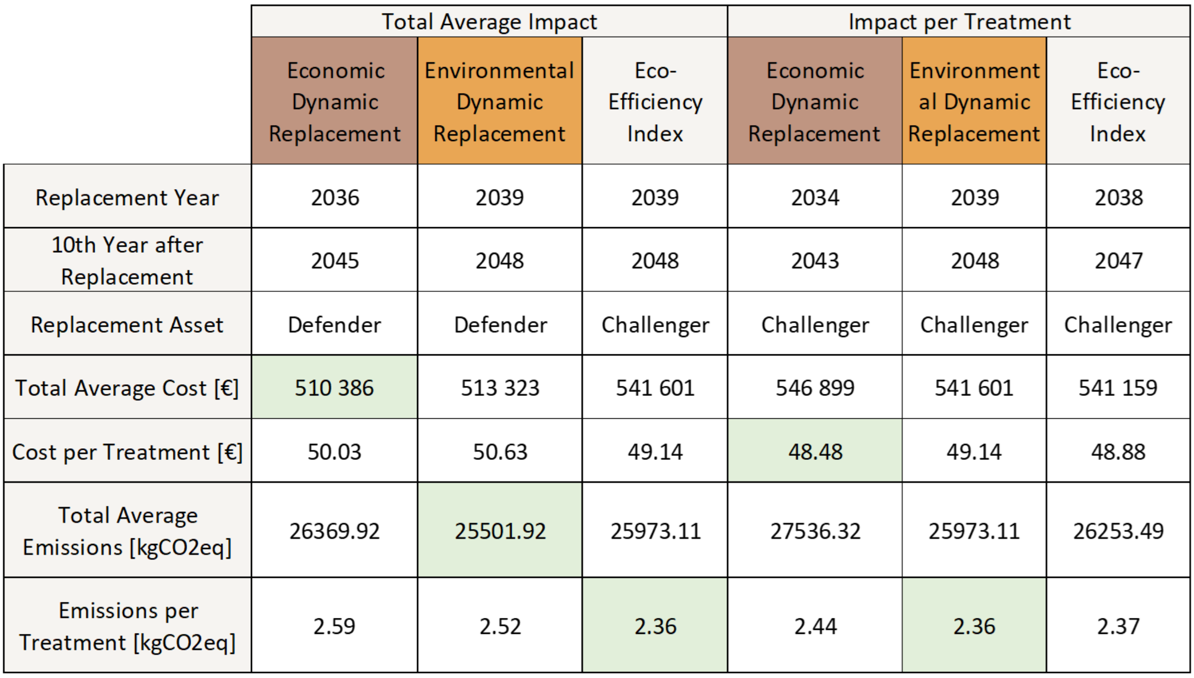
	Total Average Impact		Impact per Treatment	
	MTACM	MTACM-RPV	MTACM	MTACM-RPV
Replacement Year	2034	2036	2033	2034
Total Average Cost [€]	511 297	473 788	511 547	474 674
Cost per Treatment [€]	50.36	46.91	50.26	46.76

Figure C1: Minimum results obtained with the application of the data Varian Trubeam in study to the replacement models MTACM and MTACM-RPV



	Total Average Impact		Impact per Treatment	
	Economic Dynamic Replacement	Environmental Dynamic Replacement	Economic Dynamic Replacement	Environmental Dynamic Replacement
Replacement Year	2038	2039	2037	2039
Year with Minimum Impact	2061	2062	2058	2062
Replacement Asset	Defender	Defender	Challenger	Challenger
Total Average Cost [€]	455 885	456 291	509 549	507 628
Cost per Treatment [€]	45.39	45.49	44.35	44.45
Total Average Emissions [kgCO2eq]	23128.1	22997.76	24321.23	23767.84
Emissions per Treatment [kgCO2eq]	2.3	2.29	2.11	2.08

Figure C2: Mininum results obtained through the developed dynamic replacement model



	Total Average Impact			Impact per Treatment		
	Economic Dynamic Replacement	Environmental Dynamic Replacement	Eco-Efficiency Index	Economic Dynamic Replacement	Environmental Dynamic Replacement	Eco-Efficiency Index
Replacement Year	2036	2039	2039	2034	2039	2038
10th Year after Replacement	2045	2048	2048	2043	2048	2047
Replacement Asset	Defender	Defender	Challenger	Challenger	Challenger	Challenger
Total Average Cost [€]	510 386	513 323	541 601	546 899	541 601	541 159
Cost per Treatment [€]	50.03	50.63	49.14	48.48	49.14	48.88
Total Average Emissions [kgCO2eq]	26369.92	25501.92	25973.11	27536.32	25973.11	26253.49
Emissions per Treatment [kgCO2eq]	2.59	2.52	2.36	2.44	2.36	2.37

Figure C3: Results for the 10th year after replacement obtained through the developed dynamic replacement model

Appendix D - Meta-Analysis

To conduct a comprehensive meta-analysis, data from each article and author was collected for evaluation.
This process assesses several key metrics, including the H-Index, which reflects the author or journal impact by representing the number of articles (h) that have received at least (h) citations.
Additionally, it considers journal quartiles, a measure derived from the SCImago Journal Rank (SJR) that categorizes journals based on their impact, influence, and prestige. Quartile rankings are divided as follows: Q1 includes the top 25% of journals, Q2 covers journals ranked in the 25-50% range, Q3 includes those in the 50-75% range, and Q4 comprises the bottom 25%.
Finally, the analysis identifies the number of articles published by each author.

All journal-related information was sourced from the SCImagoJR[1] database, while author-specific data were obtained from the Scopus[2] platform. This structured approach ensures a robust and reliable evaluation of the research landscape.

In this context, two tables are presented. The first provides the averages of the collected data, while the second offers a detailed breakdown, ranging from journal-level information to individual author metrics.

The data presented was carefully collected and cross-checked, but it may still contain some inaccuracies due to the possibility of human error.
When it wasn't possible to confirm the authors' identity, those fields were left blank.
Only information about articles and books was included in the analysis, while other types of references were left out to keep the focus clear and relevant.

Table D1: References metadata averages

Average Journal H-Index	165.24
Dominant Journal Quartile	Q1
Average Authors' H-Index	18.77
Average Number of Documents by Author	83.91

---

[1] https://www.scimagojr.com/, accessed 22 Nov 2024
[2] https://www.scopus.com/, accessed 22 Nov 2024

Table D2: Detailed metadata table

Ref.	Reference Type	Journal (Scimago)	Journal H-Index	Quartiles	Authors	Authors Index (Scopus)	Authors Documents
[1]	Legislation	-	-	-	-	-	-
[2]	Document	-	-	-	-	-	-
[3]	Legislation	-	-	-	-	-	-
[4]	Standard	-	-	-	-	-	-
[5]	Article	Sustainability	169	Q2	Damjan Maletič	16	44
					Matjaž Maletič	17	46
					Basim Al-Najjar	17	48
					Boštjan Gomišček	20	47
[6]	Document	-	-	-	-	-	-
[7]	Book	-	-	-	José Torres Farinha	15	69
[8]	Article	WSEAS TRANSACTIONS ON SYSTEMS AND CONTROL	20	Q4	José Torres Farinha	15	69
					Hugo Raposo	7	20
					Diego Galar	24	156
[9]	Article	International Journal of Project	179	Q1	David Woodward	2	3
[10]	Conference Paper	-	-	-	Khaled El-Akruti	7	11
					Richard Dwight	13	43
					Tieling Zhang	19	54
					Mujbil Al-Marsumi	2	4
[11]	Standard	-	-	-	-	-	-
[12]	Article	Journal of Cleaner Production	309	Q1	Harish Kumar Jeswani	23	46
					Adisa Azapagic	72	287
					Philipp Schepelmann	4	9
					Michael Ritthoff	4	5
[13]	Article	European Journal of	305	Q1	Bram de Jonge	12	19
					Philip A. Scarf	33	128
[14]	Standard	-	-	-	-	-	-

Ref.	Reference Type	Journal (Scimago)	Journal H-Index	Quartiles	Authors	Authors Index (Scopus)	Authors Documents
[15]	Article	Structure and Infrastructure Engineering	71	Q1	Christer Stenström	10	29
					Per Norbin	4	5
					Aditya Parida	18	59
					Uday Kumar	39	229
[16]	Article	International Journal of Production Economics	231	Q1	Imad Alsyouf	18	103
[17]	Article	International Journal of Prognostics	29	Q2	Douglas Thomas	8	26
					Brian Weiss	14	52
[18]	Article	Journal of Quality in Maintenance	62	Q2	Mike Gerdes	4	6
					Dieter Scholz	6	33
					Diego Galar	24	156
[19]	Book	-	-	-	Patrick D. T. O'Connor	-	-
					Andre Kleyner	-	-
[20]	Article	IEEE Transactions on Reliability	118	Q1	G.A. Klutke	-	-
					P.C. Kiessler	5	21
					M.A. Wortman	8	30
[21]	Article	Renewable and Sustainable Energy Reviews	412	Q1	M. Aghaei	24	80
					A. Fairbrother	14	35
					A. Gok	8	18
					S. Ahmad	57	188
					S. Kazim	33	118
					K. Lobato	12	25
					G. Oreski	24	105
					A. Reinders	25	120
					J. Schmitz	29	251
					M. Theelen	18	70
					P. Yilmaz	4	9
					J. Kettle	28	109
[22]	Book	-	-	-	David Smith	-	-
[23]	Book	-	-	-	Wayne B. Nelson	24	61
[24]	Book	-	-	-	Dimitri B. Kececioglu	12	73
					Feng-Bin Sun	8	48

Ref.	Reference Type	Journal (Scimago)	Journal H-Index	Quartiles	Authors	Authors Index (Scopus)	Authors Documents
[25]	Article	IEEE Access	242	Q1	Aishwarya Gaonkar	2	2
					Rajkumar B. Patil	10	40
					San Kyeong	3	11
					Diganta Das	22	124
					Michael G. Pecht	90	1287
[26]	Document	-	-	-	-	-	-
[27]	Document	-	-	-	-	-	-
[28]	Regulation	-	-	-	-	-	-
[29]	Book	-	-	-	Keith Willson	23	45
					Keith Ison	6	20
					Slavik Tabakov	6	41
[30]	Document	-	-	-	-	-	-
[31]	Article	Journal of Quality in Maintenance Engineering	62	Q2	Rona Bahreini	4	10
					Leila Doshmangir	33	127
					Ali Imani	11	30
[32]	Article	Pan African Medical Journal	49	Q3	Merriam Bautlile Moyimane	-	-
					Sogo France Matlala	4	18
					Mokoko Percy Kekana	2	7
[33]	Article	BMC Health Services Research	146	Q1	Michael Hillebrecht	5	9
					Constantin Schmidt	-	-
					Bhim Prasad Saptoka	-	-
					Josef Riha	-	-
					Matthias Nachtnebel	6	9
					Till Bärnighausen	108	851
[34]	Article	Medical & Biological Engineering & Computing	111	Q2	Ernesto Iadanza	20	166
					Valentina Gonnelli	2	2
					Francesca Satta	3	7
					Monica Gherardelli	11	45

Ref.	Reference Type	Journal (Scimago)	Journal H-Index	Quartiles	Authors	Authors Index (Scopus)	Authors Documents
[35]	Article	Journal of Remanufacturing	23	Q2	Solomon Eze	3	5
					Winifred Ijomah	27	77
					T.C. Wong	21	50
[36]	Article	Sustainability	169	Q2	Caropul Mendes	-	-
					Hugo Raposo	7	20
					Ricardo Ferraz	4	10
					José Torres Farinha	15	69
[37]	Article	American Journal of Agricultural	133	Q1	R. K. Perrin	-	-
[38]	Article	Energy Sources, Part B: Economics, Planning, and Policy	52	Q2	Anastasia Ioannou	-	-
					Andrew Angus	19	34
					Feargal Brennan	30	181
[39]	Article	Eksploatacja i Niezawodnosc - Maintenance and Reliability	34	Q2	Hugo Raposo	7	20
					José Torres Farinha	15	69
					Luís Ferreira	27	165
					Diego Galar	24	156
[40]	Article	Sustainability	169	Q2	José Torres Farinha	15	69
					Hugo Raposo	7	20
					José Edmundo de-Almeida-e-Pais	5	10
					Mateus Mendes	13	60
[41]	Thesis	-	-	-	P. Figueiredo	-	-
[42]	Article	Anesthesia & Analgesia	227	Q1	Sherman, Jodi D.	33	113
					Raibley, Lewis A.	-	-
					Eckelman, Matthew J.	51	148
[43]	Article	Journal of Cleaner Production	309	Q1	Noha Gawdat Atia	-	-
					Makram A. Bassily	-	-
					Ahmed A. Elamer	31	88

Ref.	Reference Type	Journal (Scimago)	Journal H-Index	Quartiles	Authors	Authors Index (Scopus)	Authors Documents
[44]	Article	Journal of Cleaner Production	309	Q1	Annett Bierer	6	11
					Uwe Götze	13	80
					Lilly Meynerts	4	5
					Ronny Sygulla	3	5
[45]	Article	International Journal of Life Cycle Assessment	131	Q1	Elcin Aleixo Calado	2	2
					Marco Leite	22	70
					Arlindo Silva	-	-
[46]	Article	Journal of Cleaner Production	309	Q1	Rodrigo Goyannes Gusmão Caiado	25	76
					Raquel de Freitas Dias	-	-
					Lisiane Veiga Mattos	41	88
					Osvaldo Luiz Gonçalves Quelhas	28	166
					Waler Leal Filho	51	453
[47]	Article	Journal of Cleaner Production	309	Q1	Dominique Maxime	8	13
					Michèle Marcotte	31	76
					Yves Arcand	19	39
[48]	Article	Journal of Cleaner Production	309	Q1	Karin Müller	34	102
					Allister Holmes	6	15
					Markus Deurer	25	63
					Brent E. Clothier	56	280
[49]	Article	ACS Sustainable Chemistry &	173	Q1	Reinout Heijungs	60	221
[50]	Article	International Journal of Life Cycle Assessment	131	Q1	Minghui Wu	-	-
					Jhuma Sadhukhan	35	144
					Richard Murphy	41	154
					Ujjwal Bharadwaj	7	22
					Xiaofei Cui	2	9

Ref.	Reference Type	Journal (Scimago)	Journal H-Index	Quartiles	Authors	Authors Index (Scopus)	Authors Documents
[51]	Standard	-	-	-	-	-	-
[52]	Book	-	-	-	Nicholas Anthony John Hastings	2	2
[53]	Legislation	-	-	-	-	-	-
[54]	Article	Journal of Applied Clinical Medical Physics	59	Q2	Marco Carlone	12	60
					Wayne Beckham	27	87
					Cheryl Duzenli	20	80
					Kirpal Kohli	9	24
					Scott Tyldesley	45	180
[55]	Article	Applied Sciences	130	Q2	Kwang Hyeon Kim	6	26
					Moon-Jun Sohn	19	70
					Suk Lee	-	-
					Hae-Won Koo	9	38
					Sang-Won Yoon	8	14
					Ahmad Khalid Madadi	2	5
[56]	Thesis	-	-	-	R. Albuquerque	-	-
[57]	Standard	-	-	-	-	-	-
[58]	Thesis	-	-	-	W. Al-Talabi	-	-
[59]	Article	Journal of Cleaner Production	309	Q1	Ole Jørgen Hanssen	22	39
[60]	Article	Annual Review of Environment and Resources	147	Q1	Ken Peattie	24	79
[61]	Article	International Journal of Life Cycle Assessment	131	Q1	Eugenia Polizzi di Sorrentino	12	21
					Eva Woelbert	8	9
					Serenella Sala	55	161
[62]	Article	Advances in Radiation Oncology	36	Q2	Rachel F.	7	24
					Timothy L. Johnson	10	11
					Marcio Ribeiro	23	168
					Anna Rodrigues	9	27
					Junzo Chino	29	140
[63]	Document	-	-	-	-	-	-

Instituto Superior
de Engenharia
Politécnico de Coimbra