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Integrating Digitalization and Asset Health Index for Strategic Life Cycle Cost Analysis of Power Converters

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Abstract: In the context of energy storage systems, optimizing the life cycle of power converters is crucial for reducing costs, making informed decisions, and ensuring sustainability. This study presents a comprehensive methodology for calculating the life cycle cost (LCC) of power converters, employing a nine-step process that integrates digitalization, Internet of Things (IoT) technologies, and the Asset Health Index (AHI). The methodology adapts the Woodward model to provide a detailed cost analysis, encompassing the acquisition, operation, maintenance, and end-of-life phases. Our findings reveal significant insights into asset management, highlighting the importance of preventive and major maintenance in controlling failure rates and extending asset life. This study concludes that adopting sustainable business models and leveraging advanced technologies can enhance the reliability and maintainability of power converters, ultimately leading to more competitive and environmentally friendly energy storage solutions.

Keywords: asset management; cost analysis; digitalization; energy storage; IoT; life cycle cost; maintenance management; power converters; sustainability

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1. Introduction

In the context of maintenance management, the life cycle of an item is defined as the "series of states through which an item passes from its conception to its disposal", as per the maintenance terminology standard UNE-EN 13306:2018 [1]. This study draws on Crespo's (2007) eight-phase Maintenance Management Model [2], where life cycle cost analysis (LCCA) techniques are integrated into Phase 7 (Figure 1). The LCCA includes investment planning, facility development, asset management, and end-of-life considerations. The LCCA typically involves analyzing costs such as initial research and development, production and construction, operating and support, and disincorporation and removal. The life cycle cost analysis becomes important when considering servitization as it affords visibility of the costs that are inherent to the execution of a product or service—from conception to disposal [3]. Companies adopting service-based business models, product–service systems (PSSs), can thus design more competitive and sustainable offerings [4].

This article aims to address the need for the application of the LCCA concept in the field of servitization, which provides a comprehensive view of all the expenses associated with a product or service over every phase of the asset's life. This is especially important for businesses that are inclined toward service-supported product business models like the product–service systems (PSSs) to allow them to fashion more optimal service solutions. Basically, this paper is intended to develop and validate a comprehensive framework for the condition monitoring and asset management of power electronic converters, integrating digital twin technologies with strategic life cycle cost analysis. The intended purpose of the LCCA of an asset is diverse and can be applied to various objectives. In the present research, the general objective is to develop a methodology for calculating the life cycle cost of a power converter to support after-sales services. It encompasses the following particular objectives:

O1. The extension of non-invasive condition monitoring methods for improving the prognostic performance of the Asset Health Indices (AHIs).
O2. Examining the consequences of an AHI-LCC integration strategy for analytical recurring cost decisions in maintenance management.
O3. Introducing a system-thinking perspective for transforming asset centric power system management from a product-based view to a service-oriented paradigm.

As previously stated, the suggested process for the life cycle cost research can facilitate a number of investigations, such as assessing and contrasting design methodologies, carrying out technical or project economic feasibility studies, and determining cost drivers for efficient cost reduction. It also aims to determine the actual cost incurred by the company for a given asset, evaluate and compare alternative strategies for asset use, operation, testing, and maintenance, and assess replacement strategies and life extension options. Furthermore, it facilitates decision-making in relation to equipment investment and resource allocation, assesses collateral criteria, plans long-term financing, and supports projects for new equipment or specific stages of new equipment development.

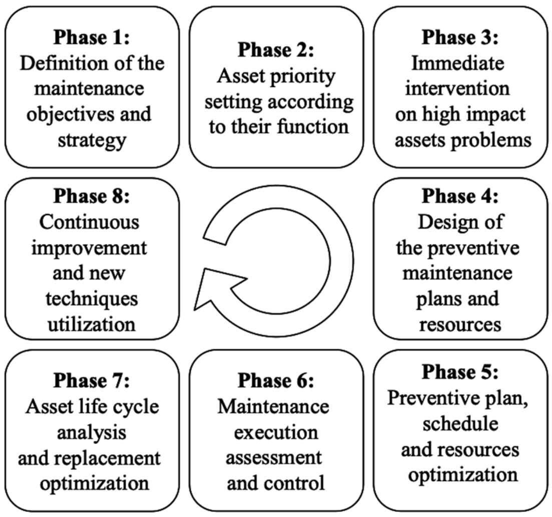

Figure 1. Maintenance management process model [2].

This article focuses on a case study that provides insights into the cost implications of a power converter, taking into account significant factors such as potential changes in inflation and discount rates, and possible increases in failure frequencies, which could impact corrective maintenance costs as per MIL-HDBK-217F [5]. Additionally, there can also be increased preventive maintenance costs, which reduce the corrective maintenance costs, meaning the overall maintenance expenses are optimally utilized while safety and functioning conditions are met. This study also looks at possible new standards and regulations related to component renovations and inspections. Given this, the present study offers a novel method for asset management and condition monitoring, which is a significant scientific advancement in the field of power systems. It contributes to the development of applications of digital twins by providing a method for non-invasive and robust condition monitoring of power electronic converters that can be extended to other components. This not only strengthens the application of the asset health indices but also the combination of digitalization with quantitative life cycle cost analysis as an organizing factor to boost the efficiency of maintenance management systems.

Nevertheless, it is assumed that this study has some limitations, primarily related to the degree of accuracy and the conclusions that are obtained from the real records as documented in the company's information system, which includes maintenance, financial, and economic data. The outcomes are further impacted by the availability of transaction and reporting mechanisms for obtaining aggregated, disaggregated, or direct information. It is crucial to remember that for some assets, there can be times when the information that is needed is not available; this problem usually becomes worse as the asset ages. Furthermore, because they are the focus of other research lines, technical feasibility studies on the Asset Health Index (AHI), prolonging usable life, and opportunities and constraints in designing new services are not included in the scope of this study.

This paper is structured to first introduce the motivation and objectives of the present study, followed by a detailed methodology for conducting the life cycle cost analysis. It then describes the power converter case study by analyzing the factors that were taken into consideration and the limitations met. The last section is about the implications of the findings and the potential avenues for further studies.

2. Background

Previous works have greatly contributed to earlier academic work in asset management and condition monitoring for power systems. Ayu and Yunusa-Kaltungo (2020) provided a thorough framework that emphasized improving power systems' dependability and availability; as a result, cost-effective maintenance techniques were suggested [6]. Peng et al. (2021) presented a digital-twin-based approach for the condition monitoring of power electronic converters non-invasively and robustly, as well as emphasizing its low cost [7]. Power transformers were analyzed in Bohatyrewicz and Mrozik (2021), where the authors highlighted that the health index method yields optimistic results based on criticality and operating conditions [8]. Zhou et al. (2023) provided a systematic overview of switchgear asset management that includes condition monitoring, health evaluation and maintenance planning for the enhanced cost-effectiveness and service life of old switchgear equipment [9]. Rediansyah et al. (2021) used the Random Forest AI methods to predict the power transformers' health index numbers associated with data uncertainty [10]. In the last study, Joseph et al. (2018) presented a critical review on the asset management of power electronic converters, focusing on condition monitoring, and maintenance policies for life cycle optimization [11]. A summary of contributions is shown in Table 1.

Table 1. Summary of previous contributions.

Research	Similarities	Differences	Research Gap	Reference
Ayu, K., and Yunusa-Kaltungo, A. (2020)	Focuses on cost-effective maintenance and asset management.	Proposes a holistic framework specifically for power systems.	Need for practical implementation of the proposed framework in diverse power systems.	[6]
Peng, Y., Zhao, S., and Wang, H. (2021)	Emphasizes condition monitoring.	Utilizes digital twin technology for DC–DC converters.	Exploration of digital twin applications in other power system components.	[7]
Bohatyrewicz, P., and Mrozik, A. (2021)	Uses health index for condition assessment.	Focuses on power transformers and their operating conditions.	Further validation of health index methods across different transformer types.	[8]
Zhou, N., Xu, Y., Cho, S., and Wee, C. (2023)	Discusses condition monitoring and maintenance strategies.	Provides a comprehensive review of switchgear asset management.	Identification of limitations in current methods and future research directions.	[9]
Rediansyah, D., Prasojo, R., Suwarno, . . ., and Abu-Siada, A. (2021)	Utilizes AI for health index prediction.	Addresses data uncertainty in power transformer health assessment.	Exploration of AI techniques for other power system components.	[10]
Joseph, T., Ugalde-Loo, C., Liang, J., and Coventry, P. (2018)	Highlights the importance of condition monitoring.	Focuses on asset management strategies for power electronic converters.	Development of new monitoring and assessment methods for HVDC and FACTS devices.	[11]

The present contribution addresses several of the abovementioned research gaps in the field of power systems. In fact, it emphasizes the necessity of applying the suggested framework to various power systems in practice, highlighting the importance of asset management and condition-monitoring techniques. A reliable and non-invasive method for monitoring the state of power electronic converters has been proposed, which furthers research into digital twin applications and could be extended to other components. It also calls for further validation of health index methods across different transformer types, focusing on the influence of criticality and operating conditions. This paper identifies the limitations of current methods and suggests future research directions, particularly in the context of AI techniques for health index prediction and handling data uncertainty in power transformers. Further, new approaches in terms of monitoring and assessment techniques for this kind of device are also introduced to demonstrate the importance of development in these fields.

3. Methodology

The proposed methodology is structured into nine distinct steps, beginning with Step 0, a preparatory phase, and culminating in Step 8, where conclusions are drawn (Figure 2).

Figure 2. Outline of the proposed procedure.

Below is a detailed explanation of each step, beginning with the iterative Step 0 that deals with meetings about organization and documentation. For each meeting, the following elements will be identified: (i) the purpose of the meeting; (ii) the date and location; (iii) the agenda; (iv) attendees, including their workplaces and positions within the organization; (v) key agreements reached; and (vi) progress made in the project.

3.1. Identification of the Asset Under Study

The power converter used in battery energy storage applications is the main topic of this study. When applying the process to a particular converter, it is necessary to locate the installation at its operational site and make sure that the equipment, system, subsystem, or installation being studied is clearly recognized. The intervention level, defined as a subdivision within a hierarchy of elements, must be established for the life cycle cost study. Examples of intervention levels include system, subsystem, and component, as per [1]. The intervention level for this study is defined within the technical structure of the power converter. Maintenance is conducted on elements specified in the maintenance manuals, which are considered for the life cycle cost analysis [12]. For this study, and in line with the health index calculations, the critical element identified is the "Stack DC/AC 350 KW, 525–690 VAC", composed of the following components according to the technical structure: electronics (IGBTs, drivers, and control), DC-Link (capacitors), and module ventilation (fans).

3.2. Description of the Asset, Interrelations and Technical and Administrative Conditions

This step involves (i) a description of the technical characteristics of the asset, which define and differentiate it, and which may influence its cost and durability; (ii) contractual conditions, including legal, contractual, or regulatory aspects related to remuneration, penalties, operating conditions, and estimated life; and (iii) a context diagram, which is a general diagram corresponding to the facility under study and adjacent installations that influence its development.

3.3. Defining the Purpose of Life Cycle Cost Analysis

The life cycle cost calculated through the proposed procedure will initially support the study of tasks specified in Step 1, with the details, operating conditions, and contractual and operational circumstances outlined in Step 2. The primary purpose of the life cycle cost (LCC) analysis is to provide a comprehensive methodology for the intelligent management of business-impacting decisions, such as reinvestment, asset retirement, equipment or technology obsolescence and replacement, and investment analysis based on technical risk control and asset degradation. In addition to this, the LCC can also be employed to compare processes and the effects within the process flow. For example, the LCC can be used to establish the environmental and economic effect of using wood and plastic in the casing of a product. This can be achieved with the help of free life cycle assessment (LCA) programs such as open LCA, which determine the CO_2 emissions and costs relating to a specific option of the material. By raising awareness of the possible decisions related to material selection and process enhancements, respectively, methods of incorporating such comparative studies may aid in improving the assessments made. This analysis is also crucial for the digitization of equipment and the industry's evolution, as it facilitates the determination and parameterization of maintenance activities, significantly reducing the associated costs through proper, efficient, and intelligent maintenance. Moreover, by combining the LCC with other asset management tools as a form of reliability and maintainability analysis, it might be possible for the organization to have even a more comprehensive view of the asset life cycle, which in turn can assist greatly with regard to strategic choices and decision-making. Any additional purposes may also be expressed in this step, allowing the asset life cycle cost analysis to be performed according to the specified objectives.

3.4. Establishment of the Life Cycle Stages

Here, in this step, what is expected of the asset throughout its activity cycle, ranging from the design, to the construction, to the time when it may stop activity or when the useful life is expected to be extended, is ascertained. Such activities are individual for each stage of the life cycle through which the asset passes. Performing these activities requires resources, which in turn translates into costs for the owner of the power converter. Therefore, Step 4 should seek to understand all the items that incurs cost during the whole life cycle of the asset. This step specifies how the items specified in Step 5 will be assessed rather than estimating the costs involved. As was already said, the following guide helps identify the cost components by outlining the tasks that compose in each stage. Many of these activities are common across the life cycle of any asset, such as a power converter. The stages for analyzing the life cycle of an asset, in alignment with the company's business and support processes, are as follows.

3.4.1. Stage 1: Investment Planning

This stage involves identifying the asset's needs by utilizing information from various areas and stakeholders.

3.4.2. Stage 2: Development of the Installation

In this stage, the installation is developed in accordance with strategic planning and business needs, ensuring its efficient development in terms of time, cost, safety, environment and quality. Generally speaking, this stage consists of the following activities.

- Award and Launch Management: This activity manages the initiation of the project, with the corresponding communication to the assigned project manager, and processes the direct award and approval of the pre-investment proposal, which is necessary to start the engineering works for the project.
- Design and Engineering: This activity consists of the elaboration of the conceptual, basic and detailed engineering of the project, including the environmental processing.
- Permits: This activity covers the preparation of the list of assets and rights affected by the project, obtaining the necessary permits and licenses for the implementation of the project.
- Materials Management: This activity includes the management of the procurement of material resources for the project, including the search for materials in the warehouse, the placing of orders, the subsequent activation and inspection of these and, finally, the approval of the certificate of receipt of materials, of conformity and of the corresponding invoice.
- Construction: The construction of the facility is the activity encompassing the contracting of the construction, the launching of the construction, and the continuous monitoring and control of the quality, schedule, cost, safety and environment of the work.
- Commissioning and Closure: In this activity, once the work on the installation has been completed, the access and connection permits have been obtained, and the technical access contract has been signed, the necessary actions are carried out to perform the relevant tests, the necessary management to obtain the commissioning certificate and the operations for the commissioning of the installation are carried out.

3.4.3. Stage 3: Asset Management

The useful life of an asset begins with its commissioning. During this stage, the integral management of the asset is carried out, ensuring customer service and the required availability and, in accordance with the requirements of the technical management of the system, carrying out operation and maintenance with safety and efficiency criteria. This phase, in turn, is made up of different activities that overlap with each other during the life of the asset. These activities are as follows. (i) Operation: This task involves operating the asset in a way that ensures supply security, personnel and installation safety, and operational efficiency in compliance with current regulations, contracts, schedules, and directives from the system's technical manager. (ii) Maintenance: This activity covers the maintenance management of the power converter. The scope of this activity encompasses the execution of the operations to be performed on the equipment, work methods and techniques to be applied, as well as the resources required to ensure its correct operation, according to the design conditions, during its useful life.

For maintenance management, a maintenance manual is established, assisted by a CMMS system, which guarantees and controls all the activities that are carried out in the operation of the asset, leaving a faithful reflection of all the activities that are executed, as it is an auditable system. According to [1], maintenance is divided into preventive (condition-based, predictive and predetermined or systematic) and corrective (immediate or scheduled) maintenance. Preventive maintenance can be extended with improving maintenance, which is a preventive maintenance strategy that aims to correct the root causes of failures, to anticipate and prevent the generation of more serious damage to assets. For example, design modifications can be implemented to increase efficiency or safety. Restoring an element to a state where it can perform its needed function is the goal of corrective maintenance, which is performed when a failure (state of loss of the equipment's required function) is identified [1]. To carry out all these activities on the asset under study, the following required resources and infrastructure must be determined, whether specifically dedicated to the asset or shared with others: (i) human resources and staffing (team leaders, operating personnel, physical resources); (ii) administrative and management functions; (iii) infrastructure: maintenance buildings (offices, warehouses, workshops, changing rooms, etc.). However, as discussed below (Stage 5), for the determination of costs, it is not necessary to perform this detailed infrastructure data capture, but the aggregated costs at the level of detail required for the life cycle cost analysis will be obtained as indicated in Step 5.

3.4.4. Stage 4: End of Life

This is the last of the asset life cycle stages, in which one of the following two decisions will be taken with respect to the asset.

- Life Extension

In the event of considering an extension of the useful life of the asset, the necessary studies and analyses must be carried out to demonstrate the technical feasibility of continuing to operate the asset, not only in terms of its current function but also with regard to possible new requirements to be taken into account in the extended life to be considered. For example, new environmental requirements (which may affect the operation of the converter). The useful life limitation of a given asset is set to prevent failures during its operation caused by degradation over time. The fact that an asset reaches its end of life does not mean that it is no longer suitable to perform its required function beyond that time, since its degradation may be less than expected. As indicated above, a technical feasibility study to determine the viability of life extension is outside the scope of this procedure. This technical feasibility study is related to the Asset Health Index (AHI). Once the possible technical feasibility of the life extension has been determined, the future cost implications of the new technical conditions caused by the life extension can be studied. Such technical conditions could lead to the modification of maintenance plans to meet safety and service provision needs.

- Cessation of Activity

If, after analyzing the feasibility of life extension, the result is negative, either due to the technical feasibility study, economic reasons or new operating requirements, the equipment will cease its activity. The cessation of the converter's activity is a phase in itself of its life cycle, i.e., it is not the event resulting from the decision to cease its activity, but it entails new decisions and actions that may involve legal, regulatory and normative aspects, in addition to economic ones. The legal and regulatory considerations that condition, together with economic and technical considerations, the actions to be taken and the possible new status of the asset, such as dismantling and disposal, scrapping, etc., as a residual entity are outside the scope of this procedure.

3.5. Obtaining the Costs to Be Included in Each Stage

This section sets out the types of costs to be calculated and the process for calculating them to obtain the total cost.

3.5.1. General Model for Life Cycle Costing

This refers to an estimation of the asset's life cycle cost elements [2]. In the analysis of the costs associated with an asset, these are typically grouped into two main groups, CAPEX (development and investment costs) and OPEX (operation, maintenance and decommissioning costs), which vary throughout the life cycle of an asset. The Woodward model [13] is used as a model for the calculation of the life cycle cost, taking from its application procedure the instructions pertaining to the life cycle study. The Woodward model is briefly described below, with the following limitations: (i) define the system's working conditions; and (ii) explain the system's operating modes (full load, half load, and no load) and the production capabilities that must be met.

1. Establish the utilization factors. These factors should indicate the operating status within each mode of operation.
2. Identify all the basic cost categories: initial investment, development, acquisition, planned maintenance, replacement.
3. Determine the total cost per failure (TCF). Identify the main types of failures and the frequency of occurrence over time, which will be a constant value throughout the life cycle of the asset (this aspect is detailed and simplified below).
4. Determine the critical costs. Identify the cost categories with the highest impact, and analyze the drivers of high costs (propose control strategies).
5. Calculate all the costs in the present value, as at the date of the study. Define the discount factor and the expected lifetime and estimate the total costs in the present value.

Referring to the scheme in Figure 3, the Woodward model proposes the following expression to calculate the different costs generated by an industrial asset over its life cycle [13,14]:

$$\mathrm{LCC(P)} = \sum_{t=1}^{T} (\mathrm{IC} + \mathrm{OC} + \mathrm{PMC} + \mathrm{TCF} + \mathrm{MMC} - \mathrm{RV}) \quad (1)$$

where:

LCC (P) = Total life cycle costs in the present value (P), for a discount rate (i) and an expected lifetime (T).
IC = Initial cost of acquisition and installation, in the present value.
OC = Operational costs.
PMC = Preventive maintenance costs, with the peculiarities discussed below.
TCF = Total cost per failure, with the peculiarities discussed below.
MMC = Major maintenance costs, with the peculiarities discussed below.
RV = Residual value.

In relation to the quantification of the cost per failure (TCF), the Woodward model [13] proposes to assess the impact of major failures on the cost structure of a production system, based on a simple process, which is summarized below. First, the most important types of failures are determined; then, each type of failure is assigned a constant value of frequency of occurrence per year (this value, in principle, will not change over the expected lifetime); then, the cost impact per year generated by the failures on production, operations, environment and safety is estimated; and finally, the total cost impact of the failures for the years of expected lifetime is estimated in the present value at a specific discount rate. The steps to be followed to estimate the failure costs according to the Woodward model [13] are detailed below.

1. Define the failure types (f), where f = 1, . . ., F for F failure types.
2. Define the expected frequency of failures per year. It is expressed in failures per year. This frequency is assumed to be a constant value per year for the expected life cycle and is calculated from the following expression:

$$\lambda(f) = N_f / T \quad (2)$$

where:

N_f = total number of failures (of type f).
T = total expected number of years of useful life.

Calculate the costs associated with each type of failure C_f in EUR/failure. These costs include spare parts costs, labor costs, lost profits due to loss of production and operational impact.

$$C_f = MTTR_f \cdot Cpe_f \quad (3)$$

where:

$MTTR_f$ = mean time to repair each failure [hours/failure].

Cpe_f = cost of lost profit per hour (production, labor, spare parts) (EUR/hour).

3. Calculate the total costs per failure per year (EUR/year), using the following expression:

$$TCF = \sum_{f=1}^{F} C_f \cdot \lambda(f) \tag{4}$$

4. Calculate the total costs per failure in present value TCF(P) (EUR). Given an annualized value, its monetary value is estimated as a function of the number of years of expected useful life (T), for a discount rate (i). The expression to be used to estimate the total costs per failure in present value is TCF(P):

$$TCF(P) = TCF \cdot \left((1+i)^T - 1\right) \cdot \left(\left(i \cdot (1+i)^T\right)\right. \tag{5}$$

Therefore, the estimated failure costs are increased by the remaining assessed expenses (investment, planned maintenance, operations, etc.). The chosen interest rate and the expected amount of years of useful life are used to determine the total cost in the present value. When the cost calculation is made to compare the investment in different asset alternatives, which equally cover the technical needs, but with different cost structures over their life cycle, this calculation would be made for each of the alternatives, finally comparing the results obtained for each of them. In the following, this model and its cost elements will be particularized for its application to the power converter.

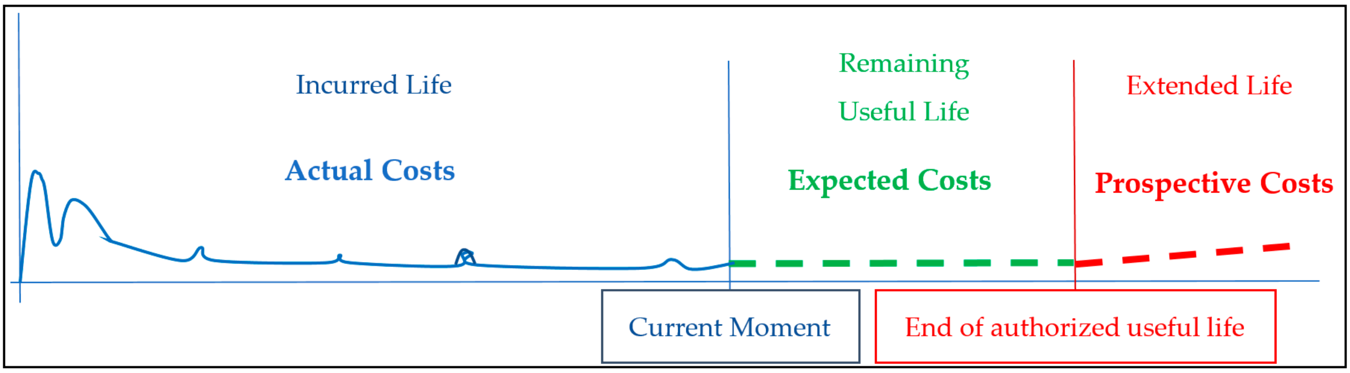

Figure 3. Cost estimation scheme according to the timing of the study.

3.5.2. Life Cycle Costing Model for a Power Converter

This section presents and explains the adaptation of the model presented in the previous section to the calculation of the life cycle of the power converter and its application from a cost point of view.

General Cost Measurement Criteria: Actual, Expected and Prospective Values

The cost values to be used in the model can be of three types (they have been schematically and generally represented in Figure 3):

- Actual values, taken from or calculated from the accounts: Costs incurred up to the point in time at which the study is being carried out and for which data are recorded.
- Expected values, established using a probabilistic criterion, because they have not yet occurred at the time the life cycle costing is being carried out. This is the case for the estimated values, at the time the analysis is carried out, for the years remaining until the end of the useful life. These values will be an extrapolation of the actual values up to that point.
- Estimated prospective values for the extended life of the asset beyond the end date of the administrative authorization.

Acquisition or Investment Cost: CI

CI: Initial acquisition and installation cost. Although the general Woodward model [13] states that it will generally be taken as present value, given the philosophy adopted here, this value will be updated to the date of the study.

Operating Cost: CO

CO: Operational costs, usually given as annualized values. Operating costs are associated with those activities necessary to guarantee safety, continuity and correct coordination between the production system and the grid in order to meet the required quality of service conditions. They shall be discounted to the present value at the date of the study.

Maintenance Costs: Breakdown and Definition of the Summands PMC, TCF and MMC

The definitions of the terms PMC, TCF and MMC in the Woodward expression [13], for application to a power converter, should take into account the following:

- The term PMC includes preventive maintenance activities, including predetermined and condition-based maintenance activities (including predictive maintenance), and corrective maintenance.
- The term TCF includes all the maintenance activities that are carried out to restore some lost or damaged characteristic of the system element specifications. In this case, it will consider the complete replacement of an element.
- The term MMC includes those activities or operations of general repair (overhaul) or those which, due to their cost and frequency characteristic, are included in this term.

Residual Value (For the Life Extension Study or for the Cessation of Activity): RV

The RV represents the residual value of the asset at the end of its useful life. In the case of an extended useful life, this value is neither calculated nor included because the asset will not cease to operate but will continue to be operated during its extended life. Therefore, this item shall not be included in the expression. Should the choice be made to stop the converter's operations due to technical feasibility or economic considerations, two kinds of actions will be considered. (i) The value of the decommissioning costs, dismantling, etc., taking a negative sign so that their value counts as an additional cost of the converter. (ii) Possible income as a consequence of disposal or scrapping, etc. These values shall take a positive sign, so that they compute subtracting expenses.

3.6. Computation: Rates to Be Applied

Based on the data obtained in the previous section and the proposed Woodward model [13], the associated costs are calculated.

3.6.1. Breakdown of the Costs into Executed, Estimated End-of-Life and Post-Life (Extended Life) Costs

The life cycle cost is to be divided into three broad headings in order to orient it toward the purpose of the study (established in a previous step).

$$\text{Extended LCC} = \text{Actual C} + \text{Estimated C} + \text{Prospective C}$$

where:

- Extended LCC: Total cost of the extended life cycle, beyond the initial useful life date.
- Actual C: Total costs incurred up to the date on which the study is being carried out.
- Estimated C: Total costs during the interval between the date the study was conducted and the end-of-life date. The sum of the actual and estimated costs is the life cycle cost (without extension, for which the converter was supposedly designed).
- Prospective C: Total costs assessed as of the date of the end of the useful life of the asset; i.e., in the event of an extension of the useful life.

All the investment costs (IC) are included as part of the actual costs (C actual). These actual costs include all the items that have been determined above at the present value as of the date of the study. All the actual costs were accrued, disbursed and accounted for in the years prior to the date of the study, with the investment costs being spread over the first of these years. Therefore, all the actual costs already include the effect of inflation and therefore this rate is not applied. For discounting, the capitalization rate obtained as indicated below is applied.

The estimated costs (C estimated) are determined as an extrapolation of the annualized costs obtained above. In this case, the rate of inflation for future expenses based on historical real costs must also be taken into account. The discount rates previously specified in the case of the real costs will be applied to update their values on the research date. With the same concerns for inflation and discount rates as for the predicted costs, the prospective costs are also evaluated based on the actual expenses incurred.

3.6.2. Discount Rates, Capitalization and Inflation

With regard to inflation rates, the recommendations given by official bodies (such as the European Central Bank [15]) will be considered, with the exceptions discussed below. In this recommendation, it considers it to be below 2%, a figure that is set as a target not to be exceeded. As the period extends into the future, the estimate makes it closer to this limit. For this reason, and as a conservative value, 2% will be taken. However, this is a general index applicable to the economy as a whole. For each sector and specific economic activity, this value should be corrected upwards or downwards according to the evolution of prices in that activity. In our situation, the costs of internal and external labor, spare component pricing, other general or common business expenses, technology, managerial advancements, technical procedures, and competition will all have an impact on the maintenance costs. Something similar can be said with regard to investments. These factors mean that, in fact, the evolution of these costs does not follow the evolution of consumer prices. In order to take these factors into account, it is necessary to take the following into account:

$$\pi = 2\%\ x$$

where π is the actual inflation rate for the type of activity and sector, and x is a correction factor that can take a positive or negative value, to be determined by studying historical data. As an estimate and for calculation purposes, as long as the factor x is not rigorously determined, it will be taken:

$$x = 0; \pi = 2\%.$$

As regards the capitalization/discount rate, reference is made to the publication of the National Markets and Competition Commission [16] for electricity generation and distribution activities. As an estimate and for calculation purposes, it will be taken:

$$i = 6.5\%$$

3.7. Analysis, According to the Purpose Established in Step 3

In Step 7, the analysis is performed as per to the objectives set out in Step 3. The primary aim of Step 3 was to develop a comprehensive methodology that facilitates the intelligent management of decisions with significant business impact. These decisions include reinvestment, asset retirement, equipment or technology obsolescence and replacement, as well as investment analysis grounded in technical risk control and asset degradation. This step should address procedures for correlating life cycle costing with the stated objectives, such as those related to the calculation of an Asset Health Index or the application of servitization to power converters. If additional objectives exist, the necessary procedures or prior studies should be incorporated at this stage.

3.8. Conclusions

The last activity is an activity of preparing a document that summarizes the aspects that are relevant to the objectives that were outlined in Step 3. These conclusions apply to any phase or stage of the study as a whole, regarding the entire installation or a component of the study, to the validity of the study, to constraints on the study, to the capture and processing of data, and to data management occurring in their lifetime. These findings should be taken into account when making decisions based on this research or when enhancing management practices and the collection and processing of data.

Regarding the actual life stage up to the time of the study, it is essential to express the relevant aspects for new installations or the management of existing installations, as informed by the calculated actual costs. For the life stage between the study's time and the end of life as per administrative authorization, the document should address issues pertinent to new installations or the management of others. In the context of the life extension study, the advantages and disadvantages of life extension should be articulated. Important aspects for decision-making and operation during this period should be presented, including the calculated length of the extension period, points for discussion regarding new operational expenditures (OPEX) for the period, precautions and potential modifications to maintenance plans, and information to be obtained, maintained, and managed concerning plant operation. Furthermore, it should be possible to determine the approach for each extended period as well as the points that should be collected for future extensions. Where feasible, the findings of the Asset Health Index (AHI) analysis should be integrated to provide a more accurate assessment of new failure rates during the extended life period. Concerning servitization, it is important to highlight how the results of the life cycle cost analysis support the transition toward service-based business models. Such analysis should be followed by suggestions for how the costs could be as minimized as possible and what scope of innovations should be considered.

4. Case Study

In this case study, we focus on the power converter utilized within an energy storage system, which incorporates a power stack. This converter is at the inception of its operational life. The converter is characterized by an AC voltage of 550 V, a nominal DC voltage of 928 V, and a nominal power output of 250 kW. To align with the facility network voltage of 415 V, the converter is complemented by a transformer that adjusts the output from 550 V. It is integrated with an energy storage system comprising two racks of batteries, each with a capacity of 500 kWh. An energy management system oversees the system, maximizing plant utilization and optimizing self-consumption. Furthermore, the converter offers the flexibility to add additional modules for future expansion.

4.1. Woodward Life Cycle Costing Model Adapted to the Proposed Procedure

A cost justification for a power converter system is summarized in Appendix A. Nevertheless, for its implementation, the following aspects have to be taken into account.

PMC: The term PMC includes preventive maintenance activities (predetermined; improving and safety; condition-based and predictive). This term does not include the major maintenance cost, which, although planned, will be considered in a separate sum.

$$\text{PMC} = \text{Predetermined CM} + \text{Improving CM} + \text{Predictive CM} \tag{6}$$

TCF: The term TCF includes only those failures that resulted in the loss of the main function of the item under consideration. In other words, this term would correspond to a cost associated with corrective maintenance.

1. Consider the total failure of the main function required of each element i, where i = 1, . . ., N corresponds to the component of the technical structure.

2. Define the expected frequency of failures per year. It is expressed in failures per year. This frequency is assumed to be a constant value per year for the expected life cycle and is calculated from the following expression:

$$\lambda(i) = N_i / T \quad (7)$$

where:

N_i = total number of failures (of element i).
T = total expected number of years of useful life.

The failure frequency, although assumed to be a constant value per year, is a parameter that is corrected or modified with the calculation of the Asset Health Index. In other words, it appears in the calculation as a restriction in the form of a multiplying factor of the failure frequency that will depend on the assessment of the AHI (result of the application of the corresponding procedure). In principle, this variation (increase) will only affect the corrective maintenance costs and its effect will be seen approximately in the last 2–3 years of its end of life cycle.

3. Calculate the costs associated with each element when it fails, CC_i, in EUR/failure. These costs include spare parts costs, labor costs, lost profits due to loss of production and operational impact. In other words, it is necessary to calculate the total costs per failure per year (EUR/year) using the following expression:

$$TCF = \sum_{i=1}^{n} CC_i \quad (8)$$

The above expression will be developed in the following, taking into account the following notations:

i: Element considered in the technical structure
n: Total of the considered elements in the technical structure
CC_i: Corrective cost (EUR/year) of element i

Developing Expression (4):

$$CC_i = LC_i + RC_i + CLP_i \quad (9)$$

where:

LC_i: Labor cost (EUR/year) of element i
RC_i: Replacement cost (EUR/year) of element i
CLP_i: Cost for loss of profit (EUR/year) of element i

Developing each of the above elements:

$$LC_i = \lambda_i \times RT_i \times LR \quad (10)$$

$$RC_i = \lambda_i \times CSP_i \quad (11)$$

$$CLPi = \lambda_i \times DT_i \times PA \times LFF_i \quad (12)$$

where:

$\lambda(i) = \lambda_i$: Failure frequency (no. failures/year) of element i
RT_i: Repair time (hours/failure) of element i
LR: Labor ratio (rate) (EUR/hour)
CSP_i: Cost of spare parts (EUR/unit)
DT_i: Downtime (hours/failure)
PA: Annual production (EUR/year)
LFF_i: % Loss of function due to failure (100% if total)

Considering:

$$PA = PEE/CA \quad (13)$$

where:

PEE: Electricity price (EUR/KWh)
CA: Annual load (KWh/year)

The cost of lost profit is:

$$CLP_i = \lambda_i \times DT_i \times PEE/CA \times LFF_i \quad (14)$$

Substituting the above in the expression of the corrective cost of element i results in:

$$CC_i = \lambda_i \times (RT_i \times LR + CSP_i + DT_i \times PEE/CA \times LFF_i) \quad (15)$$

where the cost associated with element i this failure, Ci, in EUR/failure, is:

$$C_i = RT_i \times LR + CSP_i + DT_i \times PEE/CA \times LFF_i \quad (16)$$

Applying the above expression to the total costs per failure, we obtain:

$$TCF = \sum \text{CCi} = \sum_{i=1}^{n} \lambda i \times (RTi \times LR + CSPi + DTi \times (PEE/CA) \times LFFi) \quad (17)$$

4.2. Procedure for Obtaining Data for the Calculation of the Life Cycle Cost of the Asset

It is convenient to define the steps to be followed for the capture of data that will be needed in the calculation of the life cycle cost of the asset/facility to be studied (Appendix B).

- Determine on which asset/installation the analysis is to be performed.
- Calculation of acquisition or investment costs: IC. These costs are the fundamental part of the so-called CAPEX.
- Calculation of the PMC maintenance costs: (i) identification of the functional location of the plant under study; (ii) obtaining all the WOs of the selected plant, with their order types and actual cost values in EUR; and (iii) repeat the process for each year.
- Calculation of the maintenance costs TCF and PMC: (i) obtaining the actual costs (TCF and PMC) during the elapsed life; (ii) obtaining TCF during the remaining life until the expected end of the activity and during the case of considering extended life of the converter; and (iii) preparation of the data to calculate TCF in the mentioned life cycle sections: failure and replacement frequencies, MTTR and respective unit costs.
- MMC maintenance costing.
- Calculation of the cost of the cessation of activity of the installation.

4.3. Assumptions and Simplifications Adopted

In the process of determining the life cycle cost, several methodological considerations have been adopted. The analysis focuses exclusively on the power stack and its associated components, as delineated by the technical structure. Data taken from the maintenance manual, which is only available at the power stack level and not for its subordinate components, is used to estimate the costs of preventive maintenance (PM). For the corrective maintenance (CM) costs, the most severe failure mode for each component has been identified through reliability-centered maintenance (RCM) analysis. This approach provides critical data, including the duration of unavailability, which corresponds to the repair time, and the extent of the functional loss due to failure. In terms of the failure frequency, the component exhibiting the most adverse failure mode has been identified via RCM analysis. In instances where this identification is not feasible, such as with drivers and capacitors, the failure frequency value for the entire power stack is utilized.

Additional assumptions necessary for estimating the PM and CM costs must be supplied or verified by the company. These include the labor rate, cost of spare parts, electricity prices, daily operational hours, and annual charge (Appendix C). Furthermore, the company is required to provide or confirm data for other cost components, including initial investment costs (encompassing acquisition, installation, and start-up expenses), operating costs (covering labor, energy, and consumables), and any major maintenance costs, if applicable as justified in Appendix A.

5. Results and Discussion

In this section, the results of the research will be discussed, mainly identified in relation to the interaction of digital twin technologies with condition-monitoring and asset management solutions. Consequently, the results are grouped in a way that emphasizes enhanced accuracy in the performance of predictive maintenance as well as the economic gains arising from the life cycle cost analysis. Through considering these outcomes, readers will also be able to comprehend specific uses and possible benefits of the proposed frame for improving asset management activities.

The results obtained from the application of the proposed life cycle costing methodology demonstrate a significant degree of robustness, particularly in its ability to provide comprehensive insights into the economic implications of maintenance strategies over the asset's life span. This method, which is derived from the Woodward life cycle costing [13], measures both preventive and corrective maintenance costs, making it easier to determine the total financial burden of an asset management system. When compared to other methodologies, such as traditional cost accounting or simplified life cycle assessments, the proposed approach offers enhanced precision by incorporating detailed failure mode analysis and maintenance data. This makes it possible to consult effectively and to identify specific and detailed problem areas most sensitive to the cost effect. On that note, however, there is a need to appreciate the fact that although the proposed method is detailed, it could be less efficient in terms of data acquisition and analysis compared to simpler models, hence limiting the data availability. The major advantage of this methodology, therefore, is its flexibility to accommodate different maintenance scenarios and its ability to provide strategic insights into long-term trends, including their economic consequences. However, its weakness may be derived from its insistence on receiving accurate and comprehensive data inputs, which often prove wanting in organizations that lack well-developed data recording and management systems.

Therefore, by using more advanced data analysis and machine-learning techniques, future research could enhance the model's predictive capacity, which could be helpful in complex operational scenarios. However, extending the suggestion either to include perspectives on the evaluation of sustainability indicators and possible implications of regulations for assets' management or to develop additional explorations on key current specifications of the model might also be a worthwhile avenue for future research. In conclusion, this study shows that, even though the proposed methodology provides a strong foundation of the life cycle cost analysis, the realism and reliability of the estimations are a direct function of the quality and accessibility of the data in question. It is suggested that further upgrades should be sought to overcome these drawbacks and to apply the model to a broader range of industries.

The successful application of this newly developed condition-monitoring framework for power electronic converters is shown in this study and provides promising enhancements to predictive maintenance approaches. Consequently, the application of digital twin technology is responsible for the significant improvement in the Asset Health Index prediction. In addition, the life cycle cost analysis demonstrates new cost-saving opportunities and operating efficiency for service-centric business models. The discussion of the automatable parameters and the integration of the Asset Health Index (AHI) with life cycle costing (LCC) is crucial for advancing the precision and efficiency of maintenance management systems. Certainly, the possible scope of automatable parameters, using IoT and cloud computing technologies, specifies the efficient workflow for the harvesting and analysis of the important data, improving the accuracy of life cycle cost estimations and supporting maintenance initiatives. This technological integration not only helps in saving costs related to operations and maintenance but also gives longevity to the equipment by have-scheduled interaction based on the actual data. In addition, the integration of the AHI into LCC approaches delivers a systematic management plan to track the imaginative state of assets and guarantee that the maintenance activities are executed in concordance with the AHI. This alignment is crucial for the impact on reliability standards and efficiency of resources used or to be acquired. With these methodologies, organizations are in a position to adopt an efficient and effective asset management process, which normally enables organizations to attain their strategic organizational performance targets, hence enhancing competitiveness.

5.1. Automatable Parameters

The integration of IoT and cloud-computing technologies through a platform can automate the life cycle cost analysis parameters associated with the parameters needed to calculate and update them (Appendix C). The following details how these parameters can be automated.

- Failure frequency correction factor from the AHI
  The AHI is a methodology for ordering operational, degradation and maintenance data over the life of the asset, the parameterization of which will fall within the scope of the corresponding procedure.
- Failure frequency and replacement frequency
  Operating conditions can be monitored in real time and failures or the need for replacement can be detected by integrated sensors (voltage, current, temperature) and wireless communication modules. Events are automatically logged in the cloud data-base.
- Repair time and replacement time
  The time taken for each repair or replacement intervention can be recorded using the cloud platform, from the time the failure is detected until the equipment is back in operation. Wireless communication between the equipment and the platform facilitates this.
- Labor rate and downtime
  By integrating maintenance management systems into the cloud platform, it is possible to automate labor cost calculations based on pre-defined rates and when the actual time equipment is down, providing an accurate estimate of the cost associated with each intervention.
- % Loss of function due to failure or replacement
  By analyzing real-time data stored in the cloud, it is possible to assess the impact of each failure or replacement on equipment performance by automatically calculating the percentage loss of function.
- Electricity price and hours per day of operation
  It is possible to monitor and manage electricity consumption or generation (depending on the operating mode) in real time thanks to the integration of intelligent energy management systems. Sensors and smart devices can be connected to the platform to track electrical energy costs, which vary depending on the time of day and equipment running hours. It facilitates the optimization of energy use and the identification of consumption and generation patterns to reduce costs.
- Unit cost of the spare part
  Efficient spare parts management is achieved through the automation of inventory tracking through the platform. Using RFID technology or QR codes on spare parts, it is possible to automate the updating of their price and availability instantly, which aids in maintenance planning and timely replenishment of critical parts.

Implementing these technologies not only automates the collection and analysis of critical data for life cycle cost analysis but also increases the accuracy of calculations and enables proactive maintenance management, helping to reduce the operational and maintenance costs while extending the lifetime of equipment. Due to the lack of a data source, such failure repair and cost data will not be stored in the cloud as time series. Instead, the aim will be to create tables where calculations can be performed and the data retrieved. Such tables will have to be built from historical data to look up according to the time of use and telemetry of the devices.

5.2. Integration of the AHI with the LCC

In order to keep the failure levels within acceptable parameters, preventive maintenance is performed periodically, while major maintenance is performed less frequently, often called overhauls. These major maintenance actions leave the asset in a virtually new condition after their execution. Throughout the asset's lifetime, it undergoes a deterioration process that requires a major overhaul to restore it to its original working condition. This is performed despite scheduled corrective and preventive maintenance to maintain the desired reliability standards [17]. The above problem can be addressed by studying asset aging and the corresponding health indicators (Figure 4).

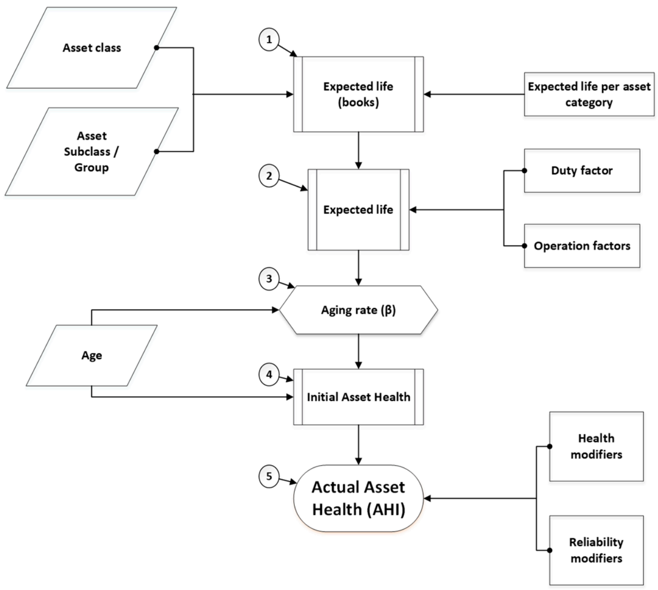

Figure 4. Process for obtaining the health index.

For a properly maintained asset, its failure rates are considered to remain within expected values as long as the health indicator remains below AHI = 4.0. This indicator can increase to AHI = 5.5 in a controlled manner, at which point the probability of failure begins to increase exponentially. Therefore, carrying out major maintenance when the AHI reaches 5.5 ensures that the failure rates remain within the expected controlled limits. If major maintenance is postponed beyond this point, the failure frequency would increase in an uncontrolled manner, resulting in higher costs for both corrective and preventive maintenance to maintain reliability within the desired parameters.

Manufacturers and installers of equipment prescribe major maintenance frequencies and actions that return the asset to its initial state. However, the actual operating conditions may differ from those assumed by the manufacturer, which may result in a worse state of asset health than expected prior to major maintenance, leading to higher maintenance costs. When calculating the LCC, it is important to consider how the failure rates change with asset aging (as measured by the AHI), adjusting the original rates with a failure frequency correction factor (F_C). Another option is to perform major maintenance earlier, returning the asset to its original state, which will restore the failure rates to the expected values. From here on, the standard [18] will be applied to integrate the result of the calculation into the health index and to adjust the failure rates of the components in the LCC analysis. In practice, it is recommended to adjust the dates of overhauls to prevent increased failure rates due to the premature aging of equipment. The multiplier factor to be applied to all the annual average failure rates is calculated according to the following formula:

$$F_C = [1 + (C \cdot H) + (C \cdot H)^2/2! + (C \cdot H)^3/3!] \quad (18)$$

where:

F_C is the so-called failure frequency correction factor.
C is a constant representing a value where the probability of failure of the asset in the worst condition is 10 times higher than the probability of failure of the asset as new.
H takes the value of:

If $H' > 4$, then $H = H'$.
If $H' \leq 4$, then $H = 0$.

The new failure rates are obtained by multiplying each of them by the failure frequency correction factor resulting from the following expression:

$$K_C = K \cdot F_C \quad (19)$$

where:

F_C is the failure frequency correction factor from the AHI.
K (or λ) is the standard failure rate of the asset.
K_C (or λ_C) is the corrected failure rate or frequency, estimated given the asset's current condition.

6. Conclusions

In this paper, a life cycle cost analysis approach that is specifically applied to a power converter is proposed and implemented. The importance of this analysis lies in the fact that it encompasses several important features. Firstly, it enables determination of the overall costs that accrue in the process of acquiring, operating, maintaining and finally, phasing out a product or a system. Second, it helps in resource allocation by pointing out savings opportunities to cover the economic life of the product, thus improving on the economic utility. Thirdly, the analysis offers a strong operational and managerial premise by evaluating all the probable costs of the product throughout its life cycle. Furthermore, it helps to assess the variety in certain design solutions, certain materials, and methods and strategies for maintaining them, with steady consideration of the economic consequences. In addition, the procedure facilitates the recognition and control of risks concerning failure and maintenance, which enhances the reliability and maintainability of the product or system. Finally, it guarantees design and operating decisions meet sustainability legislation and best-practice guidelines to reduce the organization's negative impact on the environment and the expenses required to conform to legislation.

This study's main focus has been on the key issue of preserving asset reliability by thoroughly examining maintenance plans and concentrating on how major and preventive maintenance interact. This study further established the need for a regular check-up to help control failure rates and successfully introduce preventive maintenance in endeavoring to maintain failure rates at a reasonable level as compared to that of overhaul, which is major maintenance, which entails bringing the asset to a near-original condition, thus guaranteeing its reliability in future. However, even with such efforts put in place, the assets experience a deterioration process and thus require proper aims on the time to undertake the maintenance that will sustain the required reliability levels. Highlighting a lack of knowledge in the literature regarding the failure probabilities of equipment due to asset aging, this paper presents the AHI as a fundamentally important parameter that characterizes assets' health with regard to failure probabilities. This work explains that keeping the AHI below 4.0 keeps the failure rate risk at expected levels; allowing it to increase up to 5.5 can tackle failure risks adequately when controlled. However, exceeding this threshold leads to an exponential increase in the failure probability, underscoring the need for timely major maintenance interventions.

The research methodology involved calculating the life cycle cost (LCC) and adjusting failure rates using a failure frequency correction factor (Fc), which accounts for asset aging as measured by the AHI. This approach provides a practical framework for optimizing maintenance schedules and costs, aligning with the standards [18] to integrate these calculations into the health index for more accurate LCC analysis. The findings of this study have both practical and theoretical implications. In practice, this study provides asset managers with a strong model to optimize maintenance schedules, which lowers expenses and improves asset dependability. Theoretically, it contributes to the body of knowledge on maintenance management by providing a quantitative approach to understanding the relationship between asset aging and failure rates. Further studies should be based on extending the list of variables that define asset health and are applied in the AHI model, including environmental and operating conditions. Further, extending this research work to uncover the integration of enhanced predictive analytics and intensive use of machine-learning algorithms would also improve the degree of accuracy of potential failure and the time for maintenance scheduling. Such developments are made possible by the present contribution, which also offers a solid foundation for continuing active research in the field of maintenance management.

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Appendix A

Appendix A.1. Justification for Cost Estimates Related to Power Converter System Operation and Maintenance

This appendix outlines the justification for the cost estimates provided for the power converter system. The estimates are derived from the industry norms, manufacturer guidelines, historical records of systems with comparable characteristics and other source of up-to-date information on maintaining engineering. The key areas analyzed include the initial costs (IC), operational costs (OC), preventive maintenance costs (PMC), and major overhaul costs (MMC). These values are important in the preparation of operational budgets for the short term as well as major financial strategies for the provision of system maintenance in the long run.

Appendix A.2. Cost Justification Breakdown

Appendix A.2.1. CI: Initial Cost (Investment)

- Estimated Value: EUR 50,000
    - ○ The initial cost of a power converter system varies depending on the system's power capacity, technological sophistication, and installation complexity. Based on market research and comparison with similar installations, a mid-range con-

verter for industrial applications typically falls between EUR 40,000 and EUR 60,000. This estimate reflects a standard, medium-capacity system equipped for typical industrial or commercial power conversion requirements.
    - Source: Industry quotations from suppliers like ABB and Siemens, along with historical procurement data [19,20].

Appendix A.2.2. CO: Operational Costs (Annual)

- Operations: 2500 EUR/year
    - This consists of labor costs to monitor the process, control and make adjustments during the production process, and perform minor repairs or calibration of instruments. Based on experience, for a system of this type, an operator is generally required for about 5 h per week at a typical technician rate of 25 EUR/hour. This figure also accounts for minor repairs, such as replacing connectors or resetting controllers.
    - Source: Maintenance records from similar power systems and labor cost databases for engineering services in the EU [21].
- Lubricants: 200 EUR/year
    - Lubrication is required for moving parts such as cooling fans or motorized components. The cost is estimated based on the industry standard and manufacturers' requirements, including the purchase of lubricants required over the course of a year.
    - Source: Information from the manufacturer's maintenance manuals, and lists of lubricant prices in the market from the vendors [22].
- Consumables: 300 EUR/year
    - Consumables include filters, cooling fluids, and other items subject to wear and tear. They usually have to be changed at least once a year, together with the oil, and other consumables like cooling additives are also used about once a year. The cost is derived from the historical data of procurement and existing price offered by the vendor.
    - Source: Manufacturer's maintenance schedule and cost data from suppliers such as Mouser and RS Components [23,24].
- Energy: 5000 EUR/year
    - The powering of the system involves the determination of the energy costs with reference to the power used per unit in addition to the working hours. A 100 kW converter, operating for 2000 h per year, consumes 200,000 kWh/year. At an electricity rate of 0.025 EUR/ kWh, this therefore translates to 5000 EUR/year.
    - Source: Previous installation energy consumption and estimates for electricity rates as derived from market trends in Europe [21].

Appendix A.2.3. PMC: Preventive Maintenance Costs (Annual)

- Default and Security: 500 EUR/year
    - Default preventive maintenance includes diagnostics, electrical testing, and system safety checks. Technicians perform these tasks quarterly, taking about 5 h per session. At an average cost of 25 EUR/hour, the cost is increased to 500 EUR per year.
    - Source: Information on industry standards of tasks constituting preventive maintenance and estimates of technician rates [21].
- Improving: 300 EUR/year
    - This cost encompasses marginal changes to improve system efficiency, for instance, fixation of firmware or minor upgrades to system's hardware. Some of these tasks are completed during an ordinary maintenance session, but the extra amount is for new part and work.

- Source: Industry practices for upgrading and retrofitting power systems [21].

- Predictive: 1108.21 EUR/year (as provided)
  - Predictive maintenance involves a systematic monitoring of assets by sensors and other software programs that are used to predict a failure. This cost includes the use of specialized tools and analysis software as well as the occasional input of outside experts. The figure is based on market rates for predictive maintenance software and sensor systems.
  - Source: Quotations on the tools used in predictive maintenance include Fluke or Schneider electric, and information on the cost of predictive maintenance [22].

Appendix A.2.4. MMC: Overhaul Costs (Major Maintenance) (Future)

- Year 5: EUR 10,000
- Year 10: EUR 12,000
- Year 15: EUR 15,000
  - Major overhaul generally takes place at least once in 5 years and it entails replacement of major item like power electronic modules, cooling systems, control board, etc. The increase in cost over time reflects inflation and the growing complexity of systems. The estimates are derived from industry standards where overhaul costs are generally 15–20% of the initial cost. Thus, for a EUR 50,000 system, the overhaul costs over 15 years are projected as shown above.
  - Source: Manufacturer's overhaul recommendations, similar systems' maintenance history, and the costs of the electronic components.

Appendix A.3. Conclusions

The provided cost estimates for the power converter system are based on a combination of historical data, market analysis, and manufacturer recommendations. Such values will assist in setting a realistic and sustainable financial plan for the short-term exercise and the recurrent maintenance of the assets. Finally, we include the cost of such expenses for purposes of improving system dependability and minimizing the chances of experiencing unscheduled downtime.

Table A1. Summary of the values for the LCC calculation.

Concept		Value	Unit
i: interest rate		6.5%	%
T: expected useful life period		20.00	years
IC: initial cost (investment)		55,000.00	EUR
OC: operational costs (annual)			
	Operations	2500.00	EUR/year
	Lubricants	200.00	EUR/year
	Consumables	300.00	EUR/year
	Energy	5000.00	EUR/year
PMC: preventive maintenance costs (annual)			
	Default and security	1108.21	EUR/year
	Improving	300.00	EUR/year
	Predictive	500.00	EUR/year
		1908.21	EUR/year
MMC: overhaul costs (major maintenance) (future)			
		10,000.00	EUR, year 5
		12,000.00	EUR, year 10
		15,000.00	EUR, year 15
CMC: corrective maintenance costs (annual)		4301.41	EUR/year

Table A2. Costs breakdown per year.

Year	IC	OC	PMC	MMC	CMC	LCC (Present Value)
0	55,000.00	-	-	-	-	55,000.00
1	-	7511.74	1791.74	-	4038.88	68,342.36
2	-	14,565.01	3474.13	-	7831.26	80,870.40
3	-	21,187.80	5053.84	-	11,392.18	92,633.82
4	-	27,406.39	6537.13	-	14,735.76	103,679.29
5	-	33,245.44	7929.90	7298.81	17,875.28	121,349.42
6	-	38,728.11	9237.66	-	20,823.18	131,087.76
7	-	43,876.16	10,465.60	-	23,591.17	140,231.73
8	-	48,710.01	11,618.60	-	26,190.21	148,817.63
9	-	53,248.83	12,701.23	-	28,630.63	156,879.50
10	-	57,510.64	13,717.78	6392.71	30,922.10	170,842.04
11	-	61,512.34	14,672.29	-	33,073.72	177,949.87
12	-	65,269.80	15,568.54	-	35,094.02	184,623.88
13	-	68,797.94	16,410.09	-	36,991.01	190,890.56
14	-	72,110.74	17,200.28	-	38,772.23	196,774.77
15	-	75,221.35	17,942.24	5832.40	40,444.73	208,132.24
16	-	78,142.11	18,638.92	-	42,015.15	213,320.11
17	-	80,884.61	19,293.08	-	43,489.73	218,191.34
18	-	83,459.73	19,907.31	-	44,874.31	222,765.27
19	-	85,877.68	20,484.05	-	46,174.38	227,060.04
20	-	88,148.06	21,025.60	-	47,395.11	231,092.69

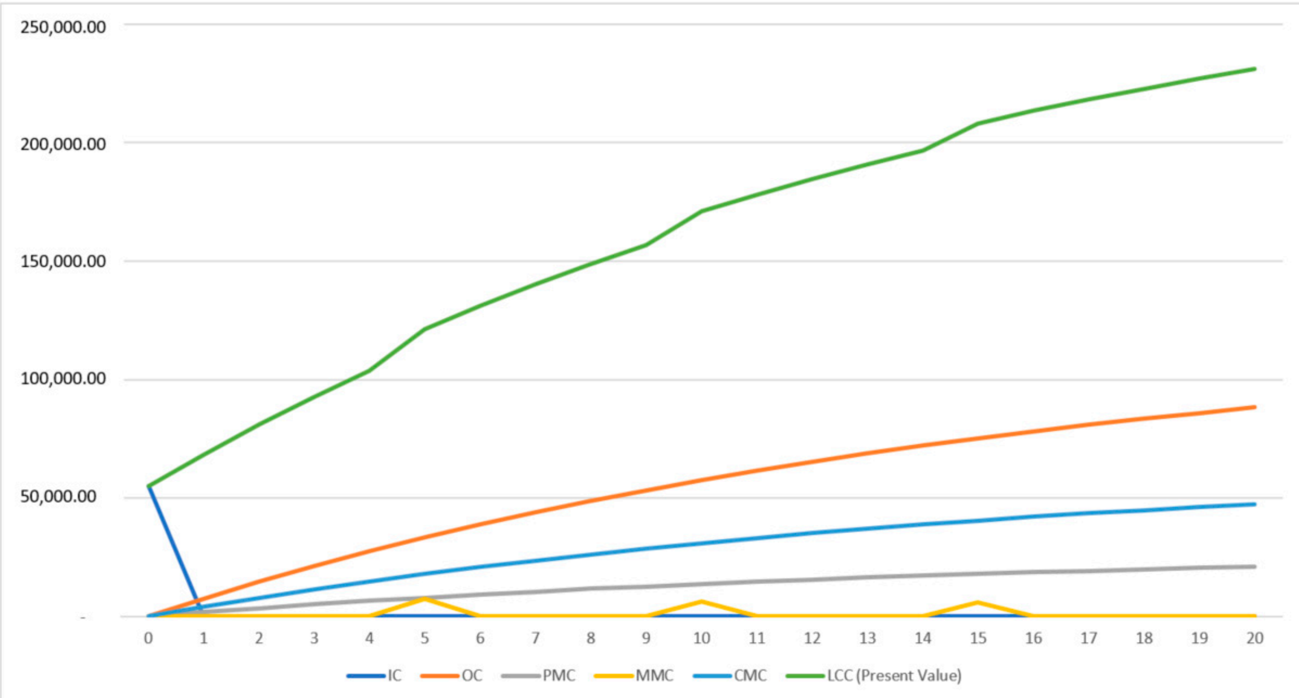

Figure A1. Costs breakdown evolution.

Appendix B

Appendix B.1. Analysis and Breakdown of Preventive and Corrective Maintenance Costs for Power Converter System

This appendix provides an analysis of the maintenance costs associated with the DC/AC stack 350 kW, as outlined in the provided maintenance data. The aim is to provide a clear overview of the expected annual production, preventive, and corrective maintenance costs, including labor, loss of profits, and replacement costs for the critical components.

Appendix B.2. Annual Production and Maintenance Costs Overview

- Annual Production Value (PA): 558,931.80 EUR/year
    - This figure shows the contribution the system makes to the gross annual production value and should be used to determine the economic impact of preventive and corrective maintenance.

Appendix B.3. Cost Breakdown

The cost consideration includes preventive and corrective maintenance of different parts within the power conversion system. Below is a detailed analysis.

Appendix B.3.1. Preventive Maintenance Costs (Total: 1108.21 EUR/Year)

Preventive maintenance (PM) is planned to minimize failures and maintain system efficiency. The total preventive maintenance cost per year is EUR 1108.21 for different multiple critical components.

- DC/AC stack: 1108.21 EUR/year
    - This cost includes labor (75 EUR/year), energy loss, and replacement components to ensure continued functionality of the power stack.

Appendix B.3.2. Corrective Maintenance Costs (Total: 4301.41 EUR/Year)

Corrective maintenance (CM) is performed after a failure occurs. The cost of corrective actions is higher because of the loss of profits, labor, and replacement costs, which amounts to 4301.41 EUR/year.

- IGBTs (Insulated-Gate Bipolar Transistors) 1 and 2:
    - Corrected Frequency: 0.125
    - Cost per Year: EUR 353.92 (each)
    - Failures in IGBTs lead to significant downtime, and their corrective costs are high due to labor, loss of profits, and replacement part expenses.
- Drivers 1 and 2:
    - Corrected Frequency: 0.0625
    - Cost per Year: EUR 60.03 (each)
    - These failures are less frequent but still affect system control, leading to moderate corrective costs.
- Control Unit:
    - Corrected Frequency: 1.375
    - Cost per Year: EUR 1389.36
    - Control failures are costly, especially considering the 550 EUR/year for labor and the potential for significant production loss.
- Capacitors (12 units):
    - Corrected Frequency: 0.0625 (each)
    - Cost per Year: EUR 58.15 (each)
    - Capacitor failures are relatively inexpensive compared to other components, but with 12 units in the system, the cumulative corrective cost can become substantial.
- Fan Modules: 1 and 2:
    - Corrected Frequency: 1.625
    - Cost per Year: EUR 693.17 (each)

- ○ Fan failures are frequent and have a moderate impact on system operation, leading to higher-than-average corrective costs.

Appendix B.4. Total Costs and Recommendations

- Total Preventive Maintenance Cost: 1108.21 EUR/year
- Total Corrective Maintenance Cost: 4301.41 EUR/year

According to the overall cost improvement, the annual expenses of corrective maintenance amount to EUR 4301.41, while the annual costs of preventive maintenance only amount to EUR 1108.21. Hence, the authors found that a rise in efforts related to preventive maintenance, especially on critical areas, which include the IGBTs and the control unit, could probably lead to a decrease in the overall corrective maintenance cost.

Appendix B.5. Conclusions

In conclusion, it means that a plan for any works on the maintenance of the system like DC/AC stack 350 kW must be individual because the cost of the corrective actions is very high. Precisely because the most frequent failures concern IGBTs, fans, and control units, increased expenditures on preventive maintenance can show high outcomes in terms of both diminished prevent downtime and overall expenses. Another positive change might be to shift the attention to the predictive maintenance approach as well.

Table A3. Maintenance costs breakdown per element.

Description	AHI Corrected Frequency	Cost per Labor (EUR/Year)	Cost per Loss of Profits (EUR/Year)	Cost per Replacement (EUR/Year)	Cost of Corrective or Preventive (EUR/Year)
DC/AC Stack	0.06250	75.00	95.71	937.50	1108.21
Electronics					
IGBT1	0.12500	150.00	191.42	12.50	353.92
IGBT2	0.12500	150.00	191.42	12.50	353.92
Driver 1	0.06250	25.00	31.90	3.13	60.03
Driver 2	0.06250	25.00	31.90	3.13	60.03
Control	1.37500	550.00	701.86	137.50	1389.36
DC-Link					
Capacitor 1	0.06250	25.00	31.90	1.25	58.15
Capacitor 2	0.06250	25.00	31.90	1.25	58.15
Capacitor 3	0.06250	25.00	31.90	1.25	58.15
Capacitor 4	0.06250	25.00	31.90	1.25	58.15
Capacitor 5	0.06250	25.00	31.90	1.25	58.15
Capacitor 6	0.06250	25.00	31.90	1.25	58.15
Capacitor 7	0.06250	25.00	31.90	1.25	58.15
Capacitor 8	0.06250	25.00	31.90	1.25	58.15
Capacitor 9	0.06250	25.00	31.90	1.25	58.15
Capacitor 10	0.06250	25.00	31.90	1.25	58.15
Capacitor 11	0.06250	25.00	31.90	1.25	58.15
Capacitor 12	0.06250	25.00	31.90	1.25	58.15
Module ventilation					
Fan Module 1	1.62500	487.50	124.42	81.25	693.17
Fan Module 2	1.62500	487.50	124.42	81.25	693.17

Appendix C

Appendix C.1. Maintenance Cost and Component Reliability Analysis for DC/AC Stack 350 KW

This appendix presents the cost structures of maintenance and reliability of the components of the DC/AC stack system, with the dependency on aspects like the failure rate, time to repair, time to downtime and spare part cost. The data have been extracted from the provided maintenance sheet and analyzed to offer insights into the operational efficiency and budgetary impact.

Appendix C.2. Operational Parameters

- Hours of operation per day: 24 h
- Labor rate: 50 EUR/hour
- Electricity price: 0.1823 EUR/KWh
- Annual energy consumption: 3,066,000 KWh

Its application is permanent, working 24 h a day, and this requires constant preventive, as well as corrective maintenance to reduce operational losses.

Appendix C.3. Key Observations

- Major Components:
    - The DC/AC stack, along with IGBTs (insulated-gate bipolar transistors), have a significant failure impact, as they result in a 100% loss of function and require 24 h for repair/replacement. These components are critical and come with high spare part costs.
- Drivers and Control Units:
    - Though the failure frequency of drivers is lower (0.0625 failures/year), the control unit exhibits a higher failure frequency of 1.375 failures/year, with an 8 h repair time. This makes the control unit a potential candidate for preventing frequent interruptions to reduce their occurrence.
- Capacitors:
    - With 12 capacitors in the system, each having a failure frequency of 0.0625/year, their relatively low repair times (8 h) and low spare part costs (EUR 20) make them less costly in terms of maintenance. However, failures can accumulate if multiple capacitors fail simultaneously.
- Fan Modules:
    - These modules have the highest failure frequency, at 1.625 failures/year each, but cause only a 20% loss of function and require 6 h for repair. Fan equipment is much less significant than power conversion equipment but its failure can lead to partial losses.

Appendix C.4. Cost Analysis

- High-cost components:
    - The DC/AC stack represents a substantial cost factor in terms of both repair time and spare parts (EUR 15,000).
    - IGBTs also stand out with long repair times (24 h each) and moderate spare part costs (EUR 100 each).
- Frequent failures:
    - Fan modules and the control unit are more prone to failure, making them key drivers of downtime. Despite their lower individual replacement costs, the frequency of failures makes them significant contributors to overall maintenance costs.

Appendix C.5. Recommendations

- Increase preventive maintenance for control units:
    - Due to its high levels of failure, this means that efforts aimed at carrying out preventive maintenance on the control unit part may alleviate the impact it has on the system time.

- Fan module inspection:
  - Regular inspection and preventive maintenance of fan modules is crucial due to their high failure frequency. Preventive actions here could prevent more severe failures of associated cooling systems.
- Monitor IGBTs closely:
  - Since the repair of IGBT1 and IGBT2 causes long outage time and has considerable effect on the system, the assets require constant health check. This means that with proper diagnosis of such problems, system downtimes and labor costs could be significantly reduced.

Appendix C.6. Conclusions

The description of the DC/AC stack system reveals the sensitivity of the components, including the DC/AC stack, IGBTs and the control unit. Maintenance strategies should bear on the time that is spent with various components, especially with high failures using preventive measures most especially on the control unit and fan modules. It is here that more efficient planning can play a role in reducing the level of disruption, and controlling for the costs over the longer term.

Table A4. Component failure and maintenance details.

Description	Failure Frequency (No. Failures/Year)	Repair Time (Hours/Failure)	Downtime (Hours/Failure)	% Loss of Function Due to Failure (100% If Total)	Spare Part Cost (EUR/Unit)
DC/AC Stack 350 KW	0.0625	24.0	24	100%	15,000.00
Electronics					
IGBT1	0.1250	24.0	24	100%	100.00
IGBT2	0.1250	24.0	24	100%	100.00
Driver 1	0.0625	8.0	8	100%	50.00
Driver 2	0.0625	8.0	8	100%	50.00
Control	1.3750	8.0	8	100%	100.00
DC-Link					
Capacitor 1	0.0625	8.0	8	100%	20.00
Capacitor 2	0.0625	8.0	8	100%	20.00
Capacitor 3	0.0625	8.0	8	100%	20.00
Capacitor 4	0.0625	8.0	8	100%	20.00
Capacitor 5	0.0625	8.0	8	100%	20.00
Capacitor 6	0.0625	8.0	8	100%	20.00
Capacitor 7	0.0625	8.0	8	100%	20.00
Capacitor 8	0.0625	8.0	8	100%	20.00
Capacitor 9	0.0625	8.0	8	100%	20.00
Capacitor 10	0.0625	8.0	8	100%	20.00
Capacitor 11	0.0625	8.0	8	100%	20.00
Capacitor 12	0.0625	8.0	8	100%	20.00
Module ventilation					
Fan Module 1	1.6250	6.0	6	20%	50.00
Fan Module 2	1.6250	6.0	6	20%	50.00

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