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Reorganization of Physical Assets and Maintenance in a Portuguese Hospital

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

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Abstract

The efficient management of hospital equipment is essential for the smooth running and improvement of the quality of healthcare services. This internship report describes the curricular internship of the academic year 2023/2024, hosted by the Portuguese Oncology Institute of Coimbra Francisco Gentil, is to study how the maintenance department and finance services work and how they can improve the management of hospital equipment. This analysis will be undertaken with the implementation of equipment control, metrological control and life cycle analysis of a unique oncology treatment equipment in Portugal, a tomotherapy equipment.

The methodology involves a detailed description of how the maintenance department and financial services work, with a focus on equipment. In addition, two studies were carried out, the first being a metrological study examining the implementation of the new legal metrology ordinances. The second is a study of the life cycle of the tomotherapy, an advanced radiotherapy treatment modality.

The quantitative data collected analyzes the efficiency, associated costs and metrological impact of each study. This study conclusions reached not only increase the operational efficiency of hospitals, but also provide a solid basis for future research and practice in hospital equipment management.

This study offers an in-depth understanding of asset management practices in the hospital sector, emphasizing the need for an innovative approach to optimize operational efficiency and to promote a smooth transition from the academic to the professional environment.

Keywords: maintenance department, life cycle analysis, metrology, efficiency

Resumo

A gestão eficiente de equipamentos hospitalares é fundamental para o bom funcionamento e melhoria da qualidade de serviços na saúde. Este relatório descreve o estágio curricular que decorreu no ano letivo de 2023/2024, tendo como entidade de acolhimento o Instituto Português de Oncologia de Coimbra Francisco Gentil. Os principais objetivos de estagio passaram pelo estudo do modo de funcionamento do departamento de manutenção e serviço financeiro e como estes podem aprimorar a gestão de equipamentos hospitalares, com foco em implementações de controlo de equipamento, controlo metrológico e na análise do ciclo de vida de um equipamento de tratamento oncológico único em Portugal, um equipamento de tomoterapia.

O relátorio descreve o modo de funcionamento do departamento de manutenção e dos serviços financeiros, tendo o foco nos equipamentos. Adicionalmente, apresenta e analisa dois estudos realizados no decorrer do estágio, sendo o primeiro um estudo metrológico que examina a implementação das novas portarias de metrologia legal. O segundo retrata um estudo do ciclo de vida do equipamento de tomoterapia, uma modalidade avançada de tratamento de radioterapia.

Os dados recolhidos de natureza quantitativa, analisam a eficiência, custos associados e impacto metrológico, relativos a cada estudo. As conclusões atingidas não só aumentam a eficiência operacional dos hospitais, mas também proporcionam uma base sólida para futuras pesquisas e práticas na gestão de equipamentos hospitalares.

Este estudo oferece uma compreensão aprofundada das práticas de gestão de ativos no setor hospitalar, enfatizando a necessidade de abordagens inovadoras e sustentáveis para otimizar a eficiência operacional e para promover uma transição suave do ambiente académico para o profissional.

Palavras-chave: departamento de manutenção, analise de ciclo de vida, metrologia, eficiência

Never give up on something that you can't go a day without thinking.
Winston Churchill

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The conclusion of this final master's report is not only representative of my efforts, but also the encouragement and support of several people who have contributed in different ways to the completion of this stage.

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ACSS	Administração Central do Sistema de Saúde (Central Administration of the HealthSystem)
ACT	Average Completion Time
AFT	Average Finalization Time
ARIMA	Auto Regressive Integrated Moving Average
CT	Computed Tomography
EAM	Enterprise Asset Management
GHAF	Gestão Hospitalar de Armazém e Farmácia (Hospital Warehouse and Pharmacy Management)
IPOCFG	Instituto Português de Oncologia de Coimbra Francisco Gentil (Portuguese Institute of Oncology of Coimbra Francisco Gentil)
IPO	Instituto Português de Oncologia (Portuguese Institute of Oncology)
IPQ	Instituto Português da Qualidade (Portuguese Institute of Quality)
IPAC	Instituto Português de Acreditação (Portuguese Accreditation Institute)
ISEC	Instituto Superior de Engenharia de Coimbra (Coimbra Institute of Engineering)
KPI	Key Performance Indicators
LCC	Life Cycle Cost
MD	Medical Device
MLC	Multileaf Collimator
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
MVCT	Megavoltage Computed Tomography
MWT	Mean Waiting Time
OIML	International Organization of Legal Metrology
SAMP	Strategic Asset Management Plan
SGF	Serviço de Gestão Financeira (Financial Management Service)
SHI	Software Hospitalar Integrado (Integrated Hospital Software)
SIE	Serviço de Instalações e Equipamentos (Facilities and Equipment Service)
SNS	Serviço Nacional de Saúde (National Health Service)
SPQ	Sistema Português da Qualidade (Portuguese Quality System)
ST+I	Serviços Técnicos de Informatica (Technical IT Services)

UAIM	Uniform Annual Income Method
VIM	International Vocabulary of Metrology
VIML	International Vocabulary of Legal Metrology
WHO	World Health Organization

1 Introduction

The purpose of this report is to describe the internship undertaken by Rodrigo Manuel Farate de Albuquerque, as part of the Internship course unit of the Master's Degree in Engineering and Management of Physical Assets, at the Instituto Superior de Engenharia de Coimbra (ISEC).

1.1 Internship Framework

The internship was carried out at the Instituto Português de Oncologia de Coimbra Francisco Gentil (IPOCFG), in the Facilities and Equipment Service (SIE), under the academic supervision of Professor José Manuel Torres Farinha and Professor Fernanda Madureira Coutinho; and with professional guidance from Engineer Vitor Neto Vaz and Engineer Jorge Emanuel Da Silva Otero.

This internship lasted 8 months and 19 days, starting on October 9^{th} 2023 and ending on June 28^{th} 2024.

1.2 Host organization - IPOCFG

The IPOCFG is an oncology institution, with over 60 years of experience, of the nature of a Public Business Entity [8]. It has multidisciplinary capacities for providing oncology services, covering a wide range of fields such as diagnosis, treatment, recovery and continuity of care so that each patient is given the most appropriate care for their needs [8].

There are two more establishments named Instituto Português de Oncologia (IPO) in the country, in Lisbon and Porto, respectively. By liaising between these institutions, through a coordinating committee and other organizations, it is possible to continue their mission [8].

It is accredited by several entities, being recognized as a Clinical Cancer Centre by the Organisation of European Cancer Institutes, and has full accreditation from Casper Healthcare Knowledge Systems [9].

In the last two years, its structure and operation have changed with the start of the refurbishment of the surgery/imaging building. It was necessary to relocate the services from the affected building in order to guarantee continuity of response to the needs of

users. This change has resulted in an increase in activity, as well as a reduction in the waiting list by 5 % compared to previous years [9].

It's an institution that over the years has won several European projects, including [9]:

- Rehabilitation of the surgery/imaging building and the replacement of two linear accelerators - possibilitated the creation of a hospital environment with better technical conditions, increased comfort and improved safety for both patients and professionals. With the acquisition of linear accelerators, it became possible to increase safety and efficiency of radiotherapy treatments;
- Humanizing digitalization - enabled the IPO to align with international best practices in the healthcare area, in compliance with the Electronic Medical Record Adoption Model. With this project, it became possible to increase the efficiency of both clinical and administrative procedures, improving the quality and quantity of service levels and reducing costs and response times;
- Proximity solutions at the Coimbra IPO: Dematerialization, Safety and Innovation - allows the IPO to strengthen its technological innovation through a multidisciplinary working method, involving pharmacy, cardiology and project management services;
- Energy efficiency - made it possible to improve the energy performance of buildings through reduced consumption and new energy-efficient technologies;
- Integrated radiotherapy treatment solution - acquisition of a Tomotherapy treatment unit, which allows the use of advanced radiotherapy techniques in the area of molecular intensity and image-guided radiotherapy, being the first of its kind in Portugal, thus increasing the recognition and standard of the IPO.

1.3 Motivation

The choice of area and topic was influenced by my participation in various congresses and conferences, allowing me to understand the state of hospital engineering. Through these experiences, I realized that I felt fascination towards this field because it was underdeveloped, yet had enormous potential for growth and impact on the well-being of healthcare in Portugal.

As part of my master's degree, which focuses on asset management, my initial goal was to find an internship in the health sector that would allow me to apply the knowledge I had acquired and make a difference in this sector in need. The internship not only confirmed my professional goals but also gave me practical experience and a clear vision of how to progress. It also allowed me to understand how I can truly contribute to the evolution of this field.

Being able to improve processes and witnessing the positive impact of my work are

two very rewarding aspects that reinforce my determination to make a difference in this area.

1.4 Objectives

At the beginning of the internship, there were more objectives than those accomplished. Some of these extra objectives were:

- ISO 55001 implementation study;
- Criticality analysis of medical equipment;
- Life cycle investment analysis;
- Logistics processes;
- Georeferencing of equipment using RFID;
- Waste analysis;
- Drafting terms of reference for the purchase of medical equipment.

These areas were excluded not because they were less important, but because they would take time to develop, with no specific area to focus on. The themes developed throughout the internship report were medical equipment maintenance management, metrology, Key Performance Indicators (KPI) and Life Cycle Cost (LCC). In addition to this internship report, three articles were produced:

- "A New Legal Metrological Scenario For Medical Devices", presented at Jornadas de Engenharia Biomédica 2024;
- "Optimizing Equipment Replacement Decisions: A Life Cycle Cost Analysis Approach Considering System Interdependencies" for the Encontro Nacional de Engenharia e Gestão Industrial 2024;
- KPIs aplicados a um SIE de um hospital português (KPIs applied to the SIE of a portuguese hospital) for the Tecnohospital Journal.

Figure 1.1 shows some of the activities developed and the corresponding time periods.

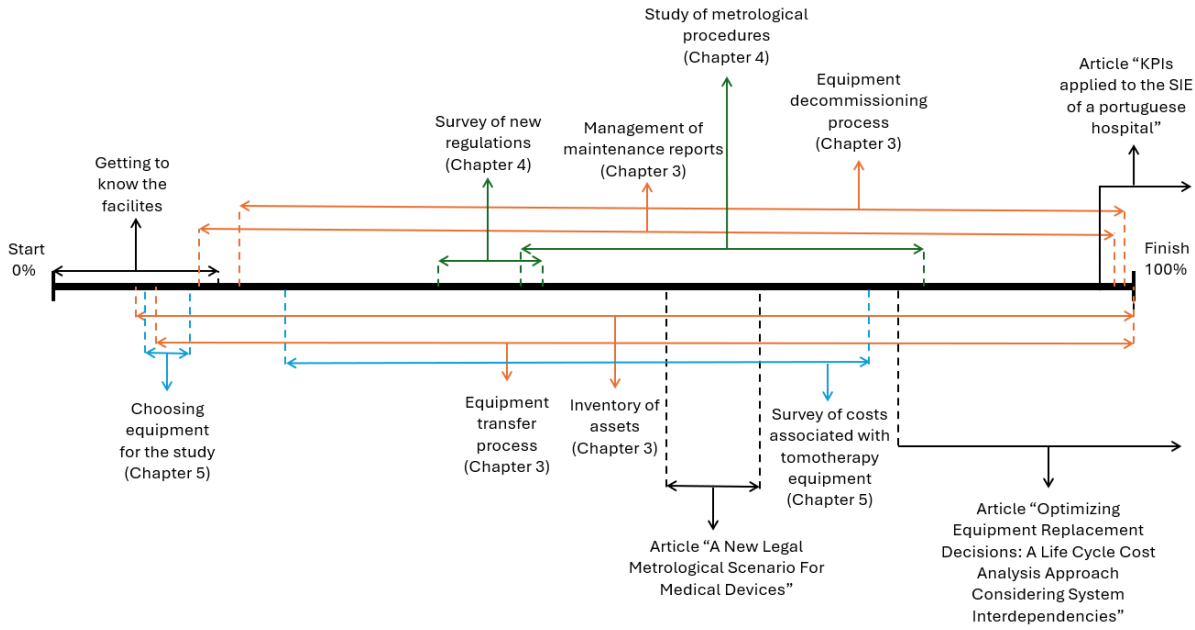


Figure 1.1: Timeline of the internship period

1.5 Report structure

This report is divided into six chapters and six appendices:

- Chapter 1 - Introduction: a brief presentation of the organization, the purpose of the internship, and the intern's motivation.
- Chapter 2 - Theoretical Framework: a literature review of the topics on which the internship report will be based on.
- Chapter 3 - Hospital Equipment Management: explanation of how the main departments where the internship took place operate and the tasks performed.
- Chapter 4 - Metrology Overview: examination of existing internal processes and conducting of a case study on implementing new regulations.
- Chapter 5 - Life Cycle Cost: analysis of the costs involved over the lifetime of the Tomotherapy, using various methods to give an estimated replacement time.
- Chapter 6 - Conclusion: presentation of the conclusions drawn during the internship and some suggestions for improvement.
- Appendix A - Template developed for the reception document.
- Appendix B - Internal document developed to standardize the designation of maintenance reports.
- Appendix C - Internal document developed to standardize designations in the medical equipment register.

- Appendix D - Complete calculations for the UAIM model.
- Appendix E - Complete calculations for the MTACM model.
- Appendix F - Complete calculations for the MRACM-RPV model.

1.6 Questions to be answered

Throughout the internship, three core questions were analyzed through consistent routine and study. Answering these questions lies at the core of this report.

- **Question 01:** How can the internal processes of the SIE increase hospital efficiency?
- **Question 02:** What is the impact for a hospital, of certain equipment falling within the scope of legal metrology?
- **Question 03:** Which parameters can affect the life cycle of heavy medical equipment?

2 State of the art

This chapter provides a theoretical foundation for the topics covered by this report, namely asset management (Chapters 3 and 5), maintenance (Chapters 3 and 5), metrology (Chapter 4) and key performance indicators (Chapters 3 and 5). This analysis includes citations from books, journal articles, conference papers, international and national standards and other relevant publications. Finally, the chapter concludes with a brief meta-analysis of the literature used.

2.1 Asset management

The standard PAS 55 was the document that kickstarted the standardization of asset management worldwide, enabling the establishment of common language and asset management standards [10].

PAS 55 defines asset management as *"... systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks, and expenditures over their life cycles to achieve the organizational strategic plan*[*10*]*."*

Over the years and with the expansion of the concept, the need to evolve the standard emerged and in 2014 the ISO 5500X family was published.

The ISO 5500X family is divided into three standards:

- **ISO 55000 (Asset management — Overview, principles and terminology)**

  ISO 55000 [2] aims to provide an overview of asset management, define terminology and outline the benefits of implementing the framework. It also explains that this standard can be applied to all types of organizations, as it is a holistic concept.

  The standard explains how an organization can maximize the value of its assets by balancing costs and benefits. By creating an interrelated system, as shown in Figure 2.1, it is possible to develop management policies and processes to achieve the necessary objectives.

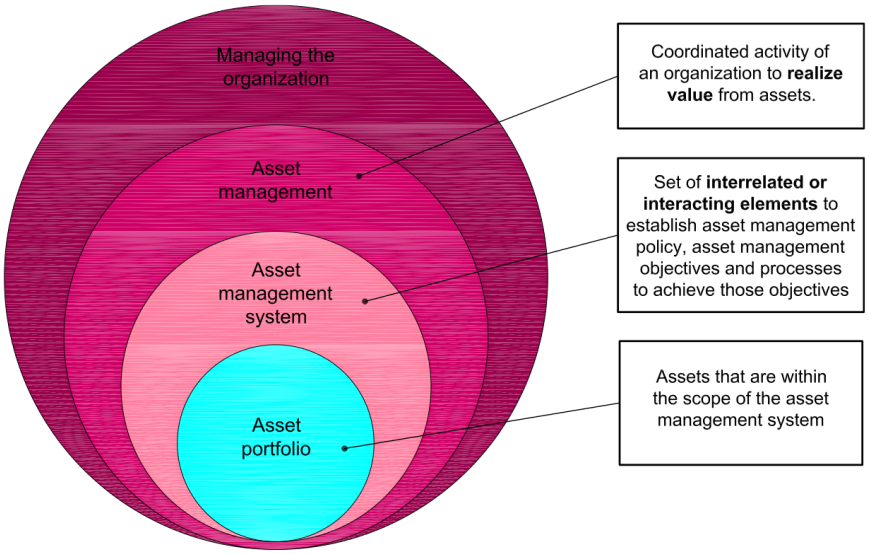


Figure 2.1: ISO 55000 system interrelationship [2]

- **ISO 55001 (Asset management — Management systems — Requirements)**

  ISO 55001 [11] defines the requirements for implementing an asset management system. To implement such a system, it is first necessary to understand the company's current state and create all the necessary documentation for asset management. For the system to work as expected, managers must encourage the integration of processes. Finally, a continuous improvement system is established to allow holistic monitoring of asset performance.

- **ISO 55002 (Asset management — Management systems — Guidelines for the application of ISO 55001)**

  ISO 55002 [12] provides the guidelines for applying the asset management system established by ISO 55001. It also includes the various processes that the management system must go through in order to take everything into account.

2.1.1 Life cycle

Farinha [3] breaks down the life cycle of an asset into 8 stages, starting with the decision to purchase the equipment (t1) and ending with its write-off/renewal (t8):

- t1 - Acquisition Strategy

  The Strategic Asset Management Plan (SAMP) is developed as a planning tool to clarify the intentions, priorities and procedures to be implemented for the equipment.

- t2 - Terms of Reference

  Various aspects are taken into account, one of the most important stages is the

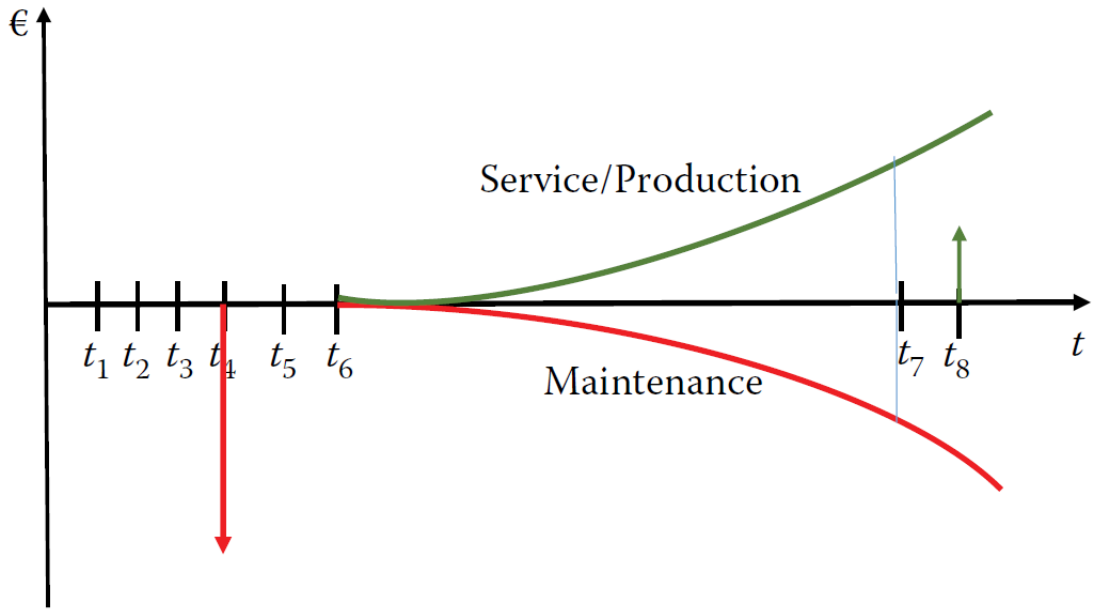


Figure 2.2: Stages of a physical asset life cycle [3]

development of documentation, known as the Terms of Reference, for the acquisition of the equipment in which the specifications of the asset are defined.

In this step, specifications are defined such as the associated risk for the user and others, technical details, specific maintenance, Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), Mean Waiting Time (MWT) ratios, among others; documentation of the equipment to ascertain its requirements covering assembly plans, lists of spare parts and the equipment's electrical diagram; details of how the equipment must be received, installed, how it must be placed in operation and what sort of tests must be carried out in order to meet the requirements, among other necessary conditions.

- t3 - Consultation

  Proposals are invited and received in accordance with the Contract Documents. This step allows us to ensure that the received offers are in line with our Terms of Reference. It also possibilitates the creation of a framework to make it easier to analyze the data so that the coming decision is the most appropriate for the organization.

- t4 – Acquisition

  The submitted proposals are analyzed, with various parameters such as Return On Investment, maintenance costs and production capabilities to select the most suitable one.

- t5 – Commissioning

  Verification is conducted to ensure the equipment complies with our Terms of Reference, conducting calibration tests and finally commissioning to check that the legal standards are met when everything is working.

- t6 - Starting Production / Starting Maintenance

  Start planning, management and control of the equipment to reconcile everything that affects the equipment, from maintenance, types of philosophy (Lean, Kaizen, Hoshin Kanri) and other relevant aspects. This way, the output of the equipment is maximized.

- t7 - Economic / Lifespan

  Econometric models are employed to evaluate the equipment's life cycle. This evaluation requires equipment values such as disposal value, operating costs, inflation rate and others.

- t8 - Renewal / Withdrawal

  Should the organization continuously monitor its econometric models, this stage only requires an annual refresh; if not, it is important to do so at the correct moment before the end of the equipment's life.

2.1.2 Depreciation models

According to Oliveira [13], the concept of depreciation is directly related to investment, that is, it lasts for more than one year in an organization and refers to wear and tear caused by the use/unuse of an asset over a certain period of time. In accounting terms, depreciation is a cost that is recovered when products are sold, thus creating a capital reserve that cannot be spent and is earmarked for the renewal of assets in the future.

In economic terms, it is not seen as a cost but as a source of funds for the organization's operations. The value is difficult to obtain due to the wide variety of existing equipment.

2.1.3 Economical models for replacement

According to Meyer[14], replacement models are crucial for good organizational management, allowing for informed decisions regarding the equipment in question. By using mathematical models, the future behavior of maintenance and operating costs can be estimated.

In addition, the mathematical models allow for comparisons to be made between the accumulated costs of maintaining the equipment and the cost of acquiring new equipment. With this study, it is possible to conclude that it is not only possible to consider

the direct costs of the equipment, it is necessary to explore indirect costs and factors such as the efficiency of new equipment and its probability of failure [14].

Farinha [3] elaborates that there are key factors in the decision of when to replace an asset. Some of these key factors include economic life, market value, obsolescence, lifespan, associated costs and the possible benefits of replacement. With some of these key factors in mind, it is possible to model equations that, by applying different depreciation methods, provide predictions of replacement years.

2.2 Maintenance

François Monchy [15] says that the terminology for "Maintenance" originated in the military, initially meaning *"... keeping the personnel and material in combat units at a constant level"*. This concept evolved into the one we have today as a result of developments during the Second World War, where failure prevention models were created based on statistics of similar failures.

According to NP EN 13306:2021, [16], maintenance is *"... 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."*

Farinha [17] states that maintenance is defined as " ... *a combination of management, technical and economic actions applied to assets to optimize their life cycles*."

2.2.1 Types of maintenance

There are several types of maintenance, three of which are the main ones: Corrective Maintenance, Predictive Maintenance and Preventive Maintenance [16]:

- Corrective Maintenance

  This type of maintenance is unplanned. Here, action is only taken after the failure has occurred. It aims to repair the faulty equipment to its normal operating state [18]:

  - Deferred Corrective Maintenance: not carried out immediately after fault detection, only carried out according to pre-established factors [16].
  - Immediate Corrective Maintenance: after a fault is detected, immediate maintenance is issued to minimize the impact [16].

- Predictive Maintenance

  According to [19],[20] and [21] this maintenance strategy is based on continuous monitoring of the equipment. Through Machine Learning models, it is possible to predict the behavior of the equipment, anticipating faults or unexpected changes at an early stage.

- Preventive Maintenance

  It consists of carrying out maintenance with the aim of mitigating the degradation of assets, acting before breakdowns occur, thus improving reliability, with two possible methods:

  - Systematic Preventive Maintenance: where maintenance is carried out at intervals of time or by some utilizations without prior condition checks. It can also be systematized by knowing the asset's failure mechanism [16].
  - Conditional Preventive Maintenance: results from a physical assessment from visual inspection to monitoring of equipment parameters through sensitization [16].

In addition to these types of maintenance, there is a new kind called Prescriptive Maintenance that, according to Matyas [22] *"... extends beyond the mere prediction of failures."*

As a process that involves an enormous amount of data, one of the biggest challenges of this technology is the collection. By analyzing the equipment history and receiving data in real-time, mathematical models [23] can be applied to create a forecast and prescribe a course of action. To minimize this obstacle, methodologies have been created, which are divided into 4 phases [22]:

- Data acquisition and pre-processing- when the quality, structure and veracity of the data being acquired is assessed. This assessment may be undertaken using failure protocols that analyze the equipment's history. This phase is extremely important as it is the foundation for decision-making;
- Data Analysis and Simulation- where causes and effects are created for coherence and to determine the remaining life of the equipment components;
- Creation of Reaction Models- where it is possible to compare the wear prediction rules and check whether the rules are being respected; if they are not, the system triggers;
- Decision Support System with prescriptive maintenance- where the result of all the analyses are displayed, In this stage, end user will decide whether to effectively comply with the proposed plan.

2.2.2 Associated costs

A maintenance manager must have a holistic view of the overall cost of their equipment and facilities. By visualizing costs, we can get an idea of the effectiveness of the management in question.

Diego Galar [24] states two main types of cost:

- Direct costs - these costs are directly linked to the maintenance service, such as the

cost of labor in carrying out both corrective and preventive maintenance; structural costs that can be represented by energy and communications costs; the cost of storing stock of spare parts and other equipment needed for the maintenance service, as well as the devaluation of tools and finally the cost of the maintenance contract, which is transposed onto external service providers that may include replacement parts, transport and others.

- Indirect costs - these costs are more difficult to quantify as they involve expenses due to equipment being idle, but they can be reflected in labor costs due to not being able to work, not manufactured or non-compliant products, among others.

2.3 Key Performance Indicators

According to [25], a KPI is "*... a metric measuring how well the organization or an individual performs an operational, tactical or strategic activity that is critical for the current and future success of the organization*".

KPIs are used across a wide range of industries, such as healthcare [26], logistics and supply chain [27], sustainability [28] and energy [29]

Within each sector, there are different groups to whom different types of KPIs are relevant, such as operations managers who want to maximize the performance of the operation, investors who are interested in financial performance, maintenance managers who aim to reduce downtime and the associated costs in their interventions on equipment and the management board which must have information regarding all the departments for which they are responsible [29].

Similarly, KPIs can be classified into three distinct categories as defined in BS 15341:2019 [30]:

- Economic: focus on the financial and economic aspects of the organization. These are fundamental to evaluating financial and economic performance. Examples of some economic KPIs are return on investment, cost per unit and profit margin;
- Technical: focus on measuring the performance of processes and operations. They are essential for managing operational efficiency. Some examples of technical KPIs are productivity rate, inventory turnover and downtime;
- Organizational: focus on measuring the overall performance of customer-related areas and personal development. They are essential for evaluating success and competitiveness within the organization. Some examples of organizational KPIs are customer satisfaction, employee turnover rate and time to hire.

To improve the interpretation of these metrics, a clear and visible dashboard should be applied. This measure could improve the organization's results, since all the information is available to the interested groups, allowing them to assess progress towards an

overall goal [25].

2.4 Metrology

The definition of metrology is *"... the science of measurement, embracing both experimental and theoretical determinations at any level of uncertainty in any field of science and technology ..."* [31], which is made possible by the interaction between measurement systems and their processes.

2.4.1 International metrology vocabulary

To achieve conformity in vocabulary and nomenclature within the technical-scientific community, a document was formulated in the second half of the 20th century with the aim of internationally harmonizing metrological concepts [32]. This document, called the International Metrology Vocabulary (VIM), is intended to be a "*... guidance document that aims at disseminating scientific and technological knowledge about metrology by harmonizing worldwide the related fundamental terminology.* [32].

Below are some of the definitions considered relevant to this report:

- **metrology**: *"... science of measurement and examination, and their applications."*
- **calibration**: *"... process carried out on a measuring instrument or a measuring system that, under specified conditions"*
- **uncertainty**: *"... lower bound of measurement uncertainty resulting from the finite amount of detail in the definition of a measurand."*
- **adjustment**: *"... set of operations carried out on a measuring system so that it provides prescribed indications corresponding to given values of a quantity being measured."*
- **maximum permissible measurement error**: *"... extreme measurement error, with respect to a known reference value, permitted by specifications or regulations for a given measurement, measuring instrument, or measuring system working at the rated operating conditions."*
- **repeatability**: *"... specified conditions of measurement where indications or measured values are obtained by replicate measurements with the same measurement procedure on the same or similar objects in the same laboratory by the same operator using the same measuring system within a short period of time."*.

Over the years, the VIM has been updated to keep up with the evolution of technological processes, allowing professionals in the field to continue harmonizing processes with current realities.

In 1961, the International Vocabulary of Legal Metrology (VIML) was created by the International Organization of Legal Metrology (OIML) with a similar objective to the

VIM, aiming to harmonize nomenclature in the field of legal metrology [32].

2.4.2 Types for metrology

- **Scientific metrology**
  The purpose of scientific metrology is to create and define new standards and units of measurement. It is also responsible for developing new methods for metrological traceability. This field is fundamental for technological evolution, both in theory and practice [33].

- **Applied (industrial) metrology**
  This part of metrology is voluntary, meaning it is not mandatory to perform. The purpose of these metrological operations is to ensure the quality of the product and to adopt good practices [33]. This type of metrology can be conducted internally or externally to the organization. However, when a calibration or test certificate is required, it must be performed by a properly accredited laboratory [4].

- **Legal metrology**
  Legal metrology covers all metrological operations regulated by legislation, including the legal control of measuring instruments and metrological surveillance [33]. According to Decree-Law no. 29/2022 [34], legal metrology is "*... destina-se a promover a defesa do consumidor e a proporcionar à sociedade em geral, e aos cidadãos em particular, a garantia do rigor das medições...*" (... intended to promote the defense of the consumer and to guarantee for the broader society, and especially the citizens, rigorous measuring ...).

  There are four operations in metrological control:

  1. The first is the model approval, where the measuring instrument is confirmed to be in conformity with the specifications applicable to its category;
  2. The second is the first verification, which consists of a series of operations to ensure that new or repaired equipment meets the respective approved models and regulatory provisions. The first verification must be requested by the manufacturer in the case of new equipment and by the user in the case of repaired equipment [34];
  3. The third operation is periodic verification, which involves a series of operations designed to check that the measuring instruments meet all the regulatory requirements. This verification takes a variable amount it time, as it depends on the type of measuring instrument. The user of the equipment is responsible for requesting the periodic verification;
  4. Lastly, the extraordinary verification exists to confirm that the equipment remains within the specifications that are applicable to its type. This verifi-

cation can be requested by the equipment manager, customers or auditors, and doesn't affect the frequency of the periodic verification.

2.4.3 Quality regulatory systems

The Portuguese Quality Institute (IPQ) is a public organization with the mission of "*... procura da qualidade de produtos e serviços para o aumento da qualidade de vida dos cidadãos, aumento da competitividade das atividades económicas num contexto de progressiva liberdade de circulação de bens*" [35]. (... seeking product and service quality for an increase in the citizens' quality of life and economic competitiveness in a context of increasing freedom of circulation of goods.)

The IPQ is responsible for coordinating the Portuguese Quality System (SPQ) with the mission of promoting quality development in all sectors of activity in Portugal. The IPQ also has two roles: as a national standardization body, it promotes national and international standards and ensures innovation in its services. Its second role is as the national metrology institution, ensuring the rigor and accuracy of measurements and guaranteeing their comparability and traceability. It also fulfills the constitutional objective of scientific, applied and legal metrology, allowing it to control measurement standards[35].

The Portuguese Accreditation Institute (IPAC) is the organization responsible for accreditation in Portugal. It focuses on managing the Portuguese accreditation system and recognizing the technical competencies of laboratories and certification of organizations. Additionally, it represents the country on international accreditation committees [36].

2.4.4 Metrological traceability

According to VIM [32], metrological traceability is the "*... property of a measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.*". This definition was created by the Joint Committee for Traceability in Laboratory Medicine, which promotes traceability and standardization in laboratories.

Traceability makes it possible to create a hierarchical link between the measurement systems and the standards used. In Figure 2.3, this hierarchy of the reference standards can be observed. This allows for a connection to be made between the standards because it is possible to consult "*... documents that its reference or standard weight was calibrated by or is traceable to the SI ...*". In addition, it is possible to identify the entire process associated with the standard, in order to identify the resolution and possible sources of error [4].

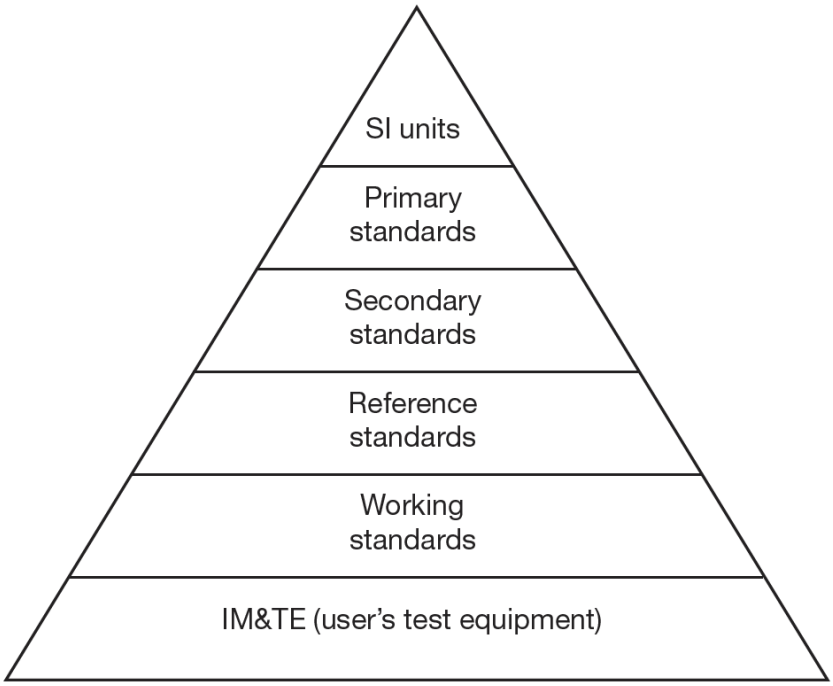


Figure 2.3: Metrological Traceability Structure [4]

2.4.5 Metrology and maintenance

The wear and tear of measuring equipment can be directly related to its continuous use, possibly influencing the measurements. To prevent this from compromising the reliability of the measured quantities, it is advisable to perform preventive maintenance at appropriate intervals to reduce the likelihood of failure.

In addition to undergoing maintenance procedures, it is also recommended that measuring equipment be calibrated. This allows for the measurement error and its uncertainty to be determined more accurately. After maintenance, the equipment must undergo metrological processes to ensure that it is measuring within acceptable ranges. As mentioned above, the maximum acceptable value for the error is defined according to the area of metrology in which the equipment is used. If the error is greater than acceptable, corrective maintenance must be carried out, followed by calibration [33].

2.4.6 Metrology in healthcare

According to [33], metrology in healthcare is important due to the fact that *"... several clinical decisions are taken and based on measurement results that constitute basic information for the provision of healthcare, with particular relevance to the accuracy and reliability of these same measurements."*.

The area of metrology in the healthcare sector deals with the application of appropriate metrological principles to guarantee the precision and accuracy of measurements,

both in clinical and laboratory contexts. This precision is essential for identifying diseases and ensuring the safety and effectiveness of the care provided [37]. There are challenges to overcome, such as traceability, as it is difficult to link measurements to reference standards [38]. According to Karaboce [39], we are living in an era in which technology changes very quickly, which poses obstacles to defining and implementing metrological procedures due to the frequent replacement of equipment and the lack of regulations requiring all medical devices to undergo a metrological procedure.

But we can also see that progress is being made from the creation of standards that support metrological processes, such as:

- ISO 10012:2003 [40] defines the requirements and generic guidelines for implementing or improving a measurement management system. Although it is not specific to the healthcare sector, it can be adapted to provide the necessary framework for this field;
- ISO 17025:2017 [41] establishes the quality requirements for laboratories where tests and calibrations are conducted. It serves to demonstrate that a laboratory is capable of producing valid and internationally recognized results;
- Good practice guides [33] encourage the training of healthcare professionals through awareness-raising systems to understand metrological processes and adopt good practices.

Ferreira [38] claims that by establishing chains of metrological traceability, using international reference standards and performing dynamic calibration of equipment, it is possible to ensure that all processes are performed correctly and that the equipment remains within the permitted tolerance limits.

2.5 Meta-Analysis

Through meta-analysis [42], it is possible to strengthen the report itself. itself. The choice of articles referenced throughout the report has its weight and can help elevate its quality.

Table 2.1: Quality of the bibliography analyzed

Type of publication	Referenced Number
Q1	18
Q2	6
Q3	3
Q4	1

The quartiles of the scientific journals refer to the impact factor, i.e. the importance of the journal in relation to others in the same field of study, and are divided into Q1 (Top 25%), Q2 (26% to 50%), Q3 (51% to 75%) and Q4 (76% to 100%).

3 Hospital Equipment Management

This chapter explains the SIE maintenance management model based on practices applied to corrective maintenance. It then discusses the Financial Management Service (SGF), analyzing its importance and impact on the equipment life cycle.

3.1 Characterization of SIE

The importance of SIE in a hospital environment results in an indisputable necessity for its complexity to be maintained, from its infrastructure to electromedicine. As such, SIE has a major impact on how a hospital operates, from the smallest where there may not be a SIE but there is a service that performs similar functions to a large hospital where sub-services can emerge within the SIE to fulfill the needs without having to outsource to another company [17].

Unfortunately, the importance of SIE is only acknowledged when the final users of the equipment/infrastructure are faced with some kind of anomaly [17]. The impact of the SIE after the anomaly is huge, but their actions while the equipment/infrastructure functions properly are decisive for the smooth operation of the hospital.

To achieve the goal of proper functioning, it is necessary to keep track, not of the acquisition, but of the decision to acquire, since it is the SIE who is subsequently responsible for its reception, installation and maintenance process. To protect the organization, specifications are drawn up by the Provisioning Service with the help of the SIE. These specifications will contain parameters defined by the organization, including [17]:

- Quality of the asset to be purchased, parameters such as equipment reliability, warranty period, projections of maintenance costs associated with the asset, technological level and cost of the equipment are considered [17];
- Hospital reality where the place of installation in the case of fixed equipment or place of use for equipment with mobility is taken into account, what conditions are available and what is required, the availability of qualified operators for the use of the asset [17];
- Supplier guarantees, which take into account response time, technical capacity, supply of spare parts, staff training and other aspects [17].

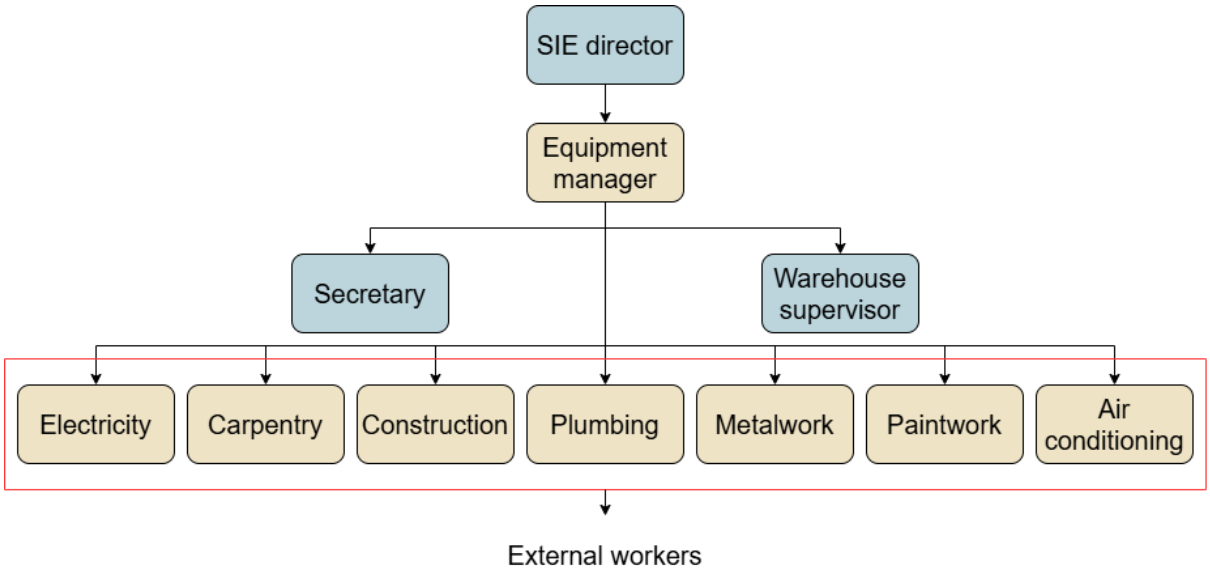


Figure 3.1: Organizational chart of SIE

Once the proposal has been selected, the purchase is made and received, where there must be confirmation between what has been purchased and what has been received to ensure that it matches. In addition, all documentation, from user manuals to equipment operating diagrams, must be received in the desired language. After reception, the installation is undertaken with the help of the supplier's technicians and under the supervision of a member of SIE so that he has a better idea of what has been done and under what conditions.

In the case of the IPOCFG, it is a hospital that in terms of structure and size can be considered medium-sized. It has the internal capacity to resolve a large percentage of infrastructure-related requests. When it comes to electromedicine, however, this service is subcontracted, as it is not feasible to have an in-house team for this purpose. The great diversity of medical equipment, along with the fact they are increasingly technological, requires a great investment not only in trained workers, but also in infrastructure, and the IPOCFG is not in a position to do this.

As can be seen in the organizational diagram in Figure 3.1, the IPOCFG SIE is hierarchized into a service director, an equipment manager, a warehouse supervisor, a secretarial services and, finally, several workshops consisting of permanent employees who belong to a subcontracted company. This resident team is responsible for maintaining the infrastructure of the entire hospital campus.

For the most part, the maintenance carried out by the SIE is both immediate and deferred, while preventive maintenance is provided by external companies.

3.1.1 Maintenance software - GHAF

All activities related to SIE are registered in an Enterprise Asset Management (EAM) called Gestão Hospitalar de Armazém e Farmácia (GHAF), which was developed by the Serviços Técnicos de Informatica (ST+I) [43]. This EAM is used by various services in the hospital because it is versatile with various modules with their specifications. The Maintenance module is used in the SIE and looks like Figure 3.2. All internal workers have access to the application, each with their restrictions so they only have access to what is assigned to them.

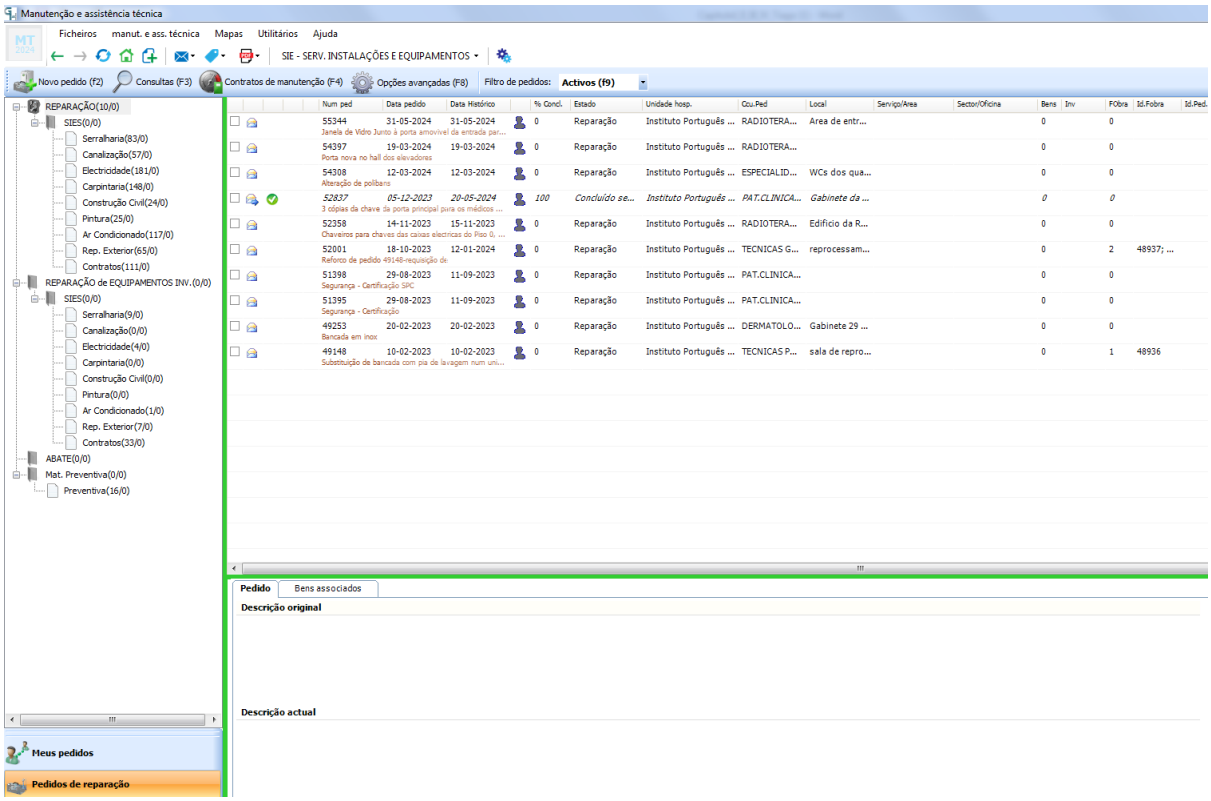


Figure 3.2: Main page of GHAF

Some of the functionalities of the Maintenance module are:

- Creation of maintenance requests and assignment of worksheets to each request, thus allowing the attachment of costs such as labor, warehouse materials and orders, among others;
- Real-time alerts, from changes in order status to workshop section changes;
- Interface with fixed assets, making it possible to consult the entire maintenance history, whether corrective or preventive, as well as contracts in which an asset is included, among others;
- Display of global KPIs;
- Preventive maintenance sub-module (Figure 3.3) that allows for the scheduling of all preventive maintenance on equipment. equipment can be grouped within

its cost center according to maintenance frequency. It also has the function of alerting users to the time remaining for preventive maintenance, based on the time assigned by the equipment manager, thus preventing failures.

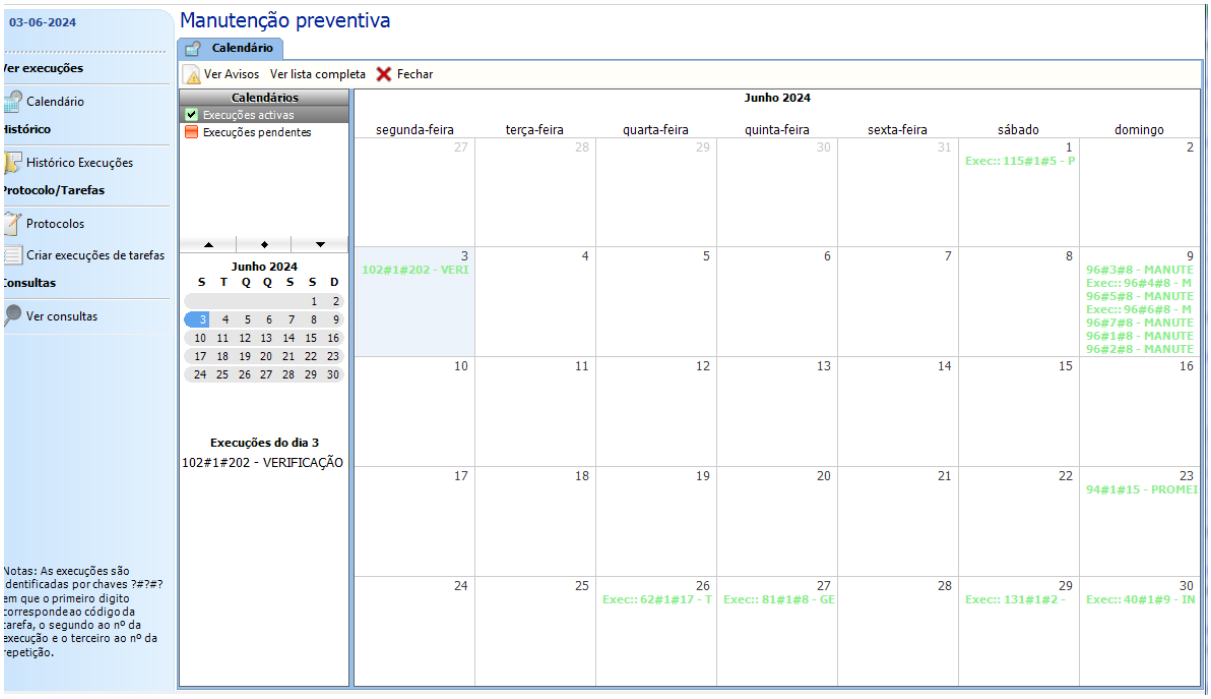


Figure 3.3: Preventive maintenance module

Although the software is considered simple, it is suitable for hospitals because it keeps processes simple, enabling the flow of information throughout the hospital ecosystem. One negative aspect of this software is that it is not very user-friendly, which increases its learning curve. GHAF can be used on a smartphone or via its desktop application. This EAM is also certified by SPMS, ISO 9001, ISO 13485, Rede PME and PME excelência21 [43].

3.1.2 Maintenance request management process

To start the process, there needs to be a maintenance request, usually made by the service manager at GHAF. To process the request, it must be described in detail so that the equipment manager can understand whether there is internal capacity to resolve the request or if it will need to be resolved externally.

If there is no internal capacity to handle the request, one of two situations arises. Either there is already a maintenance contract associated with this need, or no maintenance contract exists yet, making it necessary to ask a company to provide a quote for solving the problem.

When the request has been resolved, a report is created and uploaded to GHAF. The equipment manager marks the request as concluded and the person responsible for

the request, if satisfied with the execution of the request, proceeds to close it. Figure 3.4 provides an overview of the process for handling requests.

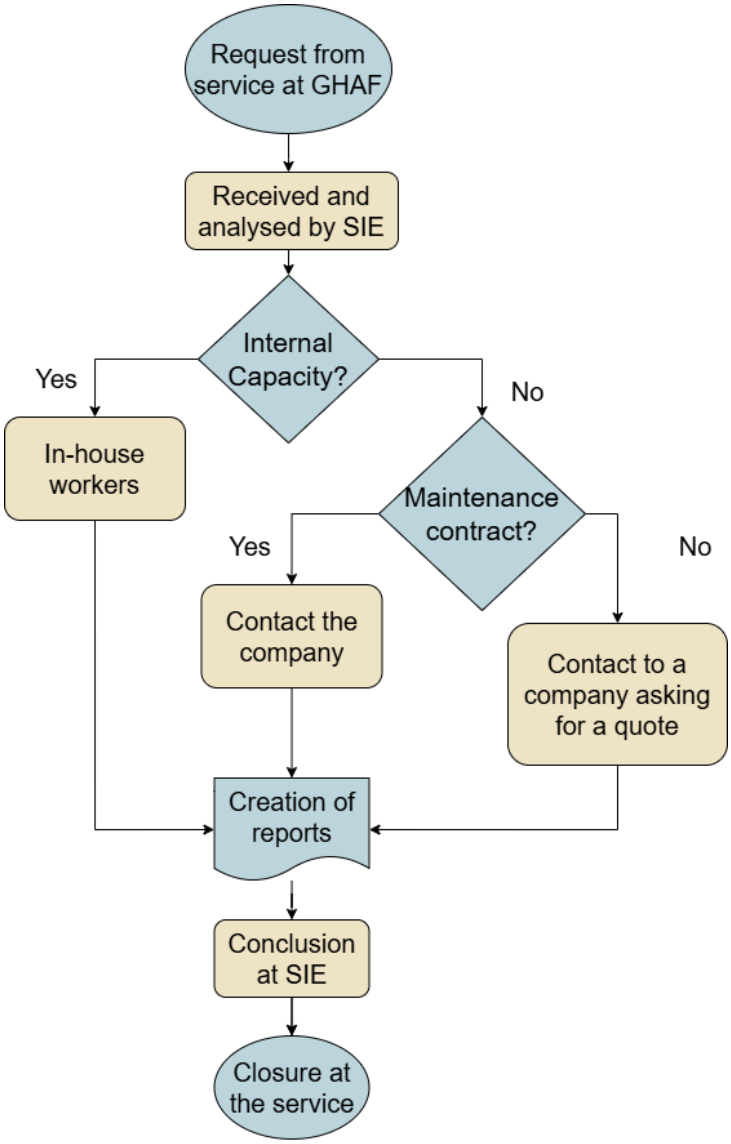


Figure 3.4: Maintenance request process

3.1.3 KPIs applied to the service

To better understand the situation of the SIE over the years, it was self-proposed to establish some KPIs related to the service. To develop these KPIs, the GHAF software was used as a baseline, where global KPIs are already displayed and where all the data is stored. Because the GHAF presents global KPIs, it doesn't portray an annual reality. To compensate for this, the annual values were extracted from the software, and non-standardized KPIs were created.

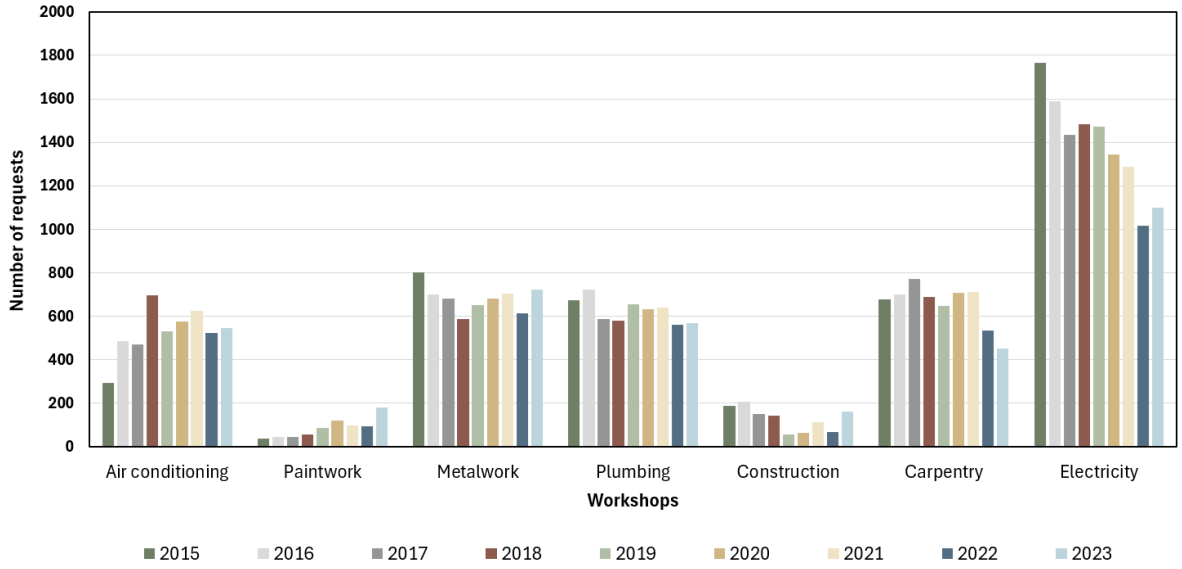


Figure 3.5: Total requests over the years by workshop

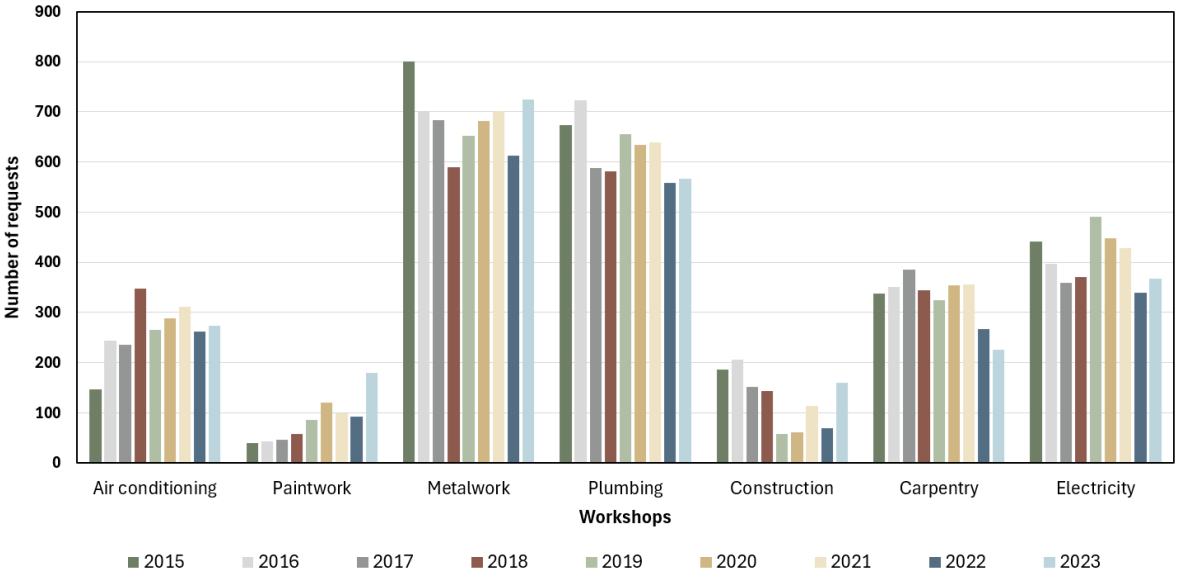


Figure 3.6: Average requests per worker over the years per workshop

Figure 3.5 illustrates the number of requests over the last 8 years. As can be seen, despite the fluctuations, the workshop with the highest number of requisitions is Electricity and the workshop with the lowest number of requisitions varies over the years between Paintwork and Construction.

Although Figure 3.5 shows that electricity has the highest number of requisitions, Figure 3.6 shows that Metalwork and Plumbing have the highest number of requisitions per worker over the years. Construction and Paintwork have the lowest number of requests per worker too.

In Figure 3.7, it is possible to see across the board that associated costs have increased in all workshops over the years. Air conditioning and Electricity have the highest costs

per workshop, which is justified by the fact that these workshops are more technical in nature and more refined in the type of requests they deal with. For reasons of data protection and confidentiality, the respective amounts are not shown in the chart.

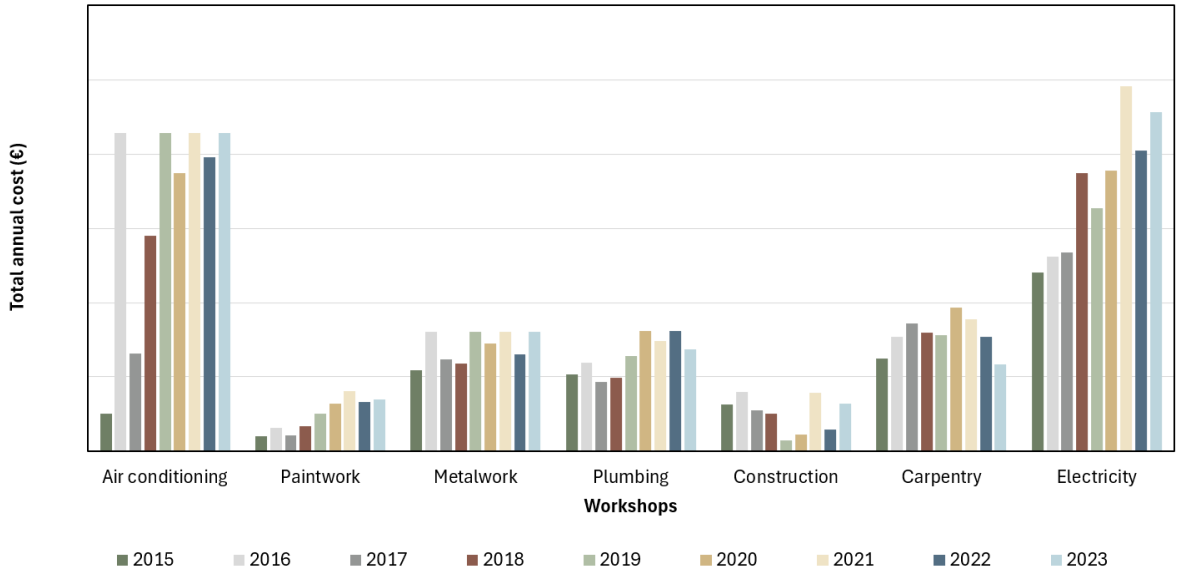


Figure 3.7: Total cost over the years per workshop

As the total cost of the workshops has increased gradually over the years, the average cost per requisition has generally followed the same trend, as illustrated in Figure 3.8. Paintwork and Air Conditioning have the highest average values per requisition, where Paintwork is justified by the fact that it has a smaller number of requisitions and the material tends to be more expensive.

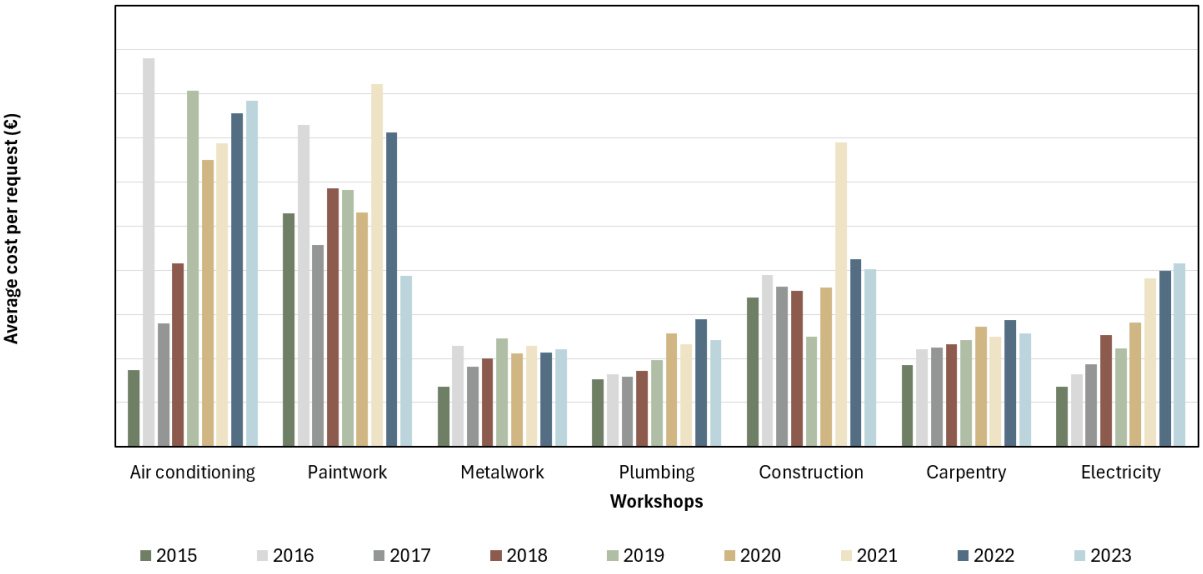


Figure 3.8: Average cost per requisition over the years per workshop

The Air Conditioning and Electrical workshops also come out on top with the highest

number of hours accumulated over the years, as indicated in Figure 3.9. This is due to the fact that generally, these tend to be more technical and finer-grained.

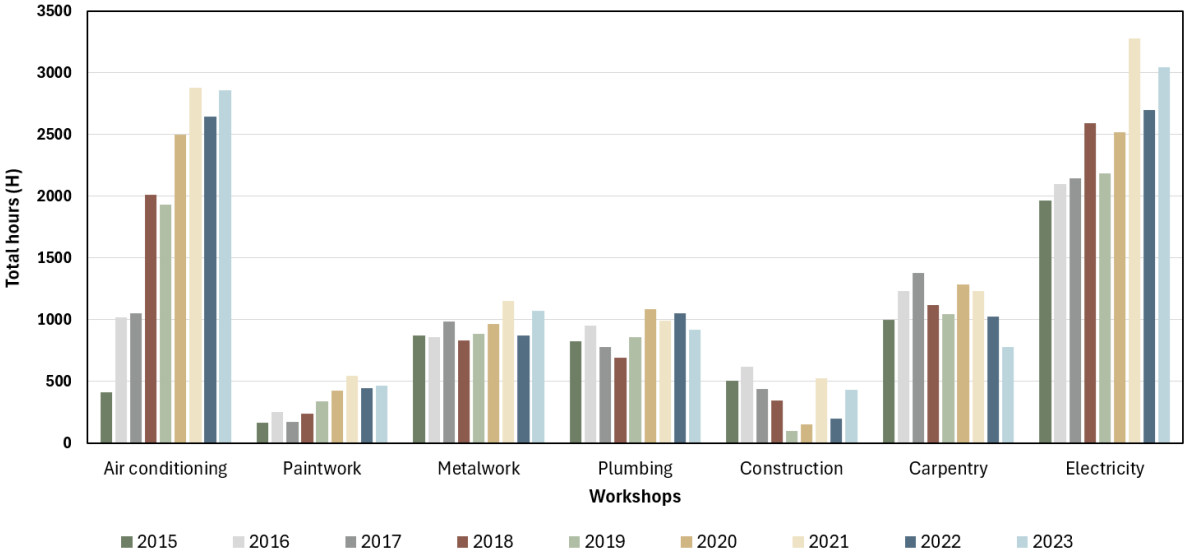


Figure 3.9: Total time per workshop over the years

In Figure 3.10, it can be seen that the average time per request for Air conditioning has increased significantly over the years, while workshops such as Metalwork, Plumbing, Carpentry and Electricity have seen their average time stabilize, showing little variation over the years.

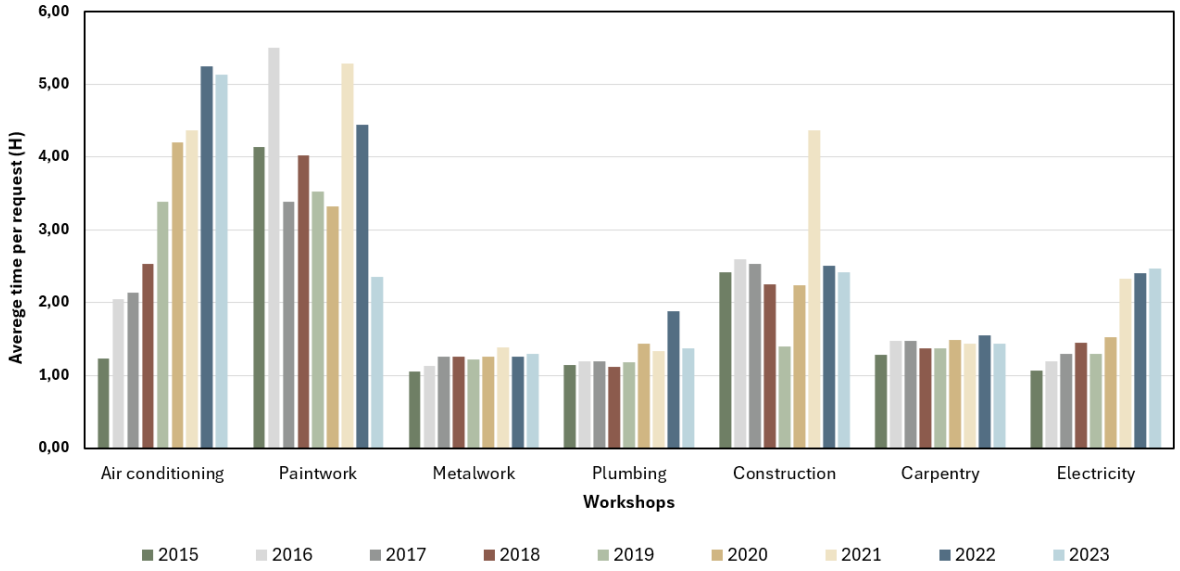


Figure 3.10: Average time per request over the years per workshop

Figure 3.11 displays color data in pairs, for example dark green and light green. This differentiation is made by the existence of two parameters, Average Completion Time (ACT) and Average Finalization Time (AFT). ACT is the time from opening the requisition to its completion.

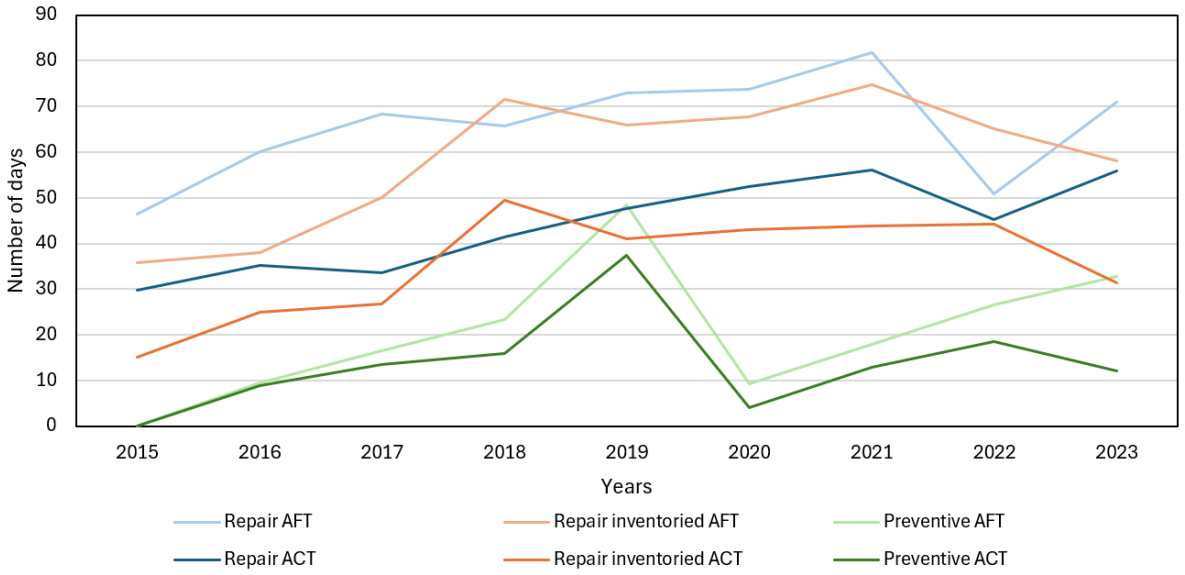


Figure 3.11: Variation of ACT and AFT through the years

This metric is produced by the SIE, as they are the ones who control the requisitions. The AFT is the time from opening the requisition to finalizing it. This parameter is controlled by whoever opens the request and is only finished when they are satisfied with the resolution.

Requisitions corresponding to preventive ACT and AFT metrics are controlled by the SIE, which is responsible for opening this type of requisition. Requests for repair and repair of inventoried are placed by the service managers. This means that if the information is compared between ACT and AFT, this time increases in relation to Preventive this is since GHAF does not have an alert system.

3.2 Characterization of Financial Management Service

Over the years the National Health Service (SNS) has increased its investment in health, and services such as SGF are needed to manage funding in the hospital field. They are responsible for financial sustainability, ensuring that the hospital has adequate funding for the resources it needs. They are also able to perform cost management, allowing them to identify areas that can be further optimized. In addition, they are responsible for invoicing and payment processes, thus producing financial indicators that allow the hospital to make strategic decisions.

In the case of IPOC's SGF, as can be seen in Figure 3.12, they are composed by the department director, treasury and accounting. Within accounting, they are subdivided into revenue, expenditure and pre-invoicing. Although the SGF is closely involved with assets, they don't have a specific department for this purpose.

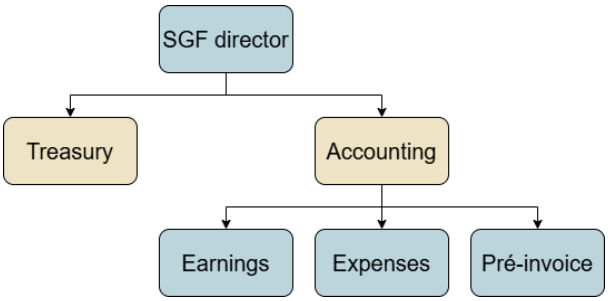


Figure 3.12: Constitution of SGF

3.2.1 Financial software - SHI

The software used to catalog assets is Software Hospitalar Integrado (SHI). The SHI has the frontend shown in Figure 3.13, where it is possible to register, transfer, amortize and decommission assets. The registration, transfer and decommissioning processes will be described below.

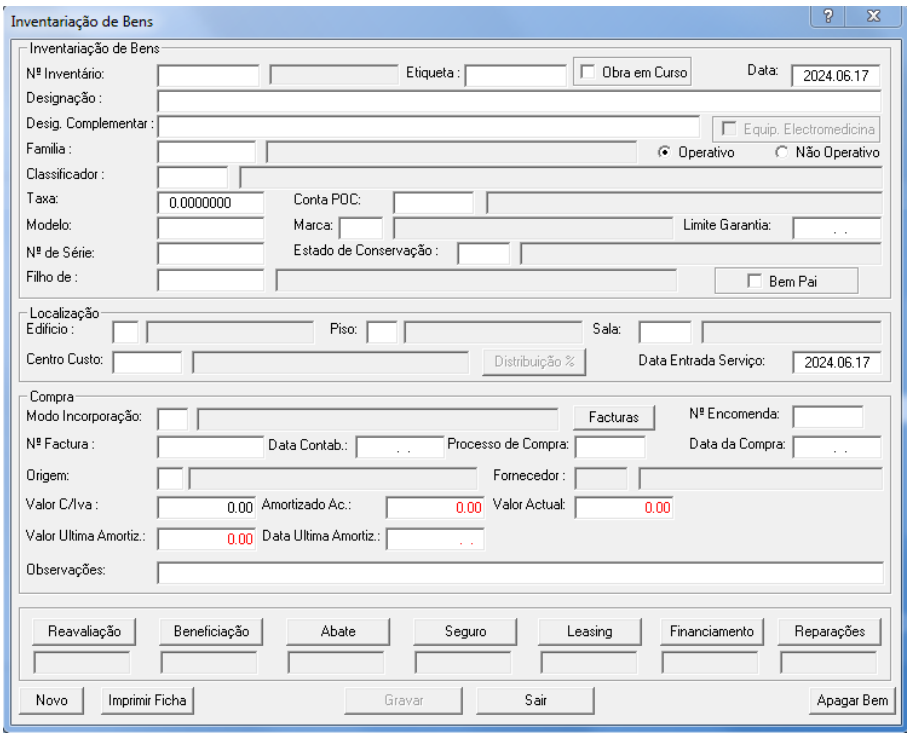


Figure 3.13: SHI software

The asset amortization process is a monthly procedure, allowing for an accounting analysis. In addition to these main functions, it is also possible to register brands, and cost centers according to building plans and register suppliers. At the moment, there is no direct communication between the SHI and the GHAF, meaning that each year, the new information on the assets acquired that year is downloaded and uploaded to GHAF. In 2024, the complete transition to GHAF was initiated, as SHI was no longer being represented.

3.2.2 Asset registration

Once the invoice has been received, the reception document has been completed and the assets have been installed (or stored), it must be registered as completely as possible. For this, some information is required, such as:

- Unique inventory number, to make it easier to search for the asset. There are also situations where the inventory number is associated with a tag number;
- Description of the asset;
- Brand, model, serial number;
- State of preservation;
- Location of the asset (Cost center);
- Accounting classification using the Complementary Classifier, which is instituted by the State as a way of standardizing classification, where assets are separated by family and associated with a depreciation rate [44];
- Invoicing and entry into service date, useful when warranty services are required.

In addition to the information already recorded by the SHI, the World Health Organization (WHO) recommends recording additional information [45]:

- Identification of manufacturer with information such as address and contact information;
- Operating requirements, to establish whether there are any specific requirements for operating the asset;
- Risk classification to determine the priority and criticality of the asset in question;
- Maintenance and metrological needs, in order to determine what will need to be done to ensure the optimal functioning of the asset;
- Maintenance requirements for the maintenance provider, so that the organization can make the best possible choice when selecting a maintenance provider.

3.2.3 Transfer of localization assets

The asset transfer procedure takes effect when a department needs to receive equipment/furniture from another department. The purpose of this procedure is to enable the asset to be included in the list of assets of the department that will receive it, as well as keeping an overview of the location of the assets within the hospital campus.

In order to do this, it is necessary to fill in the template for the transfer of assets, where the person responsible for the service of origin must fill in all fields regarding the equipment/furniture. These fields include the brand, model, serial number, inventory number, label number and other details. The person responsible for the destination service

will only have to fill in the part about the new location of the transferred asset. Both parties sign the procedure and the document goes to the SIE, where the equipment manager is informed of what will be transferred. The document is then sent to the SGF where the person responsible makes the change in the SHI.

3.2.4 Disposal (decommissioning) of assets

The decommissioning of assets takes place when the asset is obsolete, or due to a breakdown, it is too expensive to repair or spare parts are no longer available. To start the process described in Figure 3.14, the responsible company or internal team creates a report detailing the reasons why the asset needs to be decommissioned.

Figure 3.14: Decommissioning process

The report is delivered to the SIE, where the equipment Manager will analyze the report and inform the service responsible for where the asset originates. This service then fills in the decommissioning template by entering the inventory number, description of the asset, the reason for decommissioning, brand, model and serial number, so that it is later possible to correctly identify which asset is to be decommissioned, thus avoiding errors.

The document is then handed over to the scrapping committee, which is made up of the SIE equipment manager and the person responsible for the SGF equipment register, where they check whether the document is in conformity. The document is then sent to the administrator responsible for the equipment department for approval. Finally, once the document has been approved, it is passed on to the person in charge of equipment registers so that they can decommission it in the SHI.

Some assets are stored in SIE, where they undergo cannibalization processes to prevent further decommissioning of similar assets because spare parts are no longer available. The remaining assets are stored in the "Scrap Warehouse", awaiting a significant volume of assets to be destroyed.

3.3 Assignments performed throughout the internship

During the internship, one of the main objectives achieved was to establish a bridge between the SIE and the SGF. There was no one to make this connection, even though such a bridge would be crucial between these departments, since both are closely involved with the life cycle of equipment. Some of the activities undertaken to achieve this important relationship included:

- Inventory of Surgical Speciality Ward I. This was necessary due to the fact that this unit was formed from the merger of 5 wards that had been demolished as a result of the construction work taking place at the IPOCFG. In the process of creating Surgical Specialities I, the appropriate transfers and respective disposals of equipment were not implemented.

  The task was based on carrying out a complete assessment of all types of equipment and furniture in the ward and preparing the respective procedures. The end result was a completely inventoried ward, with a more comprehensive record than the initial one. This challenge would not have succeeded without the help of the head nurses and assistants;

- Inventory of services such as Operating Room, Nuclear Medicine, Gastroenterology, Pneumology, Surgical Speciality II, Day Hospital, Gynaecology, Urology, Cardiology, Dermatology, Endocrinology, Pharmacy, Catering Service, Clinical Pathology, Virology Laboratory, among others that had an incomplete inventory from 2015 to 2023;

- Collecting and performing asset decommissioning procedures from December to June;

- Collecting and processing transfers of assets between the different hospital divisions, in order to make the location more up-to-date;

- Filling in the reception document in full from November to June. The existing template was not suited to existing needs, so a new template, presented in Appendix A, was created on my own initiative, approved and implemented;

- Labelling all of the equipment/furniture acquired during the internship period.

Apart from these tasks involving the two departments, there were tasks for each department.

- SIE

  - Control of the process for allocating and completing corrective and preventive maintenance at GHAF;

  - Accompanying workers during the processing of requests;

  - Creation of a work instruction (Appendix B) for the designation of the report files, in order to make it easier to locate files within folders;

  - Digitization of overdue maintenance reports;

  - Updating all preventive maintenance, placing the digitized reports on the appropriate dates;

  - Creation of new preventive maintenance procedures at GHAF;

  - Updating maintenance contracts for 2024, listing the equipment and the corre-

sponding periodicities;

- Follow up on equipment installations and electromedical maintenance companies.

- SGF

  - Registration of acquisitions of assets in SHI;

  - Creation of a work instruction (Appendix C) to standardize the designations given to medical devices acquired, in order to standardize the inventory of these assets.

4 Metrology in healthcare

This chapter presents the metrology applied to healthcare at IPOCFG, describing the existing processes for equipment and the steps for implementing new procedures for equipment. A case study is conducted on the implementation of new metrological control ordinances for sphygmomanometers and infrared ear thermometers, covering verification tests and the requirements imposed by the OIML.

4.1 Characterization of existing procedures

To understand the situation regarding the metrological status of the equipment used at the IPOCFG, a survey was carried out on the procedures already in place at the hospital. The aim of this survey was to understand where they are located and what conditions they are subject to. In the institution in question, the Immunohemotherapy service, which is ISO 9001 certified [46], has certain obligations to carry out metrological operations on some of the measuring equipment present in the service. The reason for these requirements is contained in ISO 9001 [46]. In addition to this service, there is also the Clinical Pathology service, which is currently in the process of ISO 9001 certification.

Table 4.1 shows the measuring equipment that is currently covered by metrological processes.

Table 4.1: List of equipment considered

Equipment	Procedure	Periodicity	Resolution	Metrology
Freezer Cabinet	PO.M - DM/ TEMP-03 (Ed.O; Rev. 02)	Annual	0,1 ºC	Applied
Plasma Defroster	PO.M - DM/ TEMP-03 (Ed.O; Rev. 02)	Annual	0,1 ºC	Applied
Platelet Incubator	PO.M - DM/ TEMP-03 (Ed.O; Rev. 02)	Annual	0,1 ºC	Applied
Incubator	PO.M - DM/ TEMP-03 (Ed.O; Rev. 02)	Annual	0,1 ºC	Applied
Blood Fridge	PO.M - DM/ TEMP-03 (Ed.O; Rev. 02)	Annual	1 ºC	Applied
Thermostatic Bath	PO.M - DM/ TEMP-03 (Ed.O; Rev. 02)	Annual	0,1 ºC	Applied
Fridge	PO.M - DM/ TEMP-03 (Ed.O; Rev. 02)	Biannual	[0,1 ºC - 1 ºC]	Applied
Temperature Logger	PO.M - DM/ TEMP-04 (Rev. 05)	Annual	0,01 ºC	Applied
Industrial Sensor for Scanning Unit	PO.M - DM/ TEMP-02 (Rev. 07)	Annual	0,01 ºC	Applied
Radiation Thermometer	PO.M - DM/ TEMP-09 (Rev. 04)	Annual	0,1 ºC	Applied
Infusion Pump	IEC 60601-2-24	Annual	0,01 ml/h	Applied
Aneoid Sphygmomanometer	PO.M - DM/ECH05, Ed. D	Biannual	2 mm Hg	Applied
Portable Radiation Detection Monitors	LMRI_PT_03_rev8	Biannual	---	Legal
Radiation Dosemeter	---	Biannual	---	Legal

In addition to the equipment in the Immunohemotherapy and Clinical Pathology departments, there are two measuring devices in the Medical Physics department, as shown in Table 4.1, which are already covered by legal metrology.

Whenever measuring equipment covered by applied metrology undergoes a metrological operation, it must be accompanied by a calibration certificate issued by the relevant authorities. Several parameters are necessary to generate this document, as detailed in [33]:

- Title, name and address of the laboratory and the place where the calibration is conducted;
- Clear identification of all pages to ensure that it is part of the constitution of the calibration certificate;
- Customer identification;
- Identification of the used method;
- Description and identification of the calibrated measuring instrument;
- Date of calibration tests, along with results;
- Complete identification of the participants in the document validation process.

To be able to interpret the results, one will need information such as [33]:

- Conditions in which the calibration tests were conducted;
- Measurement uncertainty associated with the standard used;
- Traceability chain associated with measurements;
- If the measuring instrument needs to be adjusted or repaired, the results of the before and after procedure must be made available.

The general circuit through which the measuring equipment passes is shown in ISO 10012:2003 [40].

For equipment to be subject to metrological operations, it's necessary to make a request to the responsible entity, following the path described in Figure 4.1.

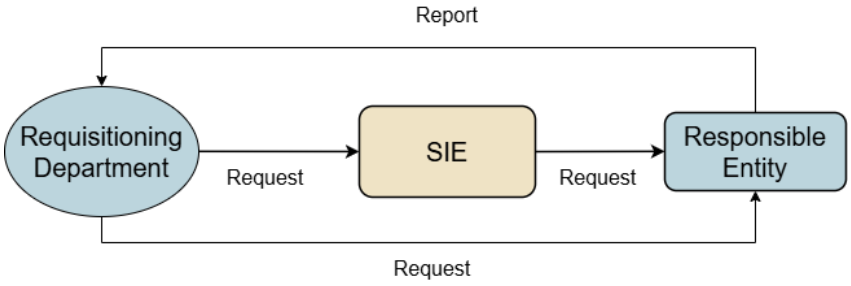


Figure 4.1: Internal procedure for requesting a metrological operation

4.2 Portugal's new metrological scenario

In 2022, Decree-Law 29/2022 was published, approving the General Regulation on the Legal Metrological Control of Measuring Methods and Instruments. This regulation defines the general characteristics, model approval procedures, periodic verification, marking of control symbols and information labels for legal metrological control of various measuring instruments, including medical equipment and devices. The Decree-Law also provides guidance on how manufacturers, repairers and users should request legal metrological control, thereby establishing general conditions to ensure the metrological quality of instruments. This document serves as the foundation for subsequent regulations published in November 2023.

4.2.1 Sphygmomanometer

Regulation no. 354/2023 [47] and Declaration of Rectification no. 1-A [48] refer to the aneroid and digital sphygmomanometers shown in Figure 4.2, which measure the blood pressure of the human body. The value measured by sphygmomanometers is expressed in SI units, which are kiloPascal (kPa) or millimeters of mercury (mmHg) [47].

(a) (b)

Figure 4.2: Types of sphygmomanometers:(a) Aneroid[1]; (b) Digital[2]

The device operates by placing a cuff around one of the upper limbs, at the level of the heart. In the case of an aneroid sphygmomanometer, the professional places a stethoscope under the cuff and inflates it until the pressure is sufficient to temporarily stop the blood flow. Deflation begins slowly, and the Korotkoff sounds can be heard, indicating the systolic (maximum arterial pressure in the arteries caused by the contraction of the ventricles) and diastolic (minimum arterial pressure caused by the filling and relaxation phase of the ventricles) values [49].

[1]Source: *https://www.flipkart.com/dr-morepen-spg-07-palm-type-aneroid-sphygmomanometer-bp-monitor/p/itmebd2z2srdaz8h*

[2]Source: *https://www.gimaitaly.com/it/assets/altreimmagini/49880.jpg*

The main diagnosis made using this equipment is hypertension, which is characterized by a systolic pressure over 140 mmHg or a diastolic pressure exceeding 90 mmHg.

To highlight the importance of metrological operations in this type of measuring equipment, a study was conducted by Turner[50]. Considering that hypertension is the most common diagnosis made using this equipment, it was concluded that overestimating the diastolic pressure by 5 mmHg increases false positives by between 102% and 166%. Conversely, underestimating the diastolic pressure by 5 mmHg results in a failure to diagnose the condition in between 57% and 67% of cases. As for systolic pressure, an overestimation of 3 to 5 mmHg increases false positives by between 24% and 43%, while underestimation in the same range results in between 19% and 30% of patients going undiagnosed.

4.2.2 Digital infrared ear thermometers

Regulation no. 367/2023 [51] and Declaration of Rectification No. 1-D [52] pertain to digital infrared ear thermometers, depicted in Figure 4.3, designed for measuring human body temperature. The readings from these thermometers are expressed in degrees Celsius (ºC) [51]. It operates by inserting the thermometer's tip into the ear canal, where an infrared sensor detects the radiation emitted by the tympanic membrane and its surroundings. This detected signal is then converted into an electrical signal, which undergoes an algorithmic process to calculate the temperature, subsequently displayed on the thermometer's screen [53].

Figure 4.3: Infrared Ear Thermometer[3]

The sole function of this measuring equipment is to measure the subject's body temperature. However, as Pušnik [54] explains, several factors can influence the obtained result, including the positioning of the thermometer and variations between users. Given

[3]Source: *https://www.hillrom.lat/pt/products/braun-thermoscan-pro-6000/*

these challenges, Pušnik [54] emphasizes the importance of implementing a proper calibration system and reinforces recommendations for users to ensure the most accurate measurements possible.

4.2.3 Tonometer

Regulation No. 368/2023 [55] pertains to tonometers, illustrated in Figure 4.4, designed for measuring human intraocular pressure. The measurements provided by the tonometer are in units of kPa or mmHg. Various types of tonometers exist, each with its specific operational mode [56]. Since this equipment is now subject to legal metrology, it must comply with the requirements stipulated in OIML R 145 [57].

Figure 4.4: Tonometer[4]

4.2.4 Instruments for measuring ionizing radiation

Ordinance No. 356/2023 [58] and Declaration of Rectification No. 1-B [59] includes instruments used for measuring ionizing radiation, specifically for Radiotherapy (Dosimeter), Nuclear Medicine (Calibrator), Radiology (Dosimeter) and Radiological Protection (Individual Monitor, Area Monitor and Contamination Monitor). These types of measuring equipment must undergo biannual checks.

Sphygmomanometers, digital infrared ear thermometers, and tonometers are now subject to legal metrological control, overseen by IPQ, which handles First Verification, Periodic Verification and Extraordinary Verification. Before being put into service, following repairs or seal breakages, this equipment must undergo a First Verification. [47] [51] [55] [58].

[4]Source: https://www.oftaltec.pt/produtos-e-equipamentos/equipamentos/diagnostico/tonometros-icar0e/novo-icare-ic100/

Periodic verification is valid for one year and must be renewed annually, while extraordinary checks occur between these periodic verifications.

Medical devices (MD) must be maintained in good repair, with inscriptions and markings compliant with metrological and technical requirements, always visible and legible.

4.3 Case study

The objective of this case study is to evaluate the implementation of two new metrological control ordinances. To achieve this, it is essential to identify the medical devices affected and assess the process they will undergo.

As part of the internship, one of the self-assigned tasks was to conduct a survey of the MD covered by regulations [47] and [51]. To accomplish this, the quality department was engaged to devise a comprehensive and reliable survey methodology, given that many of these MDs are not typically documented due to their lower value. The devised solution involved approaching Head Nurses and departmental supervisors to assist in surveying the MD within their departments. The intern created a template, as shown in Figure 4.5, to facilitate the collection of all necessary information about the MD. Information such as brand and model helped provide an estimation of the MD value within the hospital's equipment inventory.

Edifício	
Serviço	

Tipo de equipamento	Marca	Modelo	Número de serie	Localização

Figure 4.5: MD survey template

When the survey was finished, the number of MD present in the hospital was determined. It was concluded that there were 33 sphygmomanometers and 34 digital infrared ear thermometers.

After the study, a meeting was held with the Supply department. During this meeting, it was revealed that the digital ear thermometers in the IPOCFG are for counter-consumption, that is, compliance with the ordinance is the responsibility of the entity that has the counter-consumption contract.

In the following two sections, the tests to which the aneroid and digital sphygmometers are subject were reviewed. These tests were created by the OIML with the aim of standardizing the practical procedures of legal metrology.

4.3.1 Aneroid sphygmomanometers

Aneroid sphygmomanometers must follow the guidelines imposed by the OIML. For this measuring equipment, the guideline is the OIML R 148 [1], which is divided into three parts:

- **OIML R 148 - 1: Metrological and technical requirements** - it includes the terms and definitions applicable to this type of measuring equipment. It explains the metrological requirements (Table 4.2), providing the Maximum Permissible Error and the test conditions.

Table 4.2: Maximum permissible error conditions for aneroid sphygmomanometers

		Temperature	Relative Humidity	Maximum Permissible Error (MPE)
Ambient conditions		15 to 25 ºC	15 to 85 %	±0.4 kPa (±3 mmHg)
Storage conditions	Without electronic components	24 hours at -20 ºC followed by 24 hours at 70 ºC	85 % (at 70ºC)	±0.4 kPa (±3 mmHg)
	With electronic components	24 hours at -5 ºC followed by 24 hours at 50 ºC	85 % (at 50ºC)	±0.4 kPa (±3 mmHg)
Varying temperature conditions		10 to 40 ºC	85%	±0.4 kPa (±3 mmHg) or ±2 % of the reading, whichever is greater

It also presents the technical requirements (Table 4.3), which outline the technical limits for its design, construction and use.

Table 4.3: Technical conditions for aneroid sphygmomanometers

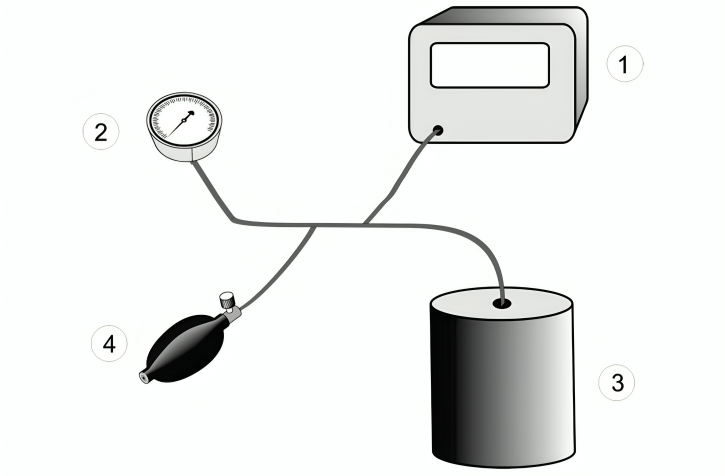
	Maximum permitted
Air leakage	0,5 kPa/min (4mmHg/min)
Pressure reduction rate	0,3 kPa/s to 0,4 kPa/s (2 mmHg/s to 3 mmHg/s)
Rapid exhaust	10 s
Hysteresis error	0 kPa to 0,5 kPa (0 mmHg to 4 mmHg)

Finally, it specifies the marking and labeling requirements for this type of measuring equipment.

- **OIML R 148 - 2: Test procedures** - although sphygmomanometers are simple to operate and build, a number of tests are required to ensure that they are working as expected. The tests that sphygmomanometers undergo include:

1. **Test for maximum permissible errors of the cuff pressure indication**

   For this test, shown in Figure 4.4, the cuff is replaced by a metal container represented by the number three in Figure 4.4. Connect the reference device and the sphygmomanometer being tested using a T-connector. Then, connect the pressure generator using another T-connector. The test is conducted between 0 mmHg and the maximum value on the scale, with increments of less than 50 mmHg. The differences between the device being tested and the reference device are recorded.



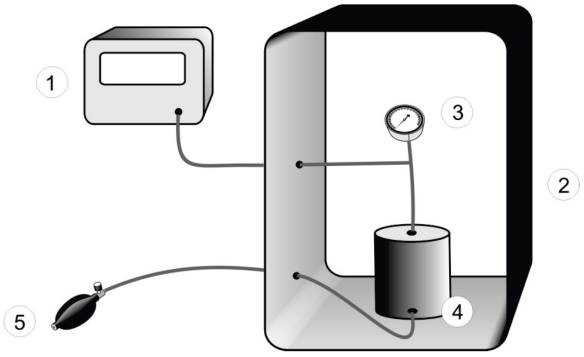
1 – Reference manometer; 2 – Manometer of the device to be tested;
3 – Metal vessel; 4 – Pressure generator

Table 4.4: Test procedure on aneroid sphygmomanometers [1]

2. **Test for maximum permissible errors of the cuff pressure indication under varying temperature conditions**

   The procedure for this test is similar to test one, with a change in the test conditions, as shown in Figure 4.6. Three tests are conducted, each test lasting at least 3 hours in the climate chamber represented by the number two in Figure 4.6, with the following conditions: 10 ºC ambient temperature and 85% relative humidity, 20 ºC ambient temperature and 85% relative humidity and 40 ºC ambient temperature and 85% relative humidity.

   The differences between the equipment being tested and the reference equipment are recorded in the temperatures of each test.



1 – Reference manometer;2 – Climatic chamber
3 – Manometer of the device to be tested;4 – Metal vessel
5 – Pressure generator

Figure 4.6: Test procedure on aneroid sphygmomanometers with varying temperatures [1]

3. **Test for maximum permissible error of the cuff pressure indication under storage conditions**

   This test is only applied to sphygmomanometers that are still in their original packaging. To conduct this test, tests one and two are combined. The equipment is placed in the conditions shown in 4.6, for one hour at 20 ºC and a relative humidity of 60 % and then test one is carried out. The differences between the equipment being tested and the reference equipment are recorded.

4. **Test for air leakage of the pneumatic system**

   Place the cuff around a cylinder of the appropriate size. Conduct the test over at least three equally spaced pressure ranges, testing for air leakage over a period of 5 minutes to determine the measured value. Finally, present the result as the rate of pressure loss per minute.

5. **Test for pressure reduction rate for deflation valves**

   Connect the reference pressure gauge to the cuff with a T-connector, and connect the output of the calibrated reference pressure gauge to the recording unit. The test should be carried out at three pressure values: 8 kPa (60 mmHg), 16 kPa (120 mmHg) and 24 kPa (180 mmHg).

   As the deflation rate can be influenced by the way the cuff is applied, a repeatability test should be conducted with at least 10 repeat measurements and in two different sizes.

   For this test, either human or artificial limbs are required, but artificial limbs are recommended.

The pressure reduction should be graphed as a function of pressure versus time. The rate of pressure reduction is calculated separately from the average value of the three pressure values and the different sizes.

6. **Test for rapid exhaust**

   In this test, the cuff is replaced with a container. The reference pressure gauge is then connected to the pneumatic system of the sphygmomanometer using a T-connector. The system is inflated to maximum pressure and then quickly released. The result is the time taken for the pressure to reduce from the maximum value to zero.

7. **Test for scale spacing and thickness of the scale marks**

   Using a graduated lens, the thickness of the scale marks and their spacing are determined in at least three different areas of the gauge.

8. **Test for security against mercury losses**

   Place the equipment to be tested in a collection container, connect the reference pressure gauge to the hose leading to the mercury tank, and switch on the pressure generator. Using the pressure generator, increase the pressure by 100 mmHg relative to the maximum reading indicated on the scale, maintain this pressure for 5 seconds, and then release the pressure. After this test, check for any mercury spillage.

9. **Test for the influence of the mercury stopping device**

   Connect the pressure generator to the tube that connects directly to the mercury reservoir. Increase the pressure until it exceeds 200 mmHg, then remove the connection tube and pressure generator. The result is obtained by measuring the time taken for the pressure to decrease from 200 mmHg to 40 mmHg.

10. **Test for the hysteresis error of aneroid manometer**

    Place the cuff around the container, then connect the reference pressure gauge to the pneumatic system with a T-connector, and connect an additional pressure generator to the same connection. Conduct the test in increasing increments of no more than 50 mmHg up to the maximum of the scale. After reaching the maximum, reverse the steps. The result is obtained from the difference between the pressure values during the increasing test and the decreasing test.

11. **Test for durability of aneroid manometers**

    Repeat test number one. Connect the sphygmomanometer to an alternating pressure generator and take 10,000 repetitive measurements, where one repetitive measurement ranges from 20 mmHg to the top of the scale and

back to 20 mmHg. After completing this test, wait 1 hour and repeat test number one to check for any differences. The result is given by the variation in the deflation and inflation values.

12. **Test for mechanical safety**

    This test is subdivided into two parts: the vibration and shock resistance test, where the sphygmomanometer must function normally after a free fall of 25 cm. To obtain the "Shock Resistant" indication, it must function normally after a fall of 1 meter. This test is repeated six times.

    The next test is for a sphygmomanometer with mercury pressure gauges, where the sphygmomanometer is dropped from a height of 1 meter, and repeated six times. Throughout the test, it should be checked that there is no mercury leakage, and after the test has finished, a visual inspection should be made to ensure there is no leakage.

13. **Test for durability of markings**

    For this test, it is necessary to rub the marks on the equipment, without excessive pressure, first for 15 seconds with a cloth containing distilled water, then for 15 seconds with a cloth containing methylated alcohol, and finally for 15 seconds with a cloth containing isopropyl alcohol.

    The adhesives must not become loose or curl at the edges.

It should be noted that only sphygmomanometers with mercury pressure gauges perform the related mercury tests, while the other sphygmomanometers skip this test.

- **OIML R 148 - 3: Test report format** - a template is presented describing the equipment and the purpose of the report, the test conditions to which the equipment was subjected and the reference methods and equipment used.

  The results of the tests are summarized, and an assessment is made of the performance and conformity of the tested equipment. Ultimately, it is a document that serves as a template to standardize evaluation reports.

4.3.2 Digital sphygmomanometers

Digital sphygmomanometers, like aneroid sphygmomanometers, are also subject to guidelines, the OIML R 149 [5].

OIML R 149 - 1: Metrological and technical requirements - the terms and definitions applied to this type of measuring equipment are established. The metrological requirements (Figure 4.7) are explained, from the maximum permissible error to the test conditions. In addition, technical conditions are presented, which establish the

technical limits from design to usage. Finally, the marking and labeling requirements for this measuring equipment are also specified.

	Temperature	Relative Humidity	Maximum Permissible Error (MPE)
Ambient conditions	10 to 40 ºC	15 to 85 %	±0.4 kPa (±3 mmHg)
Storage conditions	24 hours at -5 ºC followed by 24 hours at 50 ºC	85 % (at 70 ºC)	±0.4 kPa (±3 mmHg)

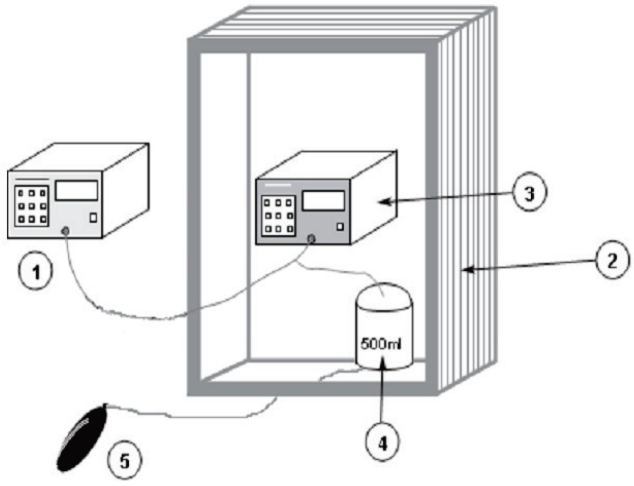
Figure 4.7: Maximum Permissible Error for digital sphygmomanometers

OIML R 149 - 2: Test procedures - although sphygmomanometers are simple to operate and set up, several tests are required to ensure they are working as expected. The tests that digital sphygmomanometers undergo are:

1. **Test for maximum permissible errors of the cuff pressure indication**

   This test is subdivided into two: environmental conditions and storage conditions.

   For the first test, place the cuff around the container, then connect the reference pressure gauge to the pressure gauge of the device under test using a T-connector. This assembly will connect to the pneumatic system, as shown in Figure 4.8. The equipment is put into test mode, according to the manufacturer's recommendations.



1 – Reference manometer; 2 – Climatic chamber;
3 – Device to be tested; 4 – Metal vessel; 5 – Pressure generator

Figure 4.8: Test procedure on automatic sphygmomanometers [5]

The additional pressure system is connected to the pressure system to aid the process. The test starts gradually and constantly, on a scale of no more than 50

mmHg, between the minimum and maximum values on the scale. For the environmental conditions test, 3 tests are conducted. Each test lasts at least 3 hours in the climate chamber, represented by the number 2 in Figure 4.8, with the following conditions: 10 ºC ambient temperature and 85% relative humidity, 20 ºC ambient temperature and 85 % relative humidity and 40 ºC ambient temperature and 85 % relative humidity.

In each combination of temperature and humidity, it's essential to wait for the sphygmomanometer to reach its operating temperature before starting the tests.

In storage conditions, the thermometer is subjected for 24 hours to a temperature of -5 ºC and immediately after it is subjected for 24 hours to 50 ºC. After this period, the ambient conditions test is repeated. For these two tests, the result is obtained from the difference between the reference pressure gauge and the equipment being tested.

2. **Test for blood pressure measurement range**

   A cuff is placed on a patient simulator so that the sphygmomanometer displays diastolic blood pressure values equal to or less than 20 mmHg and systolic blood pressure values equal to or greater than 110 mmHg. The result is obtained by visually confirming the values obtained by the equipment.

3. **Test for repeatability of blood pressure indication**

   Connect the sphygmomanometer and the patient simulator which is set to the target values for systolic and diastolic blood pressure (Figure 4.9). Perform twenty repetitions at temperatures between 10 ºC and 40 ºC and relative humidity between 15 % and 85 %.

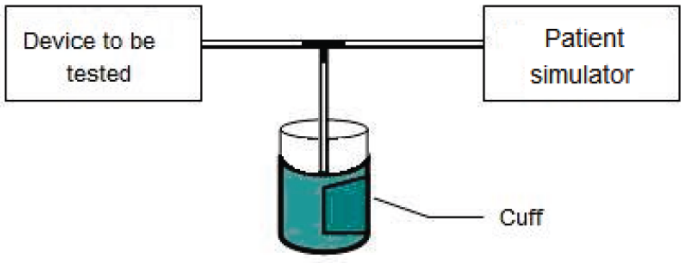


Figure 4.9: Setup to test [5]

The result on blood pressure repeatability is calculated from Equation 4.1:

$$r_{\mathrm{S(D)}} = \sqrt{\frac{\sum_{i=1}^{n} \left(\bar{L}_{\mathrm{S(D)}} - L_{\mathrm{S(D)}_i}\right)^2}{n-1}} \tag{4.1}$$

Where $\bar{L}_{\mathrm{S(D)}}$ is the repeatability of the visualized value of systolic or diastolic blood pressure; $L_{\mathrm{S(D)}_i}$ is the systolic or diastolic blood pressure value at the i-th measurement; $\mathrm{S(D)}$ is the average systolic or diastolic blood pressure of the equipment; and lastly n is the number of measurements.

4. **Test for effect of voltage variations of the power source**

   This test is subdivided into five different tests:

   Internal power supply - where the procedure involves replacing the internal power supply with a power supply that has an impedance equivalent to the one specified by the manufacturer, measuring the voltage variation with a voltmeter. Then, test the equipment by alternating the voltage in 0.1 V increments to determine the lowest voltage threshold at which the arterial voltage indication continues to appear. Carry out test number one only at an ambient temperature of 20 ºC and ambient relative humidity, with a 0.1 V increase and also at the nominal voltage. The results are obtained by measuring the difference between the blood pressure indication of the equipment being tested and the readings of the reference pressure gauge at the lower limit of voltage, increasing by 0.1 V.

   External power supply - alternating current - this procedure involves connecting the sphygmomanometer to the adjustable high current source and measuring the voltage variation using a voltmeter. Test number one is repeated, but only at an ambient temperature of 20 ºC and relative humidity, using the maximum voltage supplied by the manufacturer, as well as the maximum and minimum nominal voltage values supplied by the manufacturer. The result will be the difference between the values of the equipment being tested and the reference pressure gauge.

   External power supply - direct current - in this procedure it's necessary to connect the equipment to the direct current source and monitor it with a voltmeter. Test number one is repeated, but only at 20 ºC ambient temperature and relative humidity, with the conditions of maximum nominal voltage and maximum and minimum average voltage value indicated by the manufacturer. The result will be the difference between the values of the equipment being tested and the reference pressure gauge.

   Voltage fluctuations from the external power supply - alternating current - in this procedure, it's necessary to connect the equipment to the adjustable alternating current source and measure the voltage with a voltmeter. The voltage is then adjusted in increments of 5 V to determine the minimum value for the blood pressure indication. Test number one is repeated, but only at 20 ºC ambient temperature and relative humidity at the limit of the lowest voltage, adding 5 V. The result is the difference between the blood pressure indication of the equipment being tested and the readings of the reference pressure gauge at the lower limit

of voltage, increasing incrementally by 5 V.

Voltage variations from the external power supply - direct current - in this procedure, it's necessary to connect the equipment to the direct current source and monitor it with a voltmeter. The voltage is then adjusted in increments of 0.1 V to determine the minimum value for indicating blood pressure. Test number one is repeated, but only at 20 ºC ambient temperature and ambient relative humidity at the limit of the lowest voltage, adding 0.1 V. The result is the difference between the blood pressure indication of the equipment being tested and the readings of the reference pressure gauge at the lower voltage limit, increasing incrementally by 0.1 V.

5. **Test for air leakage of the pneumatic system**

   Before the test begins, allow the measuring equipment to reach operating temperature. Place the cuff around the metal container. Conduct the tests in at least 3 equally spaced ranges, for example 50 mmHg, 150 mmHg and 250 mmHg. Check for air leakage over a period of 5 minutes and calculate the average value. The result is expressed as a loss rate per minute.

6. **Test for pressure reduction rate of devices using the auscultatory method**

   Connect the reference pressure gauge via a T-connector to the cuff and the recording unit. The deflation rate can be influenced by the way the cuff is fitted. To verify this influence, a repeatability test is performed with a duration of at least 10 measurement repetitions and with 2 different cuff sizes. This test is performed on a person or on a patient simulator. The test should be carried out in 3 equally spaced ranges, for example 60 mmHg, 120 mmHg and 180 mmHg. The pressure reduction should be plotted as a curve as a function of pressure versus time. The rate of pressure reduction is calculated separately from the average value of the three pressure values and the different sizes.

7. **Test for rapid exhaust**

   Replace the cuff with a metal container and connect the reference pressure gauge to the pneumatic system. Inflate to the maximum point, wait 60 seconds, and then activate the exhaust valve, noting the time elapsed during deflation.

8. **Test for zero adjustment of a measuring system**

   To start the procedure, apply a pressure of +6 mmHg and then -6 mmHg to the pneumatic system and turn on the equipment's autoregulator. Check that the measurement values show a systematic error of +6 mmHg and -6 mmHg.

   Replace the cuff with a metal container and connect the reference pressure gauge to the pneumatic system, then insert a pressure/suction pump and a pressure generator into the pneumatic system.

Next, self-adjust to 0 on the sphygmomanometer, after self-adjustment increase the pressure to 100 mmHg and record the value shown, then increase +6 mmHg and self-adjust again, and repeat the previous process, with the expected value being 6 mmHg. Finally, decrease -6 mmHg and self-adjust, eventually increasing the pressure to 100 mmHg, with the expected value being 6 mmHg.

9. **Test for instrumental drift of the cuff pressure indication**

   Place the cuff around the metal container and connect the reference pressure gauge to the pneumatic circuit simulator using a T-connector. Before starting the test, allow the sphygmomanometer to reach its operating temperature, which is indicated in the instructions for use. Then take the measurement and time it until it switches off automatically. Switch the sphygmomanometer back on, set it to test mode and apply a pressure of 50 mmHg. Repeat test number one, but only at a temperature of 20 ºC $\pm$ 5 ºC and ambient humidity, and start the stopwatch. The result is obtained by varying the pressure indication on the cuff during the time interval.

10. **Test for maximum time for which the cuff is inflated**

    Place the sphygmomanometer cuff on a person or a patient simulator, and simultaneously start a repeat measurement and the stopwatch. Prolong the measurement as much as possible by, for example, moving the limb or manually blocking the deflation valve.

11. **Test for durability**

    Repeat test number one, but only at a temperature of 20 ºC $\pm$ 5 ºC and at ambient humidity. Carry out 10,000 repetitions of simulated measurements, reaching a pressure of at least 150 mmHg. The result is the difference between before and after the 10,000 repeat measurements, under the same conditions.

12. **Test for signal input and output ports**

    Replace the cuff with a metal container and connect the reference pressure gauge to the pneumatic system via a T-connector. Then increase the pressure to 100 mmHg and record the value. Repeat this test, this time short-circuiting all the contacts on the input and output ports.

    Finally, increase the pressure again to 100 mmHg, and this time set all the sphygmomanometer contacts to the maximum voltage allowed by the manufacturer. The result is obtained by comparing the tests.

13. **Test for cuff pressure deflation following an aborted measurement**

    Put the sphygmomanometer cuff on a person or a patient simulator, start the blood pressure test and stop the test. Start the test again and stop it while the pressure is reducing. If possible, repeat the test under the same conditions. The

result is obtained by visually checking that the quick space is active.

14. **Test for resistance to vibration and shock**

    For this test, the shock test should be carried out in accordance with IEC 60068-2-27:2008 Environmental testing - Part 2-27:Tests - Test Ea and the guidance:Shock using test 1 or 2. For the vibration test, IEC 60068-2-64:2008 Environmental testing part 2-64:Test - Test Fh must be followed. After these tests, the sphygmomanometer must comply with the permitted temperature range of 20ºC $\pm$ 5ºC.

15. **Test for durability of markings**

    For this test, it is necessary to rub the marks on the equipment, without exerting excessive pressure, first for 15 seconds with a cloth containing distilled water, followed by 15 seconds with a cloth containing methylated alcohol, and finally 15 seconds with a cloth containing isopropyl alcohol.

    The adhesives must not become loose or curl at the edges.

OIML R 149 - 3: Test report format - this template describes the equipment and the purpose of the report. It details the test conditions to which the equipment was subjected, as well as the methods and reference instruments used. It includes a summary of the test results and an assessment of the equipment's performance and conformity. It aims to standardize and improve the transparency of the process.

4.3.3 Discussion

The research conducted into which metrological tests are performed on sphygmomanometers, both aneroid and digital, is unclear regarding which tests are carried out for each type of verification.

Although Declaration of Rectification no. 1-A [48] only contains OIML R 148, with some research it was possible to find OIML R 149, which is specific to digital sphygmomanometers.

In addition to the maintenance costs associated with this type of equipment, the need to perform these tests entails additional expenses. These additional costs are not included in this report due to the limited data available, but it would be useful to evaluate the economic impact of these measures.

5 Life Cycle Cost

This chapter provides a holistic analysis of the life cycle of Tomotherapy at the IPO. The associated costs, benefits and rates are analyzed and applied to replacement and depreciation models.

5.1 Equipment information

The concept of Tomotherapy (Figure 5.1), which stands for "slice therapy" [6], was developed at the end of the 1980s by a group led by Thomas R. Mackie [60]. This new method was initially not well received due to some limitations in its process. A Tomotherapy system is a helical radiation dose delivery system, using a linear accelerator that rotates around the patient. It is characterized by the adaptation of the treatment to the movement of the tumor. Some of its advantages include [60] [6]:

- Possibility of adjusting the treatment plan after each treatment session;
- Possibility of checking the three-dimensional positioning of the patient in real-time;
- Modulation of radiation intensity by moving the Linear Accelerator and Multileaf Collimator (MLC) around the patient;
- Simplicity of treatment.

Figure 5.1: Equipment present at IPO

At IPO, Tomotherapy was installed on February 26th 2016 in the Radiotherapy building, on the treatment floor. Table 5.1 presents some information about Tomotherapy,

such as the purchase price [61] and expected lifetime.

Table 5.1: Equipment information

Designation	Tomoterapy System
Brand	XPTO
Model	TOXP
Serial Number	110569
Value of acquisition	2 648 000,00 €
Cession Value	30 000,00 €
Warranty	2 years
Life span (years)	16

The value of the disposal of the equipment was obtained through a meeting with one of the maintenance technicians of the company contracted for the maintenance. In this meeting, through the available documentation, it was concluded that the value of the disposal will be the value shown in Table 5.1.

5.2 Adjacent equipment components

In order for the Tomotherapy to perform as expected, components and adjacent systems are required. To make this brief characterization, an internal document supplied by the maintenance department was used.

Components

- Gantry - system of mechanisms for rotating the linear accelerator around the patient;
- Linear accelerator - directs the beam of high-energy electrons at the tungsten target, causing high-energy photons to be used for treatment and image acquisition;
- MLC - made up of a set of plates that have only 2 positions, either open or closed, which will allow intermittent radiation to hit the patient;
- Jaws - opening and closing device in 3 possible opening angles to allow radiation to pass from the linear accelerator to the MLC;
- Treatment table - where the patient lies, positioned to undergo treatment.

Adjacent systems

- Planning station - used to plan the course of the treatment, from the expected dose to real-time treatment changes;
- RDS software - responsible for connecting the data acquisition system, data receiver and gantry positioning control system;

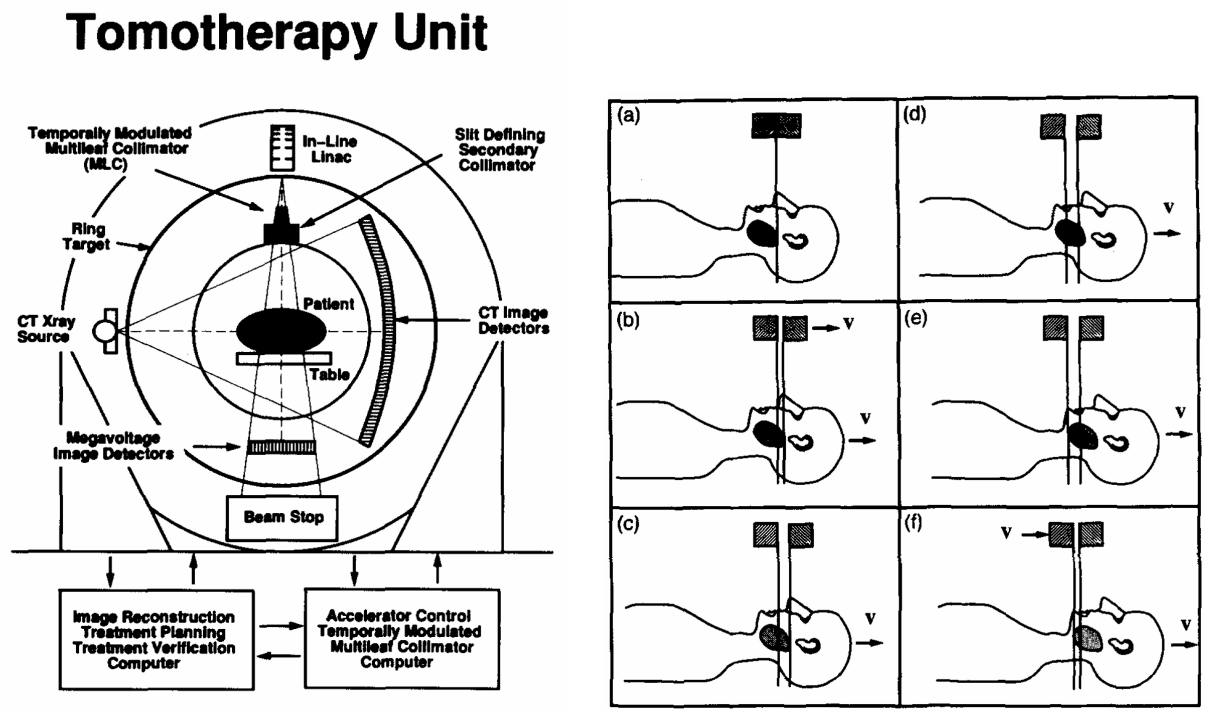
- Optimization servers - optimize treatment plans and the most appropriate doses;
- Data servers - store all the information relating to each patient's treatment plan.

5.3 Functioning mode

Assuming that the patient is undergoing treatment for the first time, he or she will have to undergo a Computed Tomography (CT) scan. There, the tumor is observed and outlined, so that the specific planning regarding the patient can then determine the best way to proceed with the treatment. The scan also helps medical physicists to calculate the dose of radiation per treatment and the size of the field that will be used.

To start the treatment (Figure 5.2a), the patient is placed on the Tomotherapy table, where a Megavoltage Computed Tomography (MVCT) is performed, so that the patient's position matches the images taken on the day of planning. After the MVCT has been carried out, if the patient is not positioned according to the initial images, they are positioned accordingly. The treatment begins with the start of the gantry rotation, where the radiation is emitted constantly.

The table moves into the gantry and the MLC, through pneumatic actuators, allows the radiation to reach the patient, thus administering the radiation dose as shown in Figure 5.2b [62].



(a) (b)

Figure 5.2: Operating mode :(a) Illustration of Tomotherapy (b) MLC functioning diagram [6]

The end of the patient's treatment is reached when the treatment zone is exceeded. Then, the gantry stops, after which the patient can leave the treatment table and the preparations for a new treatment can begin.

5.4 Depreciation models

To calculate the replacement models, the depreciation methods must be calculated previously. There are several depreciation methods, all of which work similarly, that is, there is an initial value (acquisition value) and the goal is to reach a final value (disposal value) at the end of several years (lifetime). Each different method thus seeks to calculate how the depreciation curves will behave. For this situation, the linear, exponential, sum of digits and inverse sum of digits methods are considered [3].

- Linear method

  This method uses a constant depreciation rate, d, obtained from Equation 5.1, resulting in a value of 201 690,00 €. Table 5.2 shows the disposal value, V_n obtained from Equation 5.2, for each year of the equipment's life cycle.

$$d = \frac{C_0 - R}{N} \tag{5.1}$$

$$V_n = C_0 - (n \times d) \tag{5.2}$$

  Where:
  d - Annual depreciation value
  C_0 - Initial value of equipment
  R - Residual value of equipment after N time intervals
  N - Time interval corresponding to R
  n - Period of time below N
  V_n - Value of equipment at a certain period of time (n)

Table 5.2: Linear method

Linear			
Year		d	Vn
0	2016	163 625,00 €	2 648 000,00 €
1	2017		2 484 375,00 €
2	2018		2 320 750,00 €
3	2019		2 157 125,00 €
4	2020		1 993 500,00 €
5	2021		1 829 875,00 €
6	2022		1 666 250,00 €
7	2023		1 502 625,00 €
8	2024		1 339 000,00 €
9	2025		1 175 375,00 €
10	2026		1 011 750,00 €
11	2027		848 125,00 €
12	2028		684 500,00 €
13	2029		520 875,00 €
14	2030		357 250,00 €
15	2031		193 625,00 €
16	2032		30 000,00 €

- Exponential method

  For the exponential method, depreciation begins to decrease slowly, then rapidly, decreasing slowly again at the end. To calculate the depreciation rate, T, Equation 5.3 is used, resulting in a value of 0.2539. To calculate the disposal value, V_n, Equation 5.4 is used, where the annual values are shown in Table 5.3.

$$T = 1 - \sqrt[N]{\frac{R}{C_0}} \tag{5.3}$$

$$V_n = C_0 \times (1 - T)^n \tag{5.4}$$

Where:
V_n - Value of equipment at a certain period of time (n)
T - Annual depreciation value

Table 5.3: Exponencial method

Exponential			
Year		T	Vn
0	2016	0,2442	2 648 000,00 €
1	2017		2 001 270,00 €
2	2018		1 512 493,06 €
3	2019		1 143 091,76 €
4	2020		863 910,59 €
5	2021		652 914,79 €
6	2022		493 451,20 €
7	2023		372 933,94 €
8	2024		281 851,02 €
9	2025		213 013,60 €
10	2026		160 988,56 €
11	2027		121 669,78 €
12	2028		91 953,96 €
13	2029		69 495,73 €
14	2030		52 522,56 €
15	2031		39 694,79 €
16	2032		30 000,00 €

- Sum of digits method

  In the method shown in Table 5.4, depreciation is high in the initial years and gradually decreases over the years. To calculate depreciation, it is first necessary to calculate the SD, shown in Equation 5.5, then the annual depreciation value, d, using Equation 5.6. It should be noted that every year, the value d will be a different value. Finally, the annual disposal value, V_n, is calculated from Equation 5.7.

$$SD = \frac{N(N+1)}{2} \tag{5.5}$$

$$d_n = \frac{N-(n-1)}{SD} \times (C_0 - R) \tag{5.6}$$

$$V_n = V_{n-1} - d_n \tag{5.7}$$

Where:

d_n - Annual depreciation value
V_{n-1} - Value of equipment from the previous period of time (n)

Table 5.4: Sum of digits method

Sum of digits				
Year		SD	d	Vn
0	2016	136	327 250,00 €	2 648 000,00 €
1	2017		308 000,00 €	2 340 000,00 €
2	2018		288 750,00 €	2 051 250,00 €
3	2019		269 500,00 €	1 781 750,00 €
4	2020		250 250,00 €	1 531 500,00 €
5	2021		231 000,00 €	1 300 500,00 €
6	2022		211 750,00 €	1 088 750,00 €
7	2023		192 500,00 €	896 250,00 €
8	2024		173 250,00 €	723 000,00 €
9	2025		154 000,00 €	569 000,00 €
10	2026		134 750,00 €	434 250,00 €
11	2027		115 500,00 €	318 750,00 €
12	2028		96 250,00 €	222 500,00 €
13	2029		77 000,00 €	145 500,00 €
14	2030		57 750,00 €	87 750,00 €
15	2031		38 500,00 €	49 250,00 €
16	2032		19 250,00 €	30 000,00 €

- Inverse sum of digits method

  The method described in Table 5.5 is the inverse of the one mentioned above, with depreciation being low in the initial years and gradually increasing over the years. The SD is calculated according to Equation 5.5, then the depreciation, d, is calculated from Equation 5.8, with the depreciation value always being different. Finally, the disposal value, V_n is calculated from Equation 5.7.

$$d_n = \frac{n}{SD} \times (C_0 - R) \tag{5.8}$$

Table 5.5: Inverse sum of digits method

Inverse Sum of Digits				
Year		SD	d	Vn
0	2016	136	- €	2 648 000,00 €
1	2017		19 250,00 €	2 628 750,00 €
2	2018		38 500,00 €	2 590 250,00 €
3	2019		57 750,00 €	2 532 500,00 €
4	2020		77 000,00 €	2 455 500,00 €
5	2021		96 250,00 €	2 359 250,00 €
6	2022		115 500,00 €	2 243 750,00 €
7	2023		134 750,00 €	2 109 000,00 €
8	2024		154 000,00 €	1 955 000,00 €
9	2025		173 250,00 €	1 781 750,00 €
10	2026		192 500,00 €	1 589 250,00 €
11	2027		211 750,00 €	1 377 500,00 €
12	2028		231 000,00 €	1 146 500,00 €
13	2029		250 250,00 €	896 250,00 €
14	2030		269 500,00 €	626 750,00 €
15	2031		288 750,00 €	338 000,00 €
16	2032		308 000,00 €	30 000,00 €

The inverse sum of digits method was selected in addition to traditional methods due to its appropriateness for situations where technological obsolescence is of interest [13].

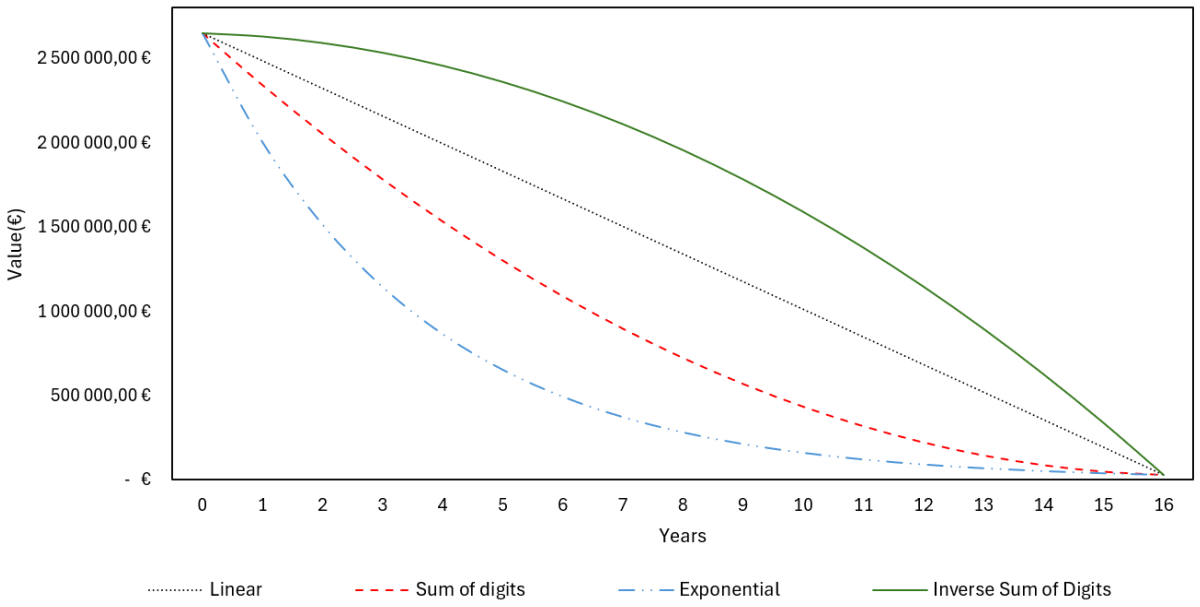


Figure 5.3: Comparison between different depreciation methods

The methods detailed above are shown in Figure 5.3. To understand which one best reflects the reality of the situation, the seller of the equipment was contacted to evaluate if it would be possible to have a value of annual depreciation to compare to a single method. The response did not allow for this to be clarified, claiming that it would be necessary to conduct an in-depth study of the status of the components.

5.5 Costs

To implement the LCC, it is necessary to do a complete and integrated assessment of all costs associated with Tomotherapy, from its acquisition to its disposal, regardless of whether it has reached the end of its life or not. This assessment will allow us to forecast what these costs will be using historical data on the equipment, thus allowing them to be applied to replacement models, and allowing for more strategic decisions to be made. The associated costs can be broken down as follows:

5.5.1 Functioning costs

Operating costs include all costs associated with operating the equipment, such as energy, which will depend on the price of kWh, system efficiency and downtime; and labor, which includes the salary costs of the equipment workers.

- **Energy costs**

  Since the consumption of each equipment is not documented, it was suggested that amperemeter clamps should be placed on the Tomotherapy panel over the course of a week. This way, it would be possible to get an overview of the weekly

Table 5.6: Electricity consumption during a week

	Weekdays	Saturday	Sunday
Hours of Peak	366,06 kWh	0 kWh	0 kWh
Hours of Full	968,76 kWh	22,1 kWh	0 kWh
Hours of Normal Empty	47,5 kWh	40,97 kWh	63,46 kWh
Hours of Super Empty	63,56 kWh	12,65 kWh	12,64 kWh

Table 5.7: Estimated annual electricity consumption

	Weekdays	Saturday	Sunday
Hours of Peak	19 026,50 kWh	0 kWh	0 kWh
Hours of Full	50 375,53 kWh	1 149,01kWh	0 kWh
Hours of Normal Empty	2 470,04 kWh	2 130,70 kWh	3 300,09 kWh
Hours of Super Empty	3 305,01 kWh	654,81 kWh	657,09 kWh

consumption, which is shown in Table 5.6.

The equipment operating mode is constant, that is, its operating cycle is similar throughout the weeks. This means that to get an idea of the equipment's annual consumption, the values collected in a week were multiplied by 52 to obtain an estimate of the annual consumption, as shown in Table 5.7. Since the equipment is in the hospital field, since 2016, it was assumed that the consumption value was constant over the years. The year 2016 is an exception because it went into service on April 16th. Thus, that year, only 37 weeks were considered. Although this is only an approximation of the real value and is subject to error, it allows for an understanding of the energy cost.

To calculate the value of the electricity bill, over the years the following formulas have been used:

$$Invoice = T_f + T_p + E_a + E_r + VAT \tag{5.9}$$

$$T_p = \frac{\text{kWh P}}{\text{n}} \times \text{€/kWh P} + kW\,\text{C} \times \text{€}/kW\,\text{C} \tag{5.10}$$

$$E_a = \sum \text{€/kWh T} \times \text{kWh T} \tag{5.11}$$

$$E_r = \sum €/\text{kVAh TC} \times \text{kVAh TC} \tag{5.12}$$

Where:

T_f - Fixed tariff term,
T_p - Power charges (contracted (C) and peak hours (P)),
E_a - Charges for active energy consumed;
E_r - Charges for reactive energy consumed;
T - Types of hours (Peak, Full, Normal Empty, Super Empty)[63]);
TC - Type of consumption (Inductive or Capacitive)
VAT - Value Added Tax;
n - Number of total hours

The contracted kW cannot be fully attributed to the equipment, so in order to calculate the impact that the equipment has on the contracted power, a study of the terms of reference was conducted to ascertain the maximum power of the equipment, which is 48 kW. To calculate the direct power to the equipment, the total contracted power, which is 1100 kW, is taken into account and the following equation is applied: $\frac{48\text{kW}}{1100\text{kW}} \times 100 = 4.36\%$.

This means that in the T_p formula, in the contracted power portion, the value of 4.36 % must also be multiplied so that only the impact corresponding to the equipment is considered.

For the costs of the various elements present in the equations for calculating the invoices, a study was conducted on the invoices from 2016 to 2023 to obtain the value of each element over the years. For data protection and confidentiality reasons, the final outcome shown in Figure 5.4 has been multiplied by an x factor.

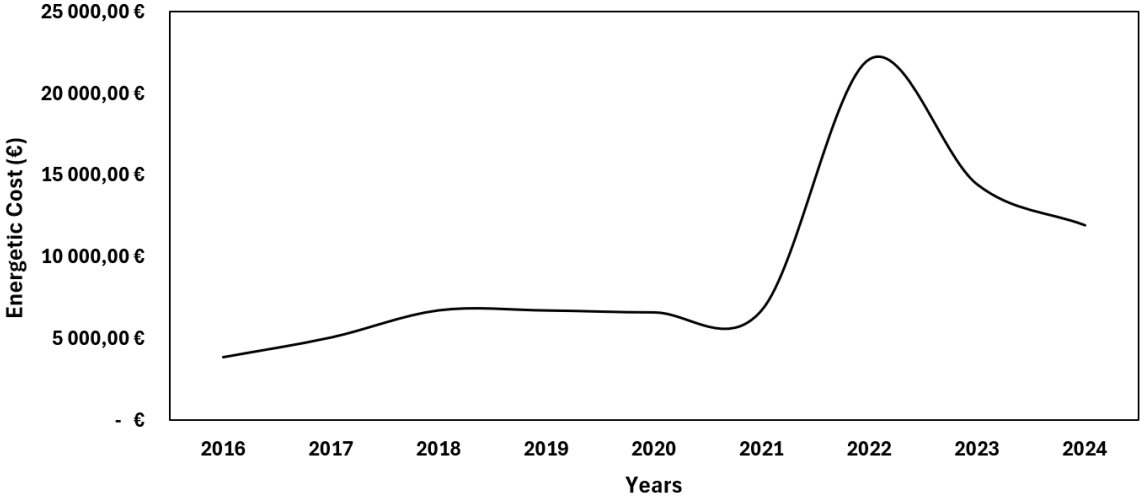


Figure 5.4: Evolution of the energy invoice value over the years

```python
# Importing libraries
import pandas as pd
from statsmodels.tsa.arima.model import ARIMA

# Convert the data to a temporal serie
FC = [430537.83, 219900.93, 288476.26, 231879.81, 241559.23, 264024.70, 278919.87, 291395.73]
QW = pd.Series(FC)

# Fitting the ARIMA model
model = ARIMA(QW, order=(1, 1, 1))
model_fit = model.fit()

# Forecast for the next 8 periods
forecast = model_fit.forecast(steps=8)

forecast
```

Figure 5.5: Code developed for forecasting values for functioning costs

The hospital is not charged for reactive energy, due to the fact that they have strategically installed capacitors, which allow for the internal production of reactive energy, therefore correcting the power factor, increasing energy efficiency and reducing energy charges.

- **Wages costs**

  As labor is essential for the operation of the equipment, it is an expense that is incorporated into operating costs. Labor costs include not only wages but also the cost of training and overtime [64]. In this case, to acquire the costs, Human Resources was asked to compile an average salary for each category of professional from 2015 to 2024. In order to understand the number of people involved and their professional categories in the Tomotherapy treatment process, meetings were held with the department director. The final amounts are multiplied by a factor of x for the purpose of information protection and confidentiality.

In order to forecast the values of the functioning costs from 2025 to 2032, the Auto-Regressive Integrated Moving Average (ARIMA) algorithm shown in Figure 5.5 was used, which serves as a statistical model for forecasting time series where there are no non-linear patterns [65].

It is divided into three parts: AutoRegressive, which creates a relationship between an observation and a fixed number of previous observations; Integrated, which removes trends that could affect the analysis; and finally Moving Average, which creates a relationship between an observation and the residual error of the moving averages of previous observations.

5.5.2 Maintenance costs

Every maintenance performed on the Tomotherapy is under a maintenance contract with the company that supplied the equipment, which has the highest level of knowl-

edge of the equipment. Maintenance contracts have been signed between the two organizations on an annual basis, where there is always an update on the services provided or the annual value. The maintenance contract is global, including labor, spare parts and remote support. In the terms of reference, there is a clause limiting the maximum value of the maintenance contract, which may not exceed 7.5 % of the value of the overall proposal [61].

To forecast the maintenance cost from 2025 to 2032, it was assumed that the costs would behave like a bathtub curve. There are various bathtub curves adapted for different types of equipment, but in this case, there is no specific bathtub curve for the Tomotherapy, so it was assumed that it would follow the behavior shown in Figure 5.6, the classic bathtub curve.

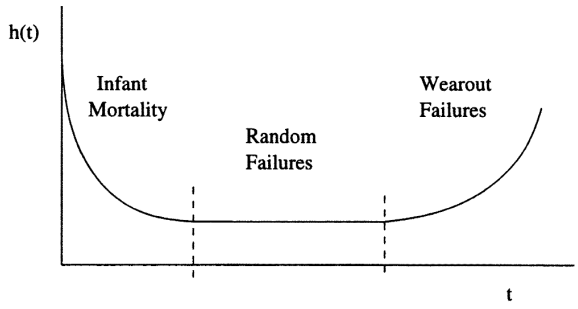


Figure 5.6: Classic bathtub curve [7]

In an attempt to resemble the bathtub curve, the code presented in Figure 5.7 was developed. A function was added to force the predicted data to be adjusted to the historical data.

```
# Importing libraries
import numpy as np
from scipy.optimize import curve_fit

# Given time series data
time_series = np.array([104178.08, 104178.08, 195000.00, 261000.00, 276000.00, 283500.00, 268500.00, 228000.00])
periods_to_forecast = 8

# Define a exponential model function
def exponential_model(x, a, b):
    return a * np.exp(b * x**2)

# Define x values for the initial time series
x = np.arange(len(time_series))

# Fit the exponential model to the existing data
params, covariance = curve_fit(exponential_model, x, time_series, p0=[1, 0.01])

# Forecast the next periods
x_forecast = np.arange(len(time_series) + periods_to_forecast)
forecasted_values = exponential_model(x_forecast, *params)

forecasted_values
```

Figure 5.7: Code developed for forecasting values for maintenance costs

5.5.3 Non-production costs

Traditionally, non-production costs refer to financial losses caused by a reduction in the production of the equipment. These costs include labor costs, lost income and equipment depreciation. In this specific case, a different approach was taken in order to calculate an estimation for the non-production costs related to Tomotherapy.

The amount received by IPOCFG for exams and treatments is determined by the institute in conjunction with the Central Administration of the Health System (ACSS). This happens through the establishment of a program contract for in-house production for the following year on the basis of previous records.

In this case, in order to quantify the outputs, the program contract was not used, but rather the unit value per treatment presented in Ministerial Order no. 234/2015, of 7 August 2015 [66].

To determine the total possible number of treatments, the study shown in Table 5.8 was conducted. After meetings with the medical physics department, it was established that Tomotherapy operates between Monday and Friday, with 13 hours of work per day (except in 2016 and 2017, when there were only 11 hours per day for in-house reasons). On public holidays, it only works for 8 hours and every day it is required to use quality assurance mode to ensure that the equipment performs as intended.

With the total number of hours per year, subtracting the value of hours of quality assurance mode, the value of public holidays is then obtained as the value of total hours possible for treatment.

Table 5.8: Total possible working hours

Year	2016	2017	2018	2019	2020	2021	2022	2023
Total days	259	364	364	364	365	364	364	364
Working days	185	260	261	261	262	261	260	260
Holidays	8	9	9	10	9	8	9	11
Working hours per day (H)	11	11	13	13	13	13	13	13
Total hours (H)	1 810	2 555	3 087	3 082	3 099	3 092	3 075	3 065

The approach only considered downtime, that is, the difference between the value of possible working hours and the actual working hours realized. This difference is obtained in two different approaches:

- **Maintenance time**

  By analyzing all the maintenance reports, both corrective and preventive, it was possible to collect the annual maintenance hours, as can be seen in Table 5.9. Since there are mainly three types of treatment performed on this equipment, the values of the treatments were collected [66] and the average was calculated. Then,

Table 5.9: Calculation of maintenance impact

Year	2016	2017	2018	2019	2020	2021	2022	2023
Total hours (H)	1 810	2 555	3 087	3 082	3 099	3 092	3 075	3 065
Preventive (H)	19,91	68,99	21,61	77,05	142,55	77,30	55,35	122,60
Corretive (H)	56,11	53,66	213,00	104,79	182,84	80,39	123,00	73,56
Possible working hours (H)	1 733,59	2 432,22	2 852,23	2 900,10	2 773,37	2 934,19	2 896,39	2 868,50
Preventive	17 782,83 €	61 614,68 €	19 300,31 €	68 818,02 €	127 323,61 €	69 041,31 €	49 436,44 €	109 501,49 €
Corretive	50 115,24 €	47 922,53 €	190 245,88 €	93 592,51 €	163 306,37 €	71 802,96 €	109 858,75 €	65 700,89 €
Total	67 898,07 €	109 537,21 €	209 546,19 €	162 410,53 €	290 629,99 €	140 844,28 €	159 295,19 €	175 202,38 €

the average time of each treatment was estimated, making it possible to calculate the value that could have been generated had there been no maintenance.

For confidentiality and information protection reasons, the amounts shown have been multiplied by an x-factor.

- **Production "losses"**

  Figure 5.10 presents values such as the number of treatments performed each year and average time per treatment. With these two values, it is possible to determine how much time is spent on treatments each year. To determine the monetary value of the difference between the hours of possible treatment and the hours of treatment, subtracting one from the other.

Table 5.10: Calculation of production "losses" impact

Year	2016	2017	2018	2019	2020	2021	2022	2023
Possible working hours (H)	1 733,59	2 432,22	2 852,23	2 900,10	2 773,37	2 934,19	2 896,39	2 868,50
Number of treatments	5 932	8 039	9 131	9 172	9 764	9 670	9 449	9 814
Hours of treatment	1680,73	2277,72	2587,12	2598,73	2766,47	2739,83	2677,22	2780,63
Production "losses"	47 209,49 €	137 996,29 €	236 788,78 €	269 168,83 €	6 165,79 €	173 591,71 €	195 756,98 €	78 479,04 €

For reasons of confidentiality and data protection, the data presented is multiplied by an x factor.

To forecast non-production costs between 2024 and 2032, the ARIMA algorithm was applied again, as shown in Figure 5.8.

```
# Importing the required libraries
import pandas as pd
from statsmodels.tsa.arima.model import ARIMA

# Convert the data to a temporal serie
NPC = [118428.25, 256291.12, 461284.20, 448461.25, 297404.14, 325397.45, 367533.72, 258909.02]
ts = pd.Series(NPC)

# Fitting the ARIMA model
model = ARIMA(ts, order=(1, 1, 1))
model_fit = model.fit()

# Forecast for the next 9 periods
forecast = model_fit.forecast(steps=9)

forecast
```

Figure 5.8: Code developed for forecasting values for non-production costs

5.6 Replacement models

Replacement models are global models that help organizations identify decision points in the equipment life cycle. Based on the replacement forecast, it is possible to discuss potential approaches regarding the purchase of new equipment.

Despite being a very useful tool for organizations, replacement models have two negative aspects. The first is their high dependence on the disposal value. To overcome this, in an ideal scenario, it would be necessary to obtain the market value every year. As this approach is not always possible or is difficult to achieve, it is necessary to analyze various depreciation methods to understand the model's behavior and make safer decisions.

The second aspect is the lack of considerations about the continuity of production. This is relevant when analyzing heavy equipment, where the process of removing and installing equipment is time-consuming. The models do not include data on the cost associated with replacing equipment, such as the loss of production.

In addition to depreciation methods the apparent rate, i_A, is used to calculate the present value of the values over the years. To obtain i_A, Equation 5.13 is used [3].

$$i_A = i + \Phi + i \times \Phi \tag{5.13}$$

Where:

i - Capitalization rate
Φ - Inflation rate

The capitalization rate for this kind of situation is not explicit. The value that was considered was 2 %, like the authors [67] and [68].

The inflation rate was gathered from [69]. The data considered for the 2016 to 2023 time period was the total inflation value. The figures for 2024 and 2025 are projected figures published by [70]. The figure for the years 2026 to 2032 is the average of the figures for 2016 to 2032.

The information and outcomes represented in the following models do not correspond to the real results for reasons of confidentiality and data protection. The real data was delivered to the SIE.

The substitution models considered for the life cycle analysis were:

- **Uniform Annual Income Method (UAIM)**

  To reach the final annual income result, the Equations 5.14, 5.15 and 5.16 used are:

$$U = \frac{i_A \times (1+i_A)^n}{(1+i_A)^n - 1} \times \sum_{j=0}^{n} \times \frac{X_j}{(1+i_A)^j} \tag{5.14}$$

$$P = \sum_{j=0}^{n} \times \frac{X_j}{(1+i_A)^j} \tag{5.15}$$

$$U' = \frac{i_A \times (1+i_A)^n}{(1+i_A)^n - 1} \tag{5.16}$$

  Where:

  U - Uniform annual income
  n — Period for which U is calculated
  X_j — Operating and Maintenance costs for the period j
  P - Present value
  U' - Factor of capital recovery

  According to Farinha [3], the minimum point of U, marked in green in Table 5.11, represents the year in which the replacement should be made.

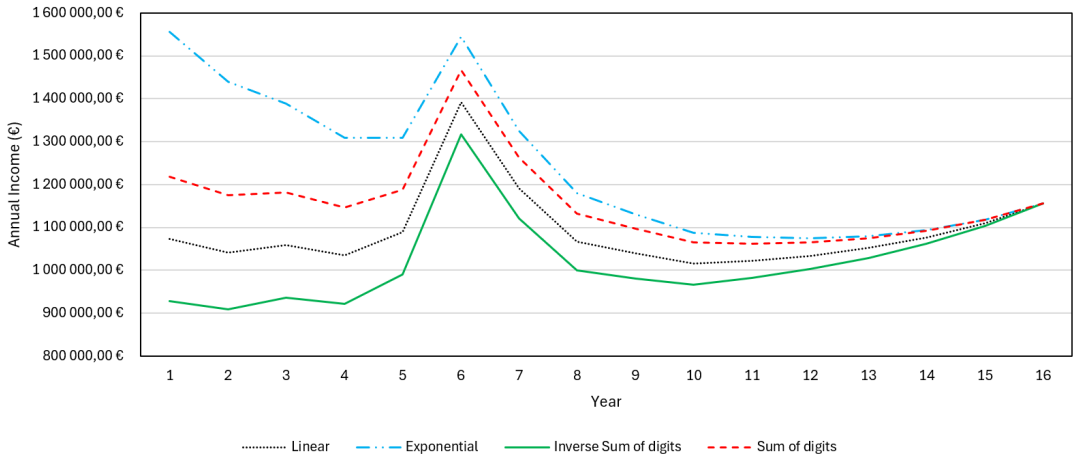


Figure 5.9: UAIM behavior with the different depreciation methods

Table 5.11: UAIM values for the different depreciation methods

Year		Linear	Sum of digits	Exponential	Inverse Sum of digits
01	2017	1 073 060,29 €	1 217 435,29 €	1 556 165,29 €	928 685,29 €
02	2018	1 041 782,08 €	1 174 527,62 €	1 439 898,98 €	909 036,53 €
03	2019	1 058 793,73 €	1 181 077,20 €	1 389 128,74 €	936 510,27 €
04	2020	1 034 281,78 €	1 146 373,95 €	1 308 347,00 €	922 189,60 €
05	2021	1 089 166,44 €	1 188 228,96 €	1 309 412,28 €	990 103,92 €
06	2022	1 392 068,37 €	1 466 999,80 €	1 544 240,66 €	1 317 136,94 €
07	2023	1 191 664,88 €	1 263 059,69 €	1 324 675,10 €	1 120 270,08 €
08	2024	1 065 866,55 €	1 131 900,03 €	1 179 189,97 €	999 833,07 €
09	2025	1 038 753,80 €	1 096 197,70 €	1 129 921,46 €	981 309,91 €
10	2026	1 015 166,52 €	1 064 428,30 €	1 087 737,99 €	965 904,73 €
11	2027	1 021 977,76 €	1 062 290,84 €	1 077 298,94 €	981 664,68 €
12	2028	1 033 918,13 €	1 065 585,42 €	1 074 533,56 €	1 002 250,84 €
13	2029	1 051 711,83 €	1 075 030,57 €	1 079 752,04 €	1 028 393,09 €
14	2030	1 076 586,76 €	1 091 848,52 €	1 093 843,45 €	1 061 325,00 €
15	2031	1 110 340,39 €	1 117 831,10 €	1 118 326,86 €	1 102 849,67 €
16	2032	1 155 571,73 €	1 155 571,73 €	1 155 571,73 €	1 155 571,73 €

In terms of interpreting the result, as shown in the Table 5.11 and Figure 5.9, the early result of the inverse sum-of-the-digits method can be explained by the low depreciation of the asset. This factor makes its disposal value high enough to consider it the best year for sale. In this case, the inverse sum-of-the-digits method is not suitable due to its result.

Consequently, the linear, exponential and sum-of-the-digits methods produce similar results in terms of the annual income point, despite the discrepancy in the transfer values. The difference between the outputs of these methods is one year, as shown in Table 5.11. The peak in year six is attributable to the high inflation rate in that year.

Appendix D contains the complete calculations used for calculating the annual income using the different depreciation methods.

- **Minimizing the Total Average Cost Method (MTACM)**

  To reach the final C_n result, the Equations 5.17, 5.18 and 5.19 used are:

$$C'_n = \frac{\sum_{j=1}^{n} \times C_{Mi}}{n} \tag{5.17}$$

$$C''_n = \frac{V_A - V_{Cn}}{n} \tag{5.18}$$

$$C_n = C'_n + C''_n \tag{5.19}$$

  Where:

  C'_n - Average annual maintenance and operating costs over the period n
  C_{Mi} - Operating and maintenance costs for the period i
  C''_n - Average annual depreciation cost over the period n
  V_A - Acquisition value
  V_{Cn} - Cession value in year n
  C_n - Total cost

  For the MTACM model, the apparent rate is not taken into account in the process of determining the lowest average cost of ownership. In this model, according to Farinha [3], the optimum time for replacing equipment is in the year in which the minimum cost is represented, as shown in green in Table 5.12.

Table 5.12: MTACM values for the different depreciation methods

Year		Linear	Sum of digits	Exponential	Inverse Sum of digits
01	2017	859 615,13 €	1 003 990,13 €	1 342 720,12 €	715 240,13 €
02	2018	904 301,67 €	1 039 051,67 €	1 308 430,14 €	769 551,67 €
03	2019	968 055,28 €	1 093 180,28 €	1 306 066,36 €	842 930,28 €
04	2020	964 518,70 €	1 080 018,70 €	1 246 916,05 €	849 018,70 €
05	2021	972 931,30 €	1 078 806,30 €	1 208 323,34 €	867 056,30 €
06	2022	990 556,65 €	1 086 806,65 €	1 186 023,12 €	894 306,65 €
07	2023	987 613,40 €	1 074 238,40 €	1 148 997,83 €	900 988,40 €
08	2024	970 920,97 €	1 047 920,97 €	1 103 064,59 €	893 920,97 €
09	2025	970 920,97 €	1 038 295,97 €	1 077 850,01 €	903 545,97 €
10	2026	971 334,21 €	1 029 084,21 €	1 056 410,36 €	913 584,21 €
11	2027	981 063,19 €	1 029 188,19 €	1 047 104,57 €	932 938,19 €
12	2028	997 526,56 €	1 036 026,56 €	1 046 905,40 €	959 026,56 €
13	2029	1 021 678,44 €	1 050 553,44 €	1 056 399,92 €	992 803,44 €
14	2030	1 055 188,22 €	1 074 438,22 €	1 076 954,47 €	1 035 938,22 €
15	2031	1 100 555,70 €	1 110 180,70 €	1 110 817,72 €	1 090 930,70 €
16	2032	1 161 457,57 €	1 161 457,57 €	1 161 457,57 €	1 161 457,57 €

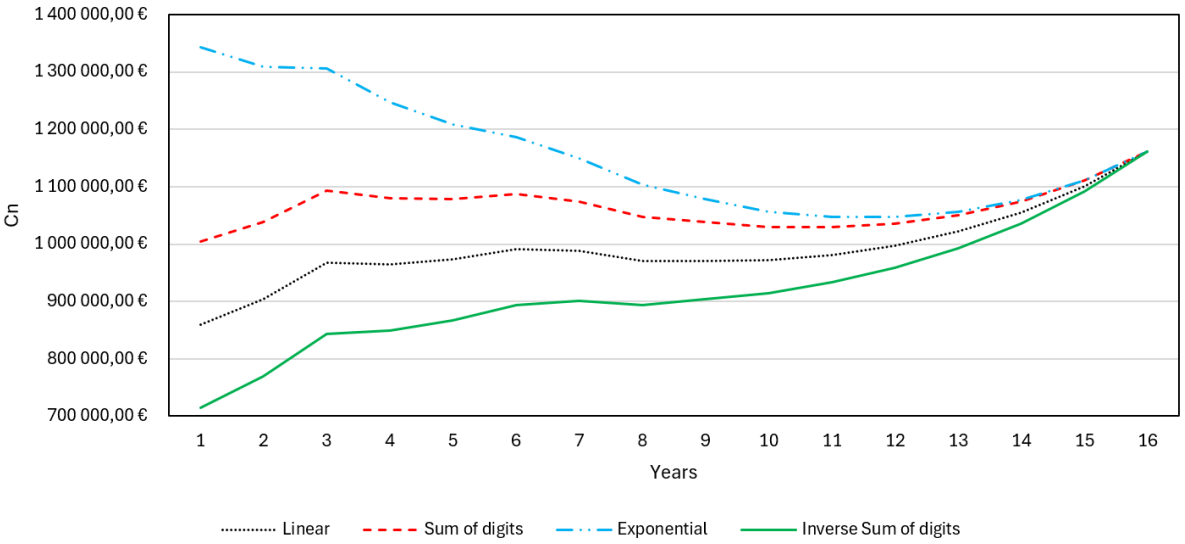


Figure 5.10: MTACM behavior with the different depreciation methods

When interpreting these results, the outcomes of the straight-line, sum of digits, and inverse sum of digits methods can be explained by the low depreciation of the asset, which makes its disposal value high enough to justify selling it to obtain the minimum cost point. In this case, the straight-line and inverse sum of digits methods are not appropriate due to their results.

For the comparative analysis, the lowest value in the sum of digits method was not considered; instead, the second lowest value was used, which occurred in the tenth year as shown in Table 5.12 and Figure 5.10. Consequently, the exponential and sum of digits methods produce close results regarding the minimum cost point, despite the initial discrepancies in the disposal values. These methods only show a difference in results of 2 years.

Appendix E contains the complete calculations used for calculating C_n using the different depreciation methods.

- **MTACM with Reduction to the Present Value (MTACM-RPV)**

  To reach the final C_n result, the Equations 5.20, 5.21 and 5.22 used are:

$$C'_n = \frac{1}{n} \times \sum_{j=1}^{n} \times \frac{C_{Mi}}{(1+i_A)^i} \tag{5.20}$$

$$C''_n = \frac{V_A - V_{Cn}/(1+i_A)^n}{n} \tag{5.21}$$

$$C_n = C'_n + C''_n \tag{5.22}$$

In the MTACM-RPV model, the apparent rate is a key factor in determining the lowest average cost of ownership. Farinha [3] explains that the best time to replace equipment is when the cost reaches its minimum, which is indicated in green in Table 5.12.

Table 5.13: MTACM-RPV values for the different depreciation methods

Year		Linear	Sum of digits	Exponential	Inverse Sum of digits
01	2017	1 125 259,82 €	1 264 849,68 €	1 592 352,87 €	985 669,96 €
02	2018	1 040 302,85 €	1 167 268,33 €	1 421 084,80 €	913 337,36 €
03	2019	1 041 031,00 €	1 157 884,24 €	1 356 696,86 €	924 177,75 €
04	2020	1 006 507,32 €	1 113 211,46 €	1 267 398,82 €	899 803,17 €
05	2021	1 005 947,23 €	1 095 844,26 €	1 205 815,42 €	916 050,20 €
06	2022	1 026 401,85 €	1 080 863,04 €	1 137 002,75 €	971 940,65 €
07	2023	949 969,08 €	1 006 132,29 €	1 054 602,47 €	893 805,88 €
08	2024	895 318,08 €	950 105,93 €	989 342,31 €	840 530,23 €
09	2025	885 383,08 €	932 974,60 €	960 914,30 €	837 791,56 €
10	2026	854 341,18 €	895 341,94 €	914 742,68 €	813 340,42 €
11	2027	846 128,88 €	879 145,66 €	891 437,42 €	813 112,10 €
12	2028	842 366,04 €	867 890,04 €	875 102,28 €	816 842,04 €
13	2029	843 374,55 €	861 872,94 €	865 618,41 €	824 876,16 €
14	2030	849 858,33 €	861 775,32 €	863 333,04 €	837 941,34 €
15	2031	862 919,48 €	868 677,33 €	869 058,40 €	857 161,62 €
16	2032	884 199,32 €	884 199,32 €	884 199,32 €	884 199,32 €

The results of this model show that, due to the impact of the apparent rate, all depreciation methods have later replacement years, as shown in Table 5.13 and Figure 5.11.

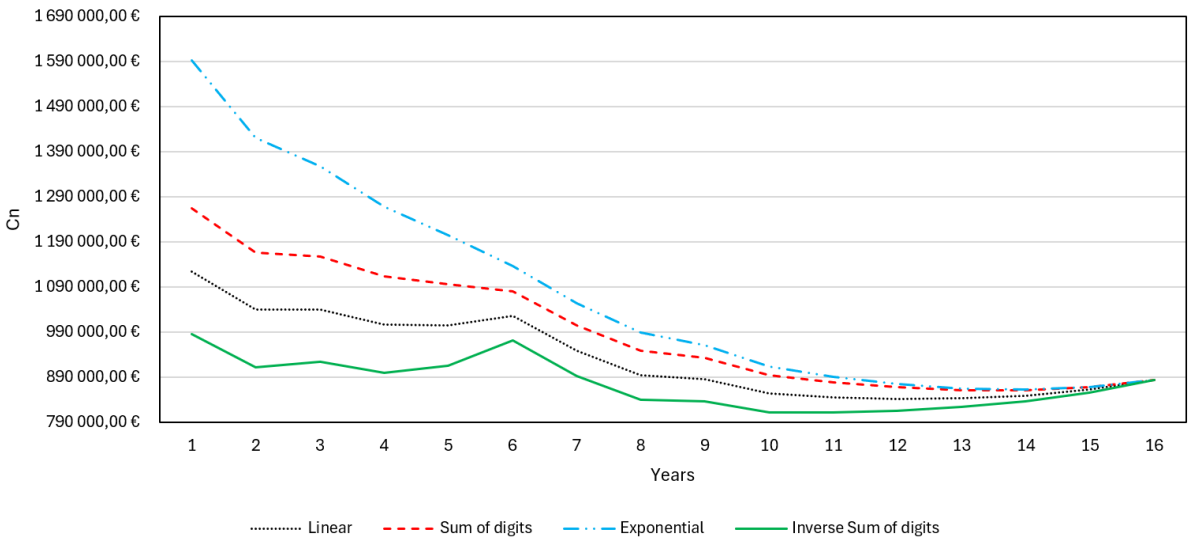


Figure 5.11: MTACM-RPV behavior with the different depreciation methods

The sum of digits and exponential methods share the same replacement year, which is the fourteenth year and also the latest among the methods analyzed. This can be attributed to their high initial depreciation. The inverse sum of digits method has the lowest minimum cost of all the analyzed methods and the earliest replacement year, which is the eleventh. Finally, the linear method has a replacement year in the twelfth year.

Appendix F contains the complete calculations used for calculating C_n using the different depreciation methods.

5.7 KPIs applied to the Tomotherapy

In an effort to understand the operational behavior of Tomotherapy over the years, KPIs were developed. These KPIs do not represent true values, having been multiplied by an x-factor for the purpose of information protection and confidentiality. The true values have been delivered to the SIE service.

- **Availability**

  Equipment availability is the probability of the equipment being operational for use [67]. There are various ways of estimating the availability, and in this case, it was used the formula in Equation 5.23. As shown in Table 5.14, the availability of the Tomotherapy has fluctuated over the years, maintaining an average of 93,71 %.

$$\text{Availability} = \frac{\text{Working hours without maintenance hours}}{\text{Total possible working hours}} \times 100\% \quad (5.23)$$

- **Occupancy**

  The occupancy rate is the probability of the equipment being occupied. The Equation 5.24 was developed to calculate its annual value. It can be seen (Table 5.14) that the occupancy rate has fluctuated slightly over the years, maintaining an average of 94,17 %.

$$\text{Occupancy} = \frac{\text{Total hours}}{\text{Possible working hours}} \times 100\% \quad (5.24)$$

Table 5.14: KPIs applied to Tomotherapy

Year	2016	2017	2018	2019	2020	2021	2022	2023
Total hours (H)	1 810	2 555	3 087	3 082	3 099	3 092	3 075	3 065
Possible working hours (H)	1 733,98	2 432,36	2 852,39	2 900,16	2 773,61	2 934,31	2 896,65	2 868,84
Hours of treatment (H)	1 681	2 278	2 587	2 599	2 766	2 740	2 677	2 781
Availability	95,80%	95,20%	92,40%	94,10%	89,50%	94,90%	94,20%	93,60%
Occupancy rate (%)	96,93%	93,64%	90,70%	89,61%	99,74%	93,37%	92,42%	96,93%
Overall efficiency (%)	92,86%	89,15%	83,81%	84,32%	89,27%	88,61%	87,06%	90,72%

- **Overall efficiency**

  The overall efficiency of the equipment provides insight into the performance of the equipment. In this case, Equation 5.25 was developed only considering availability and occupancy. It also shows as evidenced by Table 5.14 some fluctuations over the years and maintains an average of 88.22 %.

$$\text{Overall efficiency} = \text{Availability} \times \text{Occupancy} \tag{5.25}$$

5.8 Discussion

The model that shows the most promising results is MTACM-RPV, as all substitution methods show plausible results. The other replacement models show promising results with the exponential method, as it is the closest to the lifetime provided by the supplier. The inverse sum of digits depreciation method, although not a traditionally used method, has shown that it has the potential to help in decision-making, but only in specific cases.

In order to enable a better life cycle analysis, it would be necessary to find out what the actual annual depreciation value of the equipment is, and somehow create a capitalization rate appropriate to a hospital situation.

6 Conclusion

During the internship at IPOCFG, it was possible to see how important the management of medical equipment is and how engineering and medicine are increasingly interconnected.

In the introduction to this internship report, three questions were raised, to which the answer now appears:

- **Question 01:** How can the internal processes of the SIE increase hospital efficiency?

  Answer 01: With the SIE internal procedures, it's possible to control the equipment/facilities so that they are in the best condition for when they need to be used by health professionals. By continuously improving processes and adopting innovative ideas and technologies, it is possible to increase operational efficiency and improve the care provided to patients.

- **Question 02:** What is the impact for a hospital of certain equipment falling within the scope of legal metrology?

  Answer 02: In most cases, the most basic medical equipment, such as sphygmomanometers and thermometers, are used across the hospital campus, which translates into large quantities of such equipment. For this reason, this type of equipment must be considered at some level of criticality due to its transversality. With the new regulations published, it's possible to understand the importance of metrological monitoring to guarantee accurate and precise measurements. This increases patient safety and maintains the trust and reputation of healthcare services.

  If the adoption of metrological processes for basic medical equipment has a positive impact on the successful operation of the hospital, then the adoption of metrological processes for all measuring equipment should be considered. These processes in turn demand that calibration tests be carried out at intervals appropriate to the type of equipment.

- **Question 03:** Which parameters can affect the life cycle of heavy medical equipment?

  Answer 03: An assessment of the costs of heavy medical equipment can aid in decision-making throughout the equipment's life cycle. To achieve this, it is necessary to analyze all costs generated by the equipment over the years, namely

labor, energy, maintenance and non-production costs. In addition to costs, developing equipment KPIs can help determine where the equipment presents opportunities for improvement and how these can be addressed.

6.1 Suggestions for improvement

Throughout the internship, with the interaction between various departments and numerous people, it was possible to recognize that some points could be improved. In the area of asset management, it is necessary to have a Kaizen perspective, as this has a direct impact on the smooth operation of the hospital.

To address the aspects that need to be improved, here are some suggestive improvements aimed at improving the functioning of the institution:

- Although there are already internal processes for the reception of equipment, transfers, and disposals, control should be strengthened;
- Reinforcement of the human resources of the SIE, so that there is holistic control of equipment and with the new building more workforce will be needed;
- A workplace for an electromedical technician, to expedite maintenance processes, both corrective and preventive, for medical equipment;
- Implementation of large-scale metrology processes for medical equipment;
- Reinforcing the training of health professionals in the GHAF software, so that requisition operations run as efficiently as possible;
- Giving the cleaning crew and security team access to the GHAF software, so that they can submit requisitions;
- A holistic assessment of all the hospital's assets to update the inventory;
- Creation of a multidisciplinary team for the inventory that will be acquired for the new building to take control of the inventory;
- Certification of the SIE by ISO 9001:2008, ISO 55001:2014 and Joint Commission International Accreditation;
- Planning for implementing prescriptive maintenance for the most critical medical equipment.

References

[1] OIML, "Non-invasive non-automated sphygmomanometers," 2020. [Online]. Available: https://www.oiml.org/en/files/pdf_r/r148-p-e20.pdf/view

[2] ISO, "Asset management — overview, principles and terminology," ISO, Standard ISO 55000:2014, 2014.

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

[4] J. L. Bucher and American Society for Quality, Eds., *The metrology handbook*, 2nd ed. Milwaukee, Wis: ASQ Quality Press, 2012.

[5] OIML, "Non-invasive automated sphygmomanometers," 10 2020. [Online]. Available: https://www.oiml.org/en/files/pdf_r/r149-p-e20.pdf/view

[6] T. R. Mackie, T. Holmes, S. Swerdloff, P. Reckwerdt, J. O. Deasy, J. Yang, B. Paliwal, and T. Kinsella, "Tomotherapy: A new concept for the delivery of dynamic conformal radiotherapy," *Medical Physics*, vol. 20, no. 6, p. 1709–1719, Nov. 1993. [Online]. Available: http://doi.wiley.com/10.1118/1.596958

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

[8] "Portaria 76-b/2014, de 26 de março," https://diariodarepublica.pt/dr/detalhe/portaria/76-b-2014-680834, accessed: 2023-12-23.

[9] "Relatório e contas," https://www.ipocoimbra.min-saude.pt/wp-content/uploads/sites/3/2024/04/relatorio-e-contas-2023-assinado-e-rubricado-final.pdf, accessed: 2023-12-23.

[10] PAS, "Asset management part 1: Specification for the optimized management of physical assets," PAS, Standard PAS 55-1:2008, 2008.

[11] ISO, "Asset management — management systems — requirements," ISO, Standard ISO 55001:2014, 2014.

[12] ——, "Asset management — management systems — guidelines for the application of iso 55001," ISO, Standard ISO 55002:2014, 2014.

[13] J. A. N. d. Oliveira, *Engenharia economica. Uma abordagem às decisões de investimento*. McGraw-Hill: CIP - Brasil. Catalogação - na - Publicação Câmara Brasileira do Livro, SP, 1982.

[14] R. A. Meyer, "Equipment Replacement Under Uncertainty," *Management Science*, vol. 17, no. 11, pp. 750–758, Jul. 1971. [Online]. Available: https://pubsonline.informs.org/doi/10.1287/mnsc.17.11.750

[15] F. Monchy and Y. Mirochnikoff, *La fonction maintenance: formation à la gestion de la maintenance industrielle*, ser. Collection Technologies. Masson, 1991. [Online]. Available: https://books.google.pt/books?id=RSlLvwEACAAJ

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

[17] J. M. T. Farinha, *Manutenção das instalações e equipamentos hospitalares: uma abordagem terológica*. Minerva, 1997. [Online]. Available: http://tinyurl.com/2nkswec3

[18] M. Molęda, B. Małysiak-Mrozek, W. Ding, V. Sunderam, and D. Mrozek, "From corrective to predictive maintenance - a review of maintenance approaches for the power industry," *Sensors*, vol. 23, 2021. [Online]. Available: https://www.mdpi.com/1424-8220/23/13/5970

[19] T. P. Carvalho, F. A. A. M. N. Soares, R. Vita, R. da P. Francisco, J. P. Basto, and S. G. S. Alcalá, "A systematic literature review of machine learning methods applied to predictive maintenance," *Computers & Industrial Engineering*, vol. 137, p. 106024, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360835219304838

[20] F. Coutinho, "Manutenção preditiva nos equipamentos de saúde: princípios, benefícios, obstáculos e o futuro," *Tecnohospital*, vol. 105, no. 105, pp. 16–18, 2021. [Online]. Available: http://www.tecnohospital.pt/noticias/manutencao-preditiva-equipamentos-principios-beneficios/

[21] M. Pech, J. Vrchota, and J. Bednář, "Predictive maintenance and intelligent sensors in smart factory: Review," *Sensors*, vol. 21, p. 5970, 2021. [Online]. Available: https://www.mdpi.com/1424-8220/21/4/1470

[22] K. Matyas, T. Nemeth, K. Kovacs, and R. Glawar, "A procedural approach for realizing prescriptive maintenance planning in manufacturing industries," *CIRP Annals*, vol. 66, no. 1, p. 461–464, 2017. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0007850617300070

[23] B. Liu, J. Lin, L. Zhang, and U. Kumar, "A dynamic prescriptive maintenance model considering system aging and degradation," *IEEE Access*, vol. 7, p. 94931–94943, 2019. [Online]. Available: https://ieeexplore.ieee.org/document/8762155/

[24] D. Galar, P. Sandborn, and U. Kumar, *Maintenance Costs and Life Cycle Cost Analysis*, 1st ed. Boca Raton: Taylor & Francis, a CRC title, part of the Taylor

& Francis imprint, a member of the Taylor & Francis Group, the academic division of T&F Informa, plc, [2017]: CRC Press, Sep. 2017. [Online]. Available: https://www.taylorfrancis.com/books/9781498769556

[25] H. Kerzner, *Project Management Metrics, KPIs, and Dashboards*. John Wiley & Sons, Inc., oct 2011. [Online]. Available: https://doi.org/10.1002/9781119427599

[26] D. Amos, C. P. Au-Yong, and Z. N. Musa, "Developing key performance indicators for hospital facilities management services: a developing country perspective," *Engineering, Construction and Architectural Management*, vol. 27, no. 9, pp. 2715–2735, May 2020. [Online]. Available: https://doi.org/10.1108/ecam-11-2019-0642

[27] B. K. Chae, "Developing key performance indicators for supply chain: an industry perspective," *Supply Chain Management: An International Journal*, vol. 14, no. 6, pp. 422–428, Sep. 2009. [Online]. Available: https://doi.org/10.1108/13598540910995192

[28] I. Hristov and A. Chirico, "The role of sustainability key performance indicators (KPIs) in implementing sustainable strategies," *Sustainability*, vol. 11, no. 20, p. 5742, Oct. 2019. [Online]. Available: https://doi.org/10.3390/su11205742

[29] E. Gonzalez, E. M. Nanos, H. Seyr, L. Valldecabres, N. Y. Yürüşen, U. Smolka, M. Muskulus, and J. J. Melero, "Key performance indicators for wind farm operation and maintenance," *Energy Procedia*, vol. 137, pp. 559–570, Oct. 2017. [Online]. Available: https://doi.org/10.1016/j.egypro.2017.10.385

[30] "Maintenance. maintenance key performance indicators," BSI Standards Publication, 2019. [Online]. Available: https://www.en-standard.eu/bs-en-15341-2019-a1-2022-maintenance-maintenance-key-performance-indicators/

[31] R. J. Brown, "Measuring measurement – What is metrology and why does it matter?" *Measurement*, vol. 168, p. 108408, Jan. 2021. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S0263224120309428

[32] J. C. for Guides in Metrology, "International vocabulary of metrology," https://www.bipm.org/documents/20126/115700832/VIM4_2CD_clean/c6d0dfb2-ddbf-059e-1f74-9b025c9c59d8, 2023, [Accessed 09-07-2024].

[33] C. G. M. na Saúde, *Metrologia na Saúde - Guia de Boas Práticas*. Rua António Gião, 2, 2825-513 CAPARICA, Portugal: Comissão Setorial para Saúde (CS/09), 2015.

[34] P. de conselho de ministros, "Decreto-lei n.º 29/2022," https://files.dre.pt/1s/2022/04/06900/0000200012.pdf, 2022, [Accessed 25-06-2024].

[35] IPQ, "Sobre o ipq," https://www.ipq.pt/sobre-o-ipq/, 2022, [Accessed 01-07-2024].

[36] IPAC, "Plano de atividades - ano de 2024," http://www.ipac.pt/docs/publicdocs/outros/PlanodeAtividades_IPAC_2024_v140823.pdf#page=1.19, 2024, [Ac-

cessed 16-07-2024].

[37] OIML, "Legal metrology and health," https://www.oiml.org/en/about/legal-metrology/health, [Accessed 09-07-2024].

[38] M. do Ceu Ferreira, A. Matos, and R. P. Leal, "Evaluation of the role of metrological traceability in health care: a comparison study by statistical approach," *Accreditation and Quality Assurance*, vol. 20, no. 6, pp. 457–464, Jul. 2015. [Online]. Available: https://doi.org/10.1007/s00769-015-1149-9

[39] B. Karaboce, "Challenges for medical metrology," *IEEE*, vol. 23, no. 4, pp. 48–55, Jun. 2020. [Online]. Available: https://doi.org/10.1109/mim.2020.9126071

[40] ISO, "Measurement management systems — requirements for measurement processes and measuring equipment," ISO, Standard ISO 10012:2003, 2003.

[41] ISO/IEC, "General requirements for the competence of testing and calibration laboratories," ISO/IEC, Standard ISO/IEC 17025:2017, 2017.

[42] S. E. J. Richard A. Guzzo, Susan E. Jackson, "Meta-analysis analysis," *Research in Organizational Behavior*, pp. 407–442, jan 1987. [Online]. Available: https://shorturl.at/vVZ49

[43] "Gestão hospitalar de armazém e farmácia," https://sti.pt/ghaf.html, accessed: 2024-01-23.

[44] "Classificador complementar – cadastro e vidas úteis dos ativos fixos tangíveis, intangíveis e propriedades de investimento," https://www.cnc.min-financas.pt/pdf/SNC_AP/Instrumentos%20Contabilisticos/Classificador%20complementar.pdf#page=2.00, accessed: 2024-02-17.

[45] "Introduction to medical equipment inventory management," https://iris.who.int/bitstream/handle/10665/44561/9789241501392-eng.pdf?sequence=1, accessed: 2024-05-15.

[46] ISO, "Quality management systems — requirements," ISO, Standard ISO 9001:2015, 2015.

[47] República Portuguesa, "Diário da república n.º 220/2023, série i de 2023-11-14, páginas 15 - 17," 2023.

[48] "Declaração de retificação n.º 1-a/2024, de 12 de janeiro," https://diariodarepublica.pt/dr/detalhe/declaracao-retificacao/1-a-2024-836631395, accessed: 2024-4-28.

[49] "Sphygmomanometer: Learn its definition, types, parts, & working principle," https://testbook.com/physics/sphygmomanometer, accessed: 2024-05-04.

[50] M. J. Turner, A. B. Baker, and P. C. Kam, "Effects of systematic errors in blood pressure measurements on the diagnosis of hypertension," *Blood*

Pressure Monitoring, vol. 9, no. 5, p. 249–253, oct 2004. [Online]. Available: http://journals.lww.com/00126097-200410000-00004

[51] República Portuguesa, "Diário da república n.º 221/2023, série i de 2023-11-15, páginas 47 - 50," 2023.

[52] "Declaração de retificação n.º 1-d/2024, de 12 de janeiro," https://diariodarepublica.pt/dr/detalhe/declaracao-retificacao/1-d-2024-836631398, accessed: 2024-4-28.

[53] "Infrared ear thermometer: A comprehensive guide," https://www.electricity-magnetism.org/infrared-ear-thermometer/, accessed: 2024-05-04.

[54] I. Pušnik and J. Drnovšek, "Infrared ear thermometers—parameters influencing their reading and accuracy," *Physiological Measurement*, vol. 26, no. 6, pp. 1075–1084, Dec. 2005. [Online]. Available: https://iopscience.iop.org/article/10.1088/0967-3334/26/6/016

[55] República Portuguesa, "Diário da república n.º 368/2023, série 1 de 2023-11-15, pp. 51 - 53," 2023.

[56] "Iop and tonometry," https://eyewiki.aao.org/IOP_and_Tonometry, accessed: 2024-06-24.

[57] "Tonometer," https://www.oiml.org/en/files/pdf_r/r145-p-e15.pdf/view, accessed: 2024-06-24.

[58] "Diário da república n.º 220/2023, série i de 2023-11-14, páginas 21 - 24," https://diariodarepublica.pt/dr/detalhe/portaria/356-2023-224203159, 2023.

[59] "Declaração de retificação n.º 1-b/2024, de 12 de janeiro," https://diariodarepublica.pt/dr/detalhe/declaracao-retificacao/1-b-2024-836631396, accessed: 2024-06-24.

[60] T. R. Mackie, "History of tomotherapy," *Physics in Medicine and Biology*, vol. 51, no. 13, p. R427–R453, Jul. 2006. [Online]. Available: https://iopscience.iop.org/article/10.1088/0031-9155/51/13/R24

[61] "Unidade de tratamento," https://www.base.gov.pt/Base4/pt/resultados/?type=doc_documentos&id=1749790&ext=.pdf, accessed: 2024-02-13.

[62] M. F. C. Girão, "Preciseart - radioterapia adaptativa na tomoterapia para a patologia de cabeça e pescoço," in *PreciseART - Radioterapia Adaptativa na Tomoterapia para a patologia de Cabeça e Pescoço*, Sep. 2023. [Online]. Available: https://estudogeral.uc.pt/handle/10316/110711

[63] "Tarifas e preços," https://www.erse.pt/atividade/regulacao/tarifas-e-precos-eletricidade/, accessed: 2024-05-14.

[64] M. J. Moore and W. K. Viscusi, "Promoting safety through workers' compensation: The efficacy and net wage costs of injury insurance," *The RAND Journal of Economics*, vol. 20, no. 4, pp. 499–515, 1989. [Online]. Available: http://www.jstor.org/stable/2555730

[65] V. I. Kontopoulou, A. D. Panagopoulos, I. Kakkos, and G. K. Matsopoulos, "A Review of ARIMA vs. Machine Learning Approaches for Time Series Forecasting in Data Driven Networks," *Future Internet*, vol. 15, no. 8, p. 255, Jul. 2023. [Online]. Available: https://www.mdpi.com/1999-5903/15/8/255

[66] "Portaria n.º 234/2015, de 7 de agosto," https://files.diariodarepublica.pt/1s/2015/08/15300/0551605654.pdf, accessed: 2024-03-16.

[67] 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

[68] J. Torres Farinha, H. Nogueira Raposo, E. Pais Almeida, and M. Mendes, "Physical assets life cycle evaluation models—a comparative analysis aiming the sustainability," *Sustainability*, vol. 15, p. 1–18, Dec. 2023.

[69] Pordata, "Taxa de inflação (taxa de variação do Índice de preços no consumidor): total e por consumo individual por objetivo," https://rb.gy/50y4ew, 2024, accessed 2024-04-01.

[70] C. Europeia, "Comissão europeia apresenta previsões económicas do inverno de 2024: retoma tardia do crescimento num contexto de abrandamento da inflação," https://rb.gy/q1n6xa, 2024, [Accessed 08-04-2024].

Appendix

Appendix A - Template created for reception document

REPÚBLICA PORTUGUESA SAÚDE — SNS SERVIÇO NACIONAL DE SAÚDE — IPO COIMBRA

AUTO DE RECEÇÃO

Local de instalação :	Instituto Português de Oncologia de Coimbra, E.P.E.
Fornecedor :	
Número de processo :	
Nome de processo :	
Centro(s) de custo(s) :	

No dia _____ de _____de _____ estando presentes os representantes da _____ e o representante do IPO abaixo assinado, procedeu-se à receção do equipamento em referência e a seguir descrito, de acordo com a Encomenda nº_____ , tendo-se verificado que o seu fornecimento foi efetuado de acordo com o respetivo procedimento aquisitivo e se encontra em perfeitas condições de funcionamento. Do presente auto será enviada cópia ao fornecedor do equipamento para efeitos de faturação e início do prazo de garantia.

Prazo de garantia	__ meses

Lista de equipamento(s)

Descrição	Marca	Modelo	Número de série	Número de Etiqueta

Observações:

Responsável de serviço

_____

_____

_____

_____

SIE

_____

_____

Fornecedor

_____

_____

_____

_____

Appendix B - Work instruction for designation of maintenance reports

IPO COIMBRA

INSTRUÇÃO DE TRABALHO

Documentação de relatórios de manutenção

Qualidade
Um Compromisso

1. OBJETIVO

Normalizar a designação de relatórios de manutenção.

2. APLICABILIDADE

Profissionais responsáveis pela documentação no Serviço de Instalações e Equipamentos (SIE).

3. RESPONSABILIDADES

A implementação desta Instrução de trabalho é da responsabilidade da Direção do SIE.

4. REFERÊNCIAS, DEFINIÇÕES E ABREVIATURAS

SIE - Serviço de Instalações e Equipamentos

5. DESCRIÇÃO

1) Na receção de relatórios de manutenção em formato de papel, fazer a digitalização do mesmo.
2) Para a designação do ficheiro, é necessário saber o conteúdo para que seja atribuído um dos códigos associados:
   - CHECK - Checklist de equipamentos
   - REP - Relatório de reparação de equipamentos
   - MANUT - Relatório de manutenção preventiva de equipamentos
   - ANUAL - Relatório anual associado a um equipamento
   - SEM REP - Relatório de sem reparação de um equipamento
3) Após ser atribuído o código colocar a data do relatório, seguindo o ano, mês e dia como apresentando no exemplo a seguir:
   - Exemplo: CHECK_AAAA_MM_DD
     i) Nota: No caso da esterilização (PROMEICENTRO), colocar o número de inventario do serviço associado, que pode ser consultado na listagem do contrato, para ficar com o seguinte formato: 14055_MANUT_AAAA_MM_DD.
     ii) Nota: No caso dos relatórios anuais de equipamentos, se possível, colocar o número de etiqueta, com o seguinte formato: ANUAL_AAAA_MM_DD_1234.
4) Sempre que possível colocar um número de requisição associado a ficheiro colocar da seguinte forma: REP_AAAA_MM_DD#1234
5) Após a correta colocação da designação, colocar na respetiva pasta.

6. DOCUMENTOS RELACIONADOS

ELABORAÇÃO		*APROVAÇÃO*	
Rodrigo Manuel Farate de Albuquerque			
Data:			
Data Aprovação:	***Data próxima Revisão:***	***Cod:***	***1 / 1***

Appendix C - Work instruction for standardizing equipment registration designations

IPO COIMBRA

INSTRUÇÃO DE TRABALHO

Identificação dos Dispositivos Médicos

Qualidade
Um Compromisso

1. OBJETIVO

Normalizar a designação de dispositivos médicos (DM).

2. APLICABILIDADE

Profissionais responsáveis pelo registo do Imobilizado na Gestão Financeira (GFIN).

3. RESPONSABILIDADES

A implementação desta Instrução de trabalho é da responsabilidade da Direção da GFIN.

4. REFERÊNCIAS, DEFINIÇÕES E ABREVIATURAS

DM - Dispositivo médico
GFIN - Gestão Financeira
CDM - Código de Dispositivo Médico

5. DESCRIÇÃO

1) Iniciar no módulo do Imobilizado com as suas credenciais de acesso.
2) Selecionar Gestão do Imobilizado no canto superior esquerdo e na aba aberta selecionar inventariação.
3) Para iniciar o registo de inventário pressionar 3 vezes no "Enter" de forma a ficar no campo de Designação.

   Nota: ao registar dispositivos médicos, dirigir-se a [1] onde, de acordo com a informação encontrada na fatura, deve preencher os campos de Marca e/ou Modelo e/ou Código DM (CDM). Com o(s) campo(s) preenchido(s), clique em pesquisar e a designação adequada para o dispositivo será exibida no lado direito do resultado.
4) Após este passo, progredir com o registo normal dos bens do imobilizado.

6. DOCUMENTOS RELACIONADOS

[1] - https://www.infarmed.pt/web/infarmed/pesquisa-dispositivos

ELABORAÇÃO	*APROVAÇÃO*
Rodrigo Manuel Farate de Albuquerque	
Data:	

Appendix D - UAIM substitution model

	2016	2017	2018	2019	2020	2021
Years	0	1	2	3	4	5
Capitalization Rate (i)	2,00%	2,00%	2,00%	2,00%	2,00%	2,00%
Inflation Rate (θ)	0,60%	1,40%	1,00%	0,30%	0,00%	1,30%
Apparent Rate (ia)	2,61%	3,43%	3,02%	2,31%	2,00%	3,33%
Acquisition Costs	2 648 000,00 €					
Functioning Costs		430 537,83 €	219 900,93 €	288 476,26 €	231 879,81 €	241 559,23 €
Maintenance Costs		104 178,08 €	104 178,08 €	195 000,00 €	261 000,00 €	276 000,00 €
Non production Costs		374 719,38 €	461 284,20 €	448 461,25 €	297 404,14 €	325 397,45 €
Present Value (P)		879 293,12 €	739 992,75 €	870 329,04 €	730 100,21 €	715 743,10 €
Accumulated Costs		3 439 528,26 €	4 179 521,01 €	5 049 850,05 €	5 779 950,27 €	6 495 693,37 €
Linear						
Cession Value		2 484 375,00 €	2 320 750,00 €	2 157 125,00 €	1 993 500,00 €	1 829 875,00 €
Present Value (P')		2 402 033,30 €	2 186 680,18 €	2 014 521,92 €	1 841 685,86 €	1 553 722,08 €
P-P'		1 037 494,96 €	1 992 840,83 €	3 035 328,13 €	3 938 264,41 €	4 941 971,28 €
Annual Income		1 073 060,29 €	1 041 782,08 €	1 058 793,73 €	1 034 281,78 €	1 089 166,44 €
Sum of digits						
Cession Value		2 340 000,00 €	2 051 250,00 €	1 781 750,00 €	1 531 500,00 €	1 300 500,00 €
Present Value (P')		2 262 443,44 €	1 932 749,20 €	1 663 962,19 €	1 414 869,27 €	1 104 236,94 €
P-P'		1 177 084,82 €	2 246 771,81 €	3 385 887,86 €	4 365 081,00 €	5 391 456,43 €
Annual Income		1 217 435,29 €	1 174 527,62 €	1 181 077,20 €	1 146 373,95 €	1 188 228,96 €
Exponential						
Cession Value		2 001 270,00 €	1 512 493,06 €	1 143 091,76 €	863 910,59 €	652 914,79 €
Present Value (P')		1 934 940,25 €	1 425 116,27 €	1 067 524,33 €	798 119,85 €	554 381,10 €
P-P'		1 504 588,01 €	2 754 404,74 €	3 982 325,73 €	4 981 830,42 €	5 941 312,26 €
Annual Income		1 556 165,29 €	1 439 898,98 €	1 389 128,74 €	1 308 347,00 €	1 309 412,28 €
Inverse Sum of digits						
Cession Value		2 628 750,00 €	2 590 250,00 €	2 532 500,00 €	2 455 500,00 €	2 359 250,00 €
Present Value (P)		2 541 623,16 €	2 440 611,15 €	2 365 081,66 €	2 268 502,44 €	2 003 207,23 €
P-P'		897 905,10 €	1 738 909,86 €	2 684 768,40 €	3 511 447,82 €	4 492 486,14 €
Annual Income		928 685,29 €	909 036,53 €	936 510,27 €	922 189,60 €	990 103,92 €

Figure 6.1: Calculation of UAIM model (part 01)

	2022	2023	2024	2025	2026	2027
Years	6	7	8	9	10	11
Capitalization Rate (i)	2,00%	2,00%	2,00%	2,00%	2,00%	2,00%
Inflation Rate (θ)	7,80%	4,30%	2,30%	1,90%	1,46%	1,46%
Apparent Rate (ia)	9,96%	6,39%	4,35%	3,94%	3,48%	3,48%
Acquisition Costs						
Functioning Costs	264 024,70 €	278 919,87 €	291 395,73 €	283 083,34 €	285 981,22 €	284 970,95 €
Maintenance Costs	283 500,00 €	268 500,00 €	228 000,00 €	326 599,99 €	381 883,73 €	454 816,44 €
Non production Costs	367 533,72 €	258 909,02 €	171 053,24 €	166 220,94 €	165 955,15 €	165 940,53 €
Present Value (P)	517 768,02 €	522 782,28 €	491 275,54 €	548 073,67 €	591 987,20 €	621 386,34 €
Accumulated Costs	7 013 461,39 €	7 536 243,67 €	8 027 519,20 €	8 575 592,87 €	9 167 580,07 €	9 788 966,41 €
Linear						
Cession Value	1 666 250,00 €	1 502 625,00 €	1 339 000,00 €	1 175 375,00 €	1 011 750,00 €	848 125,00 €
Present Value (P')	942 815,18 €	974 224,95 €	952 739,42 €	830 246,87 €	718 312,07 €	581 867,11 €
P-P'	6 070 646,21 €	6 562 018,72 €	7 074 779,79 €	7 745 346,00 €	8 449 268,00 €	9 207 099,30 €
Annual Income	1 392 068,37 €	1 191 664,88 €	1 065 866,55 €	1 038 753,80 €	1 015 166,52 €	1 021 977,76 €
Sum of digits						
Cession Value	1 088 750,00 €	896 250,00 €	723 000,00 €	569 000,00 €	434 250,00 €	318 750,00 €
Present Value (P')	616 048,03 €	581 082,51 €	514 436,59 €	401 923,19 €	308 304,44 €	218 682,55 €
P-P'	6 397 413,36 €	6 955 161,15 €	7 513 082,61 €	8 173 669,68 €	8 859 275,63 €	9 570 283,86 €
Annual Income	1 466 999,80 €	1 263 059,69 €	1 131 900,03 €	1 096 197,70 €	1 064 428,30 €	1 062 290,84 €
Exponential						
Cession Value	493 451,20 €	372 933,94 €	281 851,02 €	213 013,60 €	160 988,56 €	121 669,78 €
Present Value (P')	279 209,77 €	241 791,23 €	200 545,62 €	150 465,91 €	114 297,04 €	83 473,13 €
P-P'	6 734 251,62 €	7 294 452,43 €	7 826 973,59 €	8 425 126,96 €	9 053 283,03 €	9 705 493,29 €
Annual Income	1 544 240,66 €	1 324 675,10 €	1 179 189,97 €	1 129 921,46 €	1 087 737,99 €	1 077 298,94 €
Inverse Sum of digits						
Cession Value	2 243 750,00 €	2 109 000,00 €	1 955 000,00 €	1 781 750,00 €	1 589 250,00 €	1 377 500,00 €
Present Value (P)	1 269 582,33 €	1 367 367,39 €	1 391 042,24 €	1 258 570,55 €	1 128 319,70 €	945 051,66 €
P-P'	5 743 879,06 €	6 168 876,28 €	6 636 476,96 €	7 317 022,32 €	8 039 260,37 €	8 843 914,75 €
Annual Income	1 317 136,94 €	1 120 270,08 €	999 833,07 €	981 309,91 €	965 904,73 €	981 664,68 €

Figure 6.2: Calculation of UAIM model (part 02)

	2028	2029	2030	2031	2032
Years	12	13	14	15	16
Capitalization Rate (i)	2,00%	2,00%	2,00%	2,00%	2,00%
Inflation Rate (θ)	1,46%	1,46%	1,46%	1,46%	1,46%
Apparent Rate (ia)	3,48%	3,48%	3,48%	3,48%	3,48%
Acquisition Costs					
Functioning Costs	285 323,16 €	285 200,37 €	285 243,18 €	285 228,25 €	285 233,46 €
Maintenance Costs	551 735,79 €	681 735,88 €	858 007,62 €	1 099 907,44 €	1 436 187,48 €
Non production Costs	165 939,73 €	165 939,69 €	165 939,68 €	165 939,68 €	165 939,68 €
Present Value (P)	664 948,94 €	725 762,10 €	810 473,40 €	927 882,17 €	1 091 035,31 €
Accumulated Costs	10 453 915,35 €	11 179 677,45 €	11 990 150,85 €	12 918 033,02 €	14 009 068,33 €
Linear					
Cession Value	684 500,00 €	520 875,00 €	357 250,00 €	193 625,00 €	30 000,00 €
Present Value (P')	453 796,76 €	333 691,73 €	221 160,81 €	115 830,08 €	17 342,24 €
P-P'	10 000 118,59 €	10 845 985,72 €	11 768 990,04 €	12 802 202,94 €	13 991 726,09 €
Annual Income	1 033 918,13 €	1 051 711,83 €	1 076 586,76 €	1 110 340,39 €	1 155 571,73 €
Sum of digits					
Cession Value	222 500,00 €	145 500,00 €	87 750,00 €	49 250,00 €	30 000,00 €
Present Value (P')	147 508,81 €	93 212,67 €	54 322,91 €	29 462,27 €	17 342,24 €
P-P'	10 306 406,54 €	11 086 464,78 €	11 935 827,94 €	12 888 570,75 €	13 991 726,09 €
Annual Income	1 065 585,42 €	1 075 030,57 €	1 091 848,52 €	1 117 831,10 €	1 155 571,73 €
Exponential					
Cession Value	91 953,96 €	69 495,73 €	52 522,56 €	39 694,79 €	30 000,00 €
Present Value (P')	60 961,88 €	44 521,53 €	32 514,85 €	23 746,16 €	17 342,24 €
P-P'	10 392 953,47 €	11 135 155,92 €	11 957 636,00 €	12 894 286,85 €	13 991 726,09 €
Annual Income	1 074 533,56 €	1 079 752,04 €	1 093 843,45 €	1 118 326,86 €	1 155 571,73 €
Inverse Sum of digits					
Cession Value	1 146 500,00 €	896 250,00 €	626 750,00 €	338 000,00 €	30 000,00 €
Present Value (P)	760 084,71 €	574 170,80 €	387 998,70 €	202 197,89 €	17 342,24 €
P-P'	9 693 830,64 €	10 605 506,65 €	11 602 152,15 €	12 715 835,12 €	13 991 726,09 €
Annual Income	1 002 250,84 €	1 028 393,09 €	1 061 325,00 €	1 102 849,67 €	1 155 571,73 €

Figure 6.3: Calculation of UAIM model (part 03)

Appendix E - MTACM substitution model

	2016	2017	2018	2019	2020	2021
Years	0	1	2	3	4	5
Capitalization Rate (i)	2,00%	2,00%	2,00%	2,00%	2,00%	2,00%
Inflation Rate (θ)	0,60%	1,40%	1,00%	0,30%	0,00%	1,30%
Apparent Rate (ia)	2,61%	3,43%	3,02%	2,31%	2,00%	3,33%
Acquisition Costs	2 648 000,00 €					
Functioning Costs		217 092,67 €	219 900,93 €	288 476,26 €	231 879,81 €	241 559,23 €
Maintenance Costs		104 178,08 €	104 178,08 €	195 000,00 €	261 000,00 €	276 000,00 €
Non production Costs		374 719,38 €	461 284,20 €	448 461,25 €	297 404,14 €	325 397,45 €
Accumulated Costs		695 990,13 €	1 481 353,34 €	2 413 290,85 €	3 203 574,80 €	4 046 531,48 €
C'n		695 990,13 €	740 676,67 €	804 430,28 €	800 893,70 €	809 306,30 €
Linear						
Cession Value		2 484 375,00 €	2 320 750,00 €	2 157 125,00 €	1 993 500,00 €	1 829 875,00 €
C''n		163 625,00 €	163 625,00 €	163 625,00 €	163 625,00 €	163 625,00 €
Cn		859 615,13 €	904 301,67 €	968 055,28 €	964 518,70 €	972 931,30 €
Sum of digits						
Cession Value		2 340 000,00 €	2 051 250,00 €	1 781 750,00 €	1 531 500,00 €	1 300 500,00 €
C''n		308 000,00 €	298 375,00 €	288 750,00 €	279 125,00 €	269 500,00 €
Cn		1 003 990,13 €	1 039 051,67 €	1 093 180,28 €	1 080 018,70 €	1 078 806,30 €
Exponential						
Cession Value		2 001 270,00 €	1 512 493,06 €	1 143 091,76 €	863 910,59 €	652 914,79 €
C''n		646 730,00 €	567 753,47 €	501 636,08 €	446 022,35 €	399 017,04 €
Cn		1 342 720,12 €	1 308 430,14 €	1 306 066,36 €	1 246 916,05 €	1 208 323,34 €
Inverse Sum of digits						
Cession Value		2 628 750,00 €	2 590 250,00 €	2 532 500,00 €	2 455 500,00 €	2 359 250,00 €
C''n		19 250,00 €	28 875,00 €	38 500,00 €	48 125,00 €	57 750,00 €
Cn		715 240,13 €	769 551,67 €	842 930,28 €	849 018,70 €	867 056,30 €

Figure 6.4: Calculation of MTACM model (part 01)

	2022	2023	2024	2025	2026	2027
Years	6	7	8	9	10	11
Capitalization Rate (i)	2,00%	2,00%	2,00%	2,00%	2,00%	2,00%
Inflation Rate (θ)	7,80%	4,30%	2,30%	1,90%	1,46%	1,46%
Apparent Rate (ia)	9,96%	6,39%	4,35%	3,94%	3,48%	3,48%
Acquisition Costs						
Functioning Costs	264 024,70 €	278 919,87 €	291 395,73 €	286 083,34 €	291 981,22 €	293 970,95 €
Maintenance Costs	283 500,00 €	268 500,00 €	228 000,00 €	326 599,99 €	381 883,73 €	454 816,44 €
Non production Costs	367 533,72 €	258 909,02 €	171 053,24 €	166 220,94 €	165 955,15 €	165 940,53 €
Accumulated Costs	4 961 589,90 €	5 767 918,78 €	6 458 367,75 €	7 237 272,02 €	8 077 092,12 €	8 991 820,05 €
C'n	826 931,65 €	823 988,40 €	807 295,97 €	807 295,97 €	807 709,21 €	817 438,19 €
Linear						
Cession Value	1 666 250,00 €	1 502 625,00 €	1 339 000,00 €	1 175 375,00 €	1 011 750,00 €	848 125,00 €
C''n	163 625,00 €	163 625,00 €	163 625,00 €	163 625,00 €	163 625,00 €	163 625,00 €
Cn	990 556,65 €	987 613,40 €	970 920,97 €	970 920,97 €	971 334,21 €	981 063,19 €
Sum of digits						
Cession Value	1 088 750,00 €	896 250,00 €	723 000,00 €	569 000,00 €	434 250,00 €	318 750,00 €
C''n	259 875,00 €	250 250,00 €	240 625,00 €	231 000,00 €	221 375,00 €	211 750,00 €
Cn	1 086 806,65 €	1 074 238,40 €	1 047 920,97 €	1 038 295,97 €	1 029 084,21 €	1 029 188,19 €
Exponential						
Cession Value	493 451,20 €	372 933,94 €	281 851,02 €	213 013,60 €	160 988,56 €	121 669,78 €
C''n	359 091,47 €	325 009,44 €	295 768,62 €	270 554,04 €	248 701,14 €	229 666,38 €
Cn	1 186 023,12 €	1 148 997,83 €	1 103 064,59 €	1 077 850,01 €	1 056 410,36 €	1 047 104,57 €
Inverse Sum of digits						
Cession Value	2 243 750,00 €	2 109 000,00 €	1 955 000,00 €	1 781 750,00 €	1 589 250,00 €	1 377 500,00 €
C''n	67 375,00 €	77 000,00 €	86 625,00 €	96 250,00 €	105 875,00 €	115 500,00 €
Cn	894 306,65 €	900 988,40 €	893 920,97 €	903 545,97 €	913 584,21 €	932 938,19 €

Figure 6.5: Calculation of MTACM model (part 02)

	2028	2029	2030	2031	2032
Years	12	13	14	15	16
Capitalization Rate (i)	2,00%	2,00%	2,00%	2,00%	2,00%
Inflation Rate (θ)	1,46%	1,46%	1,46%	1,46%	1,46%
Apparent Rate (ia)	3,48%	3,48%	3,48%	3,48%	3,48%
Acquisition Costs					
Functioning Costs	297 323,16 €	300 200,37 €	303 243,18 €	306 228,25 €	309 233,46 €
Maintenance Costs	551 735,79 €	681 735,88 €	858 007,62 €	1 099 907,44 €	1 436 187,48 €
Non production Costs	165 939,73 €	165 939,69 €	165 939,68 €	165 939,68 €	165 939,68 €
Accumulated Costs	10 006 818,73 €	11 154 694,66 €	12 481 885,15 €	14 053 960,52 €	15 965 321,14 €
C'n	833 901,56 €	858 053,44 €	891 563,22 €	936 930,70 €	997 832,57 €
Linear					
Cession Value	684 500,00 €	520 875,00 €	357 250,00 €	193 625,00 €	30 000,00 €
C''n	163 625,00 €	163 625,00 €	163 625,00 €	163 625,00 €	163 625,00 €
Cn	997 526,56 €	1 021 678,44 €	1 055 188,22 €	1 100 555,70 €	1 161 457,57 €
Sum of digits					
Cession Value	222 500,00 €	145 500,00 €	87 750,00 €	49 250,00 €	30 000,00 €
C''n	202 125,00 €	192 500,00 €	182 875,00 €	173 250,00 €	163 625,00 €
Cn	1 036 026,56 €	1 050 553,44 €	1 074 438,22 €	1 110 180,70 €	1 161 457,57 €
Exponential					
Cession Value	91 953,96 €	69 495,73 €	52 522,56 €	39 694,79 €	30 000,00 €
C''n	213 003,84 €	198 346,48 €	185 391,25 €	173 887,01 €	163 625,00 €
Cn	1 046 905,40 €	1 056 399,92 €	1 076 954,47 €	1 110 817,72 €	1 161 457,57 €
Inverse Sum of digits					
Cession Value	1 146 500,00 €	896 250,00 €	626 750,00 €	338 000,00 €	30 000,00 €
C''n	125 125,00 €	134 750,00 €	144 375,00 €	154 000,00 €	163 625,00 €
Cn	959 026,56 €	992 803,44 €	1 035 938,22 €	1 090 930,70 €	1 161 457,57 €

Figure 6.6: Calculation of MTACM model (part 03)

Appendix F - MTACM-RPV substitution model

	2016	2017	2018	2019	2020	2021
Years	0	1	2	3	4	5
Capitalization Rate (i)	2,00%	2,00%	2,00%	2,00%	2,00%	2,00%
Inflation Rate (θ)	0,60%	1,40%	1,00%	0,30%	0,00%	1,30%
Apparent Rate (ia)	2,61%	3,43%	3,02%	2,31%	2,00%	3,33%
Acquisition Costs	2 648 000,00 €					
Functioning Costs		430 537,83 €	219 900,93 €	288 476,26 €	231 879,81 €	241 559,23 €
Maintenance Costs		104 178,08 €	104 178,08 €	195 000,00 €	261 000,00 €	276 000,00 €
Non production Costs		374 719,38 €	461 284,20 €	448 461,25 €	297 404,14 €	325 397,45 €
Present Value		879 293,12 €	739 992,75 €	870 329,04 €	730 100,21 €	715 743,10 €
Accumulated Costs		879 293,12 €	1 619 285,87 €	2 489 614,91 €	3 219 715,13 €	3 935 458,23 €
C'n		879 293,12 €	809 642,94 €	829 871,64 €	804 928,78 €	787 091,65 €
Linear						
Cession Value		2 484 375,00 €	2 320 750,00 €	2 157 125,00 €	1 993 500,00 €	1 829 875,00 €
Present Value		2 402 033,30 €	2 186 680,18 €	2 014 521,92 €	1 841 685,86 €	1 553 722,08 €
C''n		245 966,70 €	230 659,91 €	211 159,36 €	201 578,54 €	218 855,58 €
Cn		1 125 259,82 €	1 040 302,85 €	1 041 031,00 €	1 006 507,32 €	1 005 947,23 €
Sum of digits						
Cession Value		2 340 000,00 €	2 051 250,00 €	1 781 750,00 €	1 531 500,00 €	1 300 500,00 €
Present Value		2 262 443,44 €	1 932 749,20 €	1 663 962,19 €	1 414 869,27 €	1 104 236,94 €
C''n		385 556,56 €	357 625,40 €	328 012,60 €	308 282,68 €	308 752,61 €
Cn		1 264 849,68 €	1 167 268,33 €	1 157 884,24 €	1 113 211,46 €	1 095 844,26 €
Exponential						
Cession Value		2 001 270,00 €	1 512 493,06 €	1 143 091,76 €	863 910,59 €	652 914,79 €
Present Value		1 934 940,25 €	1 425 116,27 €	1 067 524,33 €	798 119,85 €	554 381,10 €
C''n		713 059,75 €	611 441,86 €	526 825,22 €	462 470,04 €	418 723,78 €
Cn		1 592 352,87 €	1 421 084,80 €	1 356 696,86 €	1 267 398,82 €	1 205 815,42 €
Inverse Sum of digits						
Cession Value		2 628 750,00 €	2 590 250,00 €	2 532 500,00 €	2 455 500,00 €	2 359 250,00 €
Present Value		2 541 623,16 €	2 440 611,15 €	2 365 081,66 €	2 268 502,44 €	2 003 207,23 €
C''n		106 376,84 €	103 694,42 €	94 306,11 €	94 874,39 €	128 958,55 €
Cn		985 669,96 €	913 337,36 €	924 177,75 €	899 803,17 €	916 050,20 €

Figure 6.7: Calculation of MTACM-RPV model (part 01)

	2022	2023	2024	2025	2026	2027
Years	6	7	8	9	10	11
Capitalization Rate (i)	2,00%	2,00%	2,00%	2,00%	2,00%	2,00%
Inflation Rate (θ)	7,80%	4,30%	2,30%	1,90%	1,46%	1,46%
Apparent Rate (ia)	9,96%	6,39%	4,35%	3,94%	3,48%	3,48%
Acquisition Costs						
Functioning Costs	264 024,70 €	278 919,87 €	291 395,73 €	286 083,34 €	291 981,22 €	293 970,95 €
Maintenance Costs	283 500,00 €	268 500,00 €	228 000,00 €	326 599,99 €	381 883,73 €	454 816,44 €
Non production Costs	367 533,72 €	258 909,02 €	171 053,24 €	166 220,94 €	165 955,15 €	165 940,53 €
Present Value	517 768,02 €	522 782,28 €	491 275,54 €	550 192,77 €	596 247,01 €	627 560,91 €
Accumulated Costs	4 453 226,25 €	4 976 008,53 €	5 467 284,06 €	6 017 476,84 €	6 613 723,85 €	7 241 284,76 €
C'n	742 204,38 €	710 858,36 €	683 410,51 €	683 410,51 €	661 372,39 €	658 298,61 €
Linear						
Cession Value	1 666 250,00 €	1 502 625,00 €	1 339 000,00 €	1 175 375,00 €	1 011 750,00 €	848 125,00 €
Present Value	942 815,18 €	974 224,95 €	952 739,42 €	830 246,87 €	718 312,07 €	581 867,11 €
C''n	284 197,47 €	239 110,72 €	211 907,57 €	201 972,57 €	192 968,79 €	187 830,26 €
Cn	1 026 401,85 €	949 969,08 €	895 318,08 €	885 383,08 €	854 341,18 €	846 128,88 €
Sum of digits						
Cession Value	1 088 750,00 €	896 250,00 €	723 000,00 €	569 000,00 €	434 250,00 €	318 750,00 €
Present Value	616 048,03 €	581 082,51 €	514 436,59 €	401 923,19 €	308 304,44 €	218 682,55 €
C''n	338 658,66 €	295 273,93 €	266 695,43 €	249 564,09 €	233 969,56 €	220 847,04 €
Cn	1 080 863,04 €	1 006 132,29 €	950 105,93 €	932 974,60 €	895 341,94 €	879 145,66 €
Exponential						
Cession Value	493 451,20 €	372 933,94 €	281 851,02 €	213 013,60 €	160 988,56 €	121 669,78 €
Present Value	279 209,77 €	241 791,23 €	200 545,62 €	150 465,91 €	114 297,04 €	83 473,13 €
C''n	394 798,37 €	343 744,11 €	305 931,80 €	277 503,79 €	253 370,30 €	233 138,81 €
Cn	1 137 002,75 €	1 054 602,47 €	989 342,31 €	960 914,30 €	914 742,68 €	891 437,42 €
Inverse Sum of digits						
Cession Value	2 243 750,00 €	2 109 000,00 €	1 955 000,00 €	1 781 750,00 €	1 589 250,00 €	1 377 500,00 €
Present Value	1 269 582,33 €	1 367 367,39 €	1 391 042,24 €	1 258 570,55 €	1 128 319,70 €	945 051,66 €
C''n	229 736,28 €	182 947,52 €	157 119,72 €	154 381,05 €	151 968,03 €	154 813,49 €
Cn	971 940,65 €	893 805,88 €	840 530,23 €	837 791,56 €	813 340,42 €	813 112,10 €

Figure 6.8: Calculation of MTACM-RPV model (part 02)

	2028	2029	2030	2031	2032
Years	12	13	14	15	16
Capitalization Rate (i)	2,00%	2,00%	2,00%	2,00%	2,00%
Inflation Rate (θ)	1,46%	1,46%	1,46%	1,46%	1,46%
Apparent Rate (ia)	3,48%	3,48%	3,48%	3,48%	3,48%
Acquisition Costs					
Functioning Costs	297 323,16 €	300 200,37 €	303 243,18 €	306 228,25 €	309 233,46 €
Maintenance Costs	551 735,79 €	681 735,88 €	858 007,62 €	1 099 907,44 €	1 436 187,48 €
Non production Costs	165 939,73 €	165 939,69 €	165 939,68 €	165 939,68 €	165 939,68 €
Present Value	672 904,47 €	735 371,65 €	821 616,57 €	940 444,75 €	1 104 909,10 €
Accumulated Costs	7 914 189,23 €	8 649 560,89 €	9 471 177,45 €	10 411 622,21 €	11 516 531,31 €
C'n	659 515,77 €	665 350,84 €	676 512,68 €	694 108,15 €	719 783,21 €
Linear					
Cession Value	684 500,00 €	520 875,00 €	357 250,00 €	193 625,00 €	30 000,00 €
Present Value	453 796,76 €	333 691,73 €	221 160,81 €	115 830,08 €	17 342,24 €
C''n	182 850,27 €	178 023,71 €	173 345,66 €	168 811,33 €	164 416,11 €
Cn	842 366,04 €	843 374,55 €	849 858,33 €	862 919,48 €	884 199,32 €
Sum of digits					
Cession Value	222 500,00 €	145 500,00 €	87 750,00 €	49 250,00 €	30 000,00 €
Present Value	147 508,81 €	93 212,67 €	54 322,91 €	29 462,27 €	17 342,24 €
C''n	208 374,27 €	196 522,10 €	185 262,65 €	174 569,18 €	164 416,11 €
Cn	867 890,04 €	861 872,94 €	861 775,32 €	868 677,33 €	884 199,32 €
Exponential					
Cession Value	91 953,96 €	69 495,73 €	52 522,56 €	39 694,79 €	30 000,00 €
Present Value	60 961,88 €	44 521,53 €	32 514,85 €	23 746,16 €	17 342,24 €
C''n	215 586,51 €	200 267,57 €	186 820,37 €	174 950,26 €	164 416,11 €
Cn	875 102,28 €	865 618,41 €	863 333,04 €	869 058,40 €	884 199,32 €
Inverse Sum of digits					
Cession Value	1 146 500,00 €	896 250,00 €	626 750,00 €	338 000,00 €	30 000,00 €
Present Value	760 084,71 €	574 170,80 €	387 998,70 €	202 197,89 €	17 342,24 €
C''n	157 326,27 €	159 525,32 €	161 428,66 €	163 053,47 €	164 416,11 €
Cn	816 842,04 €	824 876,16 €	837 941,34 €	857 161,62 €	884 199,32 €

Figure 6.9: Calculation of MTACM-RPV model (part 03)

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