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A Practical Approach to Service-Oriented Life Cycle Cost considering Asset Health Index and Digitalization in Power Converters

V. González-Prida, A. de la Fuente, J. Gómez & A. Crespo

Department of Industrial Management I, University of Seville, Camino de los Descubrimientos S/N, 41092 Sevilla, Spain

A. Guillén

Department of Management and Instituto Complutense de Estudios Internacionales (ICEI). University Complutense of Madrid, Carretera de Húmera S/N, 28223 Madrid, Spain

The practical application of a Life Cycle Cost (LCC) analysis on power converters for energy storage systems is described in this study. The main goal is to suggest a cost-effective structure for allocating converter expenses, where factors such as the cost of electric energy and annual production must be taken into account. The approach includes a number of key phases, such as calculating CAPEX and OPEX as well as classifying and estimating total costs using the Woodward model. The study also stresses the need for updating cost values regularly, linking LCC with business decisions such as equipment depreciation and reinvestment. This contribution is significant since it includes the use of cloud computing for maintenance improvements together with the adoption of IoT technology solutions for data collecting, as well as the application of Asset Health Index (AHI) for failure rate update and monitoring. Consequently, it has been positively proven that the multi-detail decision-making asset management model covers the search for a sustainable alternative in the domains of general asset, sustainability, and economic value. The findings indicate that the application of this LCC methodology can significantly improve power converter management by utilizing digital technologies and assisting in the development of service-oriented business models that maximize efficiency.

Keywords: Asset Management; Asset Health Index; Digitalisation; IoT & Digital Twins; Life Cycle Cost; Power Converters; Reliability; Servitization; Sustainability; Woodward Model.

1. Introduction

According to the maintenance terminology standard (UNEEN 13306:2018), the life cycle of an item consists of the "series of states through which an item passes from its conception to its disposal". Taking Crespo's (2007) 8phase Maintenance Management Model as a reference, the application of Life Cycle Cost Analysis techniques is part of Phase 7 of the aforementioned model (Figure 1). The usual stages of an asset's lifecycle are the following: (i) Investment planning; (ii) Facility development; (iii) Asset management; (iv) End-of-life. Therefore, in life cycle cost analyses, the items commonly considered are:

- Initial research and development costs.
- Production and construction costs.
- Operating and support costs.
- Disincorporation and removal costs.

The motivation for this research lies in the necessity of performing LCCA within the framework of servitisation, which offers a holistic view of all costs associated with a product or service from inception to disposal. This is even more important for companies implementing service-oriented business strategies, including Product-Service-Systems (PSS), so that they can develop superior value propositions. The objective of this article is to develop a methodology for calculating the lifecycle cost of a power converter to support aftersales services. The research seeks to address several questions: How can LCCA be applied to evaluate and compare design approaches? What would be the economic viability and cost factors in projects? How can alternative strategies for asset use and maintenance be assessed? These questions guide the exploration of LCCA's role in decision-making for equipment investment and resource allocation.

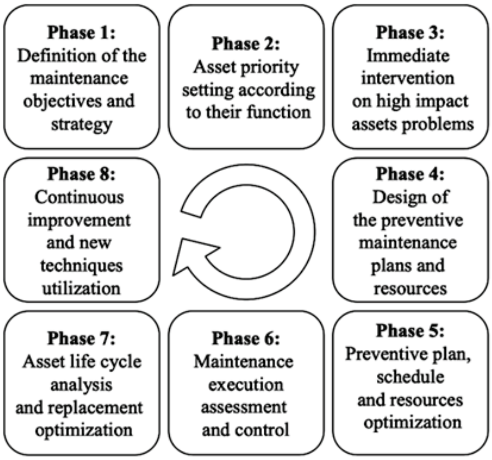

Fig. 1. Maintenance management process model (Crespo, 2007).

This study distinguishes itself from previous research by focusing on the specific application of LCCA to power converters, considering factors such as inflation and discount rates, failure rates, and regulatory requirements. While the application of LCCA to broader purposes is beyond this article's scope, it sets the stage for future research lines. Some of the limitations include the following: the use of the companies' data means that the accuracy of the results depends on the accuracy of the data being processed; the availability of information over a period of time will affect the precision of the results.

2. Proposed Procedure

The proposed procedure is articulated in nine steps, from Step 0 or preparatory step to Step 8 where the conclusions are drawn. Each of the steps is detailed below, which would begin with an iterative step 0 relating to the organisation and recording of meetings. Thus, for each meeting, the following will be identified: (i) Purpose of the meeting; (ii) Date and place of the meeting; (iii) Agenda of the meeting; (iv) Attendees with identification of their workplaces and positions in the organisation; (v) Most important agreements made at the meeting; (vi) Progress made in the project.

2.1 *STEP 1: Identification of the facility under study*

The case of the present study will deal with a Power Converter with application to battery energy storage. However, the particularisation of this procedure to a specific converter will require the identification of the installation at its functional location (such that the installation / system / subsystem / equipment to be studied is clearly identified unambiguously and unambiguously). The intervention level is defined as that subdivision within a hierarchy of elements, examples of intervention levels being: system, subsystem and component (UNEEN 13306:2018). The intervention level at which the life cycle cost study is to be carried out must be defined. This intervention level is the one defined in the Technical Structure of the power converter. The elements on which maintenance is carried out are those reflected in the maintenance manuals themselves, being these elements those considered to establish the life cycle cost analysis (IEC TR 62380). However, for this study, and in accordance with the calculations of the Health Index, only the following element has been considered as critical for this study: "Stack DC/AC 350 KW, 525690 VAC" which in turn is composed according to the Technical Structure:

- Electronics (IGBTs, Drivers and Control),
- DC-Link (Capacitors) and
- Module ventilation (fans).

2.2 *STEP 2: Description of the asset, interrelationships and technical and administrative conditions*

(i) Description of technical characteristics: Description of the asset (technical characteristics that define and differentiate the asset). Characteristics that may influence its cost and durability; (ii) Contractual conditions: Circumstances and legal, contractual or regulatory aspects related to its remuneration, penalties, operating conditions and estimated life; (iii) Context diagram (related installations): General Diagram corresponding to the facility under study and adjacent ones that influence the development of this.

2.3 *STEP 3: Define the purpose of the life cycle cost analysis*

The life cycle cost calculated by the proposed procedure will initially be used to support the study of those tasks that will have been specified in Step 1, with the details, operating conditions and contractual and operational circumstances specified in Step 2. Essentially, the purpose of life cycle cost (LCC) analysis will be to provide a comprehensive methodology to enable intelligent management of business-impactful decisions such as reinvestment, asset retirement, equipment/technology obsolescence and replacement, as well as investment analysis based on technical risk control and asset degradation. Furthermore, this analysis is fundamental for the digitisation of equipment and the evolution of the industry, as it allows the determination and parameterisation of maintenance activities, which can substantially reduce the associated costs through proper, efficient and intelligent maintenance. However, any additional purpose may be expressed in this step, whereby the asset life cycle cost analysis is performed according to the purpose referred to here.

2.4 *STEP 4: Establishing life cycle phases*

In this step, the activities required by the asset are determined, from its initial approach to its cessation of activity or extension of its useful life. The activities are specific to each of the phases through which the asset passes during its life cycle. To perform each of the activities requires resources that will ultimately result in costs to the owner of the power converter. Therefore, this Step 4 serves to determine all items that will incur costs over the life cycle of the asset. This Step 4 does not determine the values of those costs (which is the subject of Step 5), but is a guide to establish the items that will later need to be valued. In the guide that follows (which, as noted above, serves to assist in the determination of cost elements), the activities that make up each phase are defined. Most of these activities are common to the life cycle of any asset (power converter in this case). The phases for the analysis of the life cycle of an asset, in accordance with the business and support processes developed by the company, are as follows:

2.4.1 *Phase 1: Investment planning*

This is the phase in which the needs of the asset are detected by taking as inputs the information received from the different areas and stakeholders.

2.4.2 *Phase 2: Development of the installation*

At this stage, installation is created out of the delivered strategic plan, and in line with the core business needs which provides efficient development in terms of time, cost, safety, environment, and quality. This stage commonly comprises, for instance, the award and launch management which means the beginning of the project together with subsequent communication with the appointed project manager. Design and engineering encompass the development of conceptual, basic, and detailed engineering, including environmental processing. Permits mean a list of the assets and rights to be affected, as well as acquiring the permits and licenses. Procuring material resources mean purchasing material resources, managing orders, and approving receipts and invoices are also part of the materials management policy. Construction involves contracting, launching, and continuously monitoring quality, schedule, cost, safety, and environmental aspects. Commissioning and closure include obtaining access and connection permits, signing technical access contracts, conducting tests, and performing operations for commissioning the installation.

2.4.3 *Phase 3: Asset management*

The useful life of an asset commences with its commissioning. At this stage, the overall asset management is performed for customer service and required availability, according to the technical management system. This involves operation and maintenance but with the requirement safe and efficient manner. Activities included in this stage include operation; It deals with supply security, safety and operational efficiency Maintenance: It deals with the management of maintenance operations, methods, techniques and resources with a view to operating in the correct manner as constructed for the right conditions. Maintenance management is backed up by a Maintenance Manual and a CMMS system; ensuring that all activities are described and traceable. Maintenance is categorized into preventive (condition-based, predictive, and predetermined) and corrective (immediate or scheduled), as per UNEEN 13306:2018. Preventive maintenance may encompass improving maintenance that entails responsible for failure causing elements to be fixed so that they cannot result to additional harm. Corrective maintenance restores functionality after failure recognition. Required resources and infrastructure, whether dedicated or shared, include human resources, administrative functions, and infrastructure such as maintenance buildings. Detailed infrastructure data capture is unnecessary for cost determination; as aggregated costs will be obtained in Step 5.

2.4.4 *Phase 4: End of life*

This final step is the choice between an extension of life or finalizing all activities. For life extension, necessary studies and analyses must demonstrate technical feasibility, considering current and potential new requirements, such as environmental regulations. The technical feasibility study, related to asset health indicators, is beyond this procedure's scope. If life extension is feasible, future cost implications and maintenance plan modifications can be assessed. If life extension is not feasible due to technical, economic, or operational reasons, the asset will cease activity. This cessation consists new decisions and actions, which may include legal regulations and economical aspects in dismantling and disposal of the asset not included in this procedure.

2.5 *STEP 5: Obtaining the costs to be included in each phase*

This step includes categorizing the cost to be quantified and the approach to be adopted when evaluating those costs in order to arrive at the total cost. The estimation of an asset's life cycle cost elements is crucial, as outlined by Crespo (2007). Typically, these costs are categorized into two primary groups: CAPEX that includes development or investment costs and OPEX, which includes operating or maintenance costs and decommissioning costs. These costs fluctuate throughout the asset's life cycle The Woodward model, as described by Woodward (1997), serves as a framework for calculating life cycle costs, incorporating specific instructions for conducting a life cycle study. Key aspects of the model include establishing operational conditions, describing operating modes (full load, half load, no load), and determining production capacities. Utilization factors must be established to indicate the operating status within each mode. Basic cost categories such as initial investment, development, acquisition, planned maintenance, and replacement must be identified. The total cost per failure (TCPF) is determined by identifying main failure types and their frequency over time, which remains constant throughout the asset's life cycle. Critical costs are identified, and strategies for controlling high-cost drivers are proposed. All costs are calculated in present value, using a defined discount factor and expected lifetime. The Woodward model proposes the following expression for calculating costs over an asset's life cycle (Woodward, 1997, Blanchard and Fabrycky, 1991):

$$\text{LCC(P)}= \sum_{t=1}^{T}(\mathrm{CI} + \mathrm{CO} + \mathrm{CMP} + \mathrm{TCPF} + \mathrm{CMM} - \mathrm{VR}) \quad (1)$$

where:

- LCC(P) represents the total lifecycle costs in present value for a discount rate (i) and an expected lifetime (T).
- IC denotes the initial cost of acquisition and installation in present value.
- CO refers to operational costs.
- CMP includes preventive maintenance costs.
- TCPF is the total cost per failure.
- CMM represents major maintenance costs.
- RV is the residual value.

In assessing the total cost per failure (TCPF), the Woodward model evaluates the impact of major failures on the cost structure of a production system. This involves determining failure types, assigning a constant frequency of occurrence per year, estimating the cost impact on production, operations, environment, and safety, and calculating the total cost impact in present value at a specific discount rate. The steps involve identifying failure types, estimating the probability of failures and costs that accompany a given type of failure. Now, the aforementioned model is adapted to calculate the life cycle costs of a power converter, focusing on cost measurement criteria, acquisition costs, operating costs, maintenance costs, and residual value. Cost values are categorized as actual, expected, and prospective. Actual values are derived from recorded data, expected values are probabilistic estimates for the remaining useful life, and prospective values are estimates for an extended life beyond the administrative authorization. The initial acquisition and installation cost is updated to the study date, aligning with the Woodward model's philosophy. Operational costs, typically annualized, are associated with activities ensuring safety, continuity, and coordination between the production system and the grid. These costs are discounted to present value at the study date. Maintenance Costs will be: CMP (it includes preventive maintenance activities; TCPF (it encompasses maintenance activities restoring lost or damaged system characteristics; CMM (it involves general repair activities or those with significant cost and frequency. The residual value at the end of the asset's useful life is considered. For an extended life, this value is excluded as the asset continues operation. If activity ceases, decommissioning costs and potential income from disposal are accounted for, with respective signs indicating additional costs or income.

2.6 *STEP 6: Computation (of the cost for each phase and total cost). Fees to be applied*

Based on the data obtained in the preceding section and the application of the Woodward Model, the associated costs are systematically calculated. The life cycle cost is categorized into three primary components to align with the study's objectives: executed costs, estimated end-of-life costs, and post-life (extended life) costs. The formula for the extended life cycle cost ($LCC_{Extended}$) is expressed as:

$$LCC_{Extended} = C_{Actual} + C_{Estimated} + C_{Prospective} \quad (2)$$

In this context, the Extended LCC represents the total cost of the extended life cycle, surpassing the initial useful life date. The Actual C encompasses all costs incurred up to the date of the study. Estimated C refers to the total costs anticipated between the study date and the endoflife date, with the sum of actual and estimated costs constituting the life cycle cost without extension, for which the converter was originally designed. Prospective C includes the total costs evaluated at the end of the asset's useful life, particularly in the event of an extension. Investment costs (IC) are incorporated within the actual costs (C actual), which are calculated at present value as of the study date. These costs, properly incurred and booked in earlier years, already contain inflation and do not therefore require further inflation adjustment. The capitalisation rate, as outlined below, is applied for discounting purposes. Estimated costs ($C_{estimated}$) are extrapolated from annualized costs, with their discounted value aggregated at the study date. Future costs are adjusted for inflation based on historical data, using the same discount rates as for actual costs. Similarly, forward-looking costs are measured with regard to inflation and the discounting rates. As for the discount rates, capitalisation and inflation, the official recommendations are considered, including those of the European Central Bank. This rate is adjusted for specific sectors based on historical price trends.

2.7 *STEP 7: Analysis, according to the purpose set out in Step 3*

The main purpose of Step 3 was to provide a comprehensive methodology to enable intelligent management of high business impact decisions such as reinvestment, asset retirement, equipment/technology obsolescence and replacement, as well as investment analysis based on technical risk control and asset degradation. Issues such as procedures to be used to correlate life cycle costing to the stated purpose (such as those related to the calculation of an Asset Health Index or for Servitisation and application to Power Converters) should be addressed here. If there are other additional purposes, the required procedures or previous studies shall be incorporated here.

2.8 *STEP 8: Conclusions*

A document should be drafted containing the aspects that are relevant from the point of view of the objectives set out in Step 3. Without being exhaustive, important aspects for the decision and operation of this period shall be presented here, such as: (i) The length of the extension period that has been calculated; (ii) Points to raise and discuss in terms of new OPEX for the period; (iii) Precautions and possible modifications of maintenance plans, etc.; (iv) Information to be obtained, maintained and managed, related to the operation of the plant, such as: (i) The length of the extension period that has been calculated, (ii) The points to raise and discuss in terms of new OPEX for the period; (iii) Precautions and possible modifications of maintenance plans, etc.(iv) Information to be obtained, maintained and managed relating to the operation in this period; (v) The approach for each extended period for the next extension and the most important points to be collected in view of this new extension; (vi) Where possible, combine with the findings of the AHI health indicator analysis for a more accurate assessment of the new failure rates in the extended life period. Regarding servitisation: It should be noted here how the results of the lifecycle cost analysis support the transition towards service-based business models, suggesting recommendations for cost optimisation and pointing to opportunities for innovation.

3. Particularization to a Case Study

The adaptation of the Woodward Life Cycle Costing model to the proposed procedure necessitates consideration of several key elements. PMC minimally includes predetermined, improvement, safety, condition, and predictive maintenance. It is important to note that Major Maintenance Cost, although planned, is accounted for separately. The calculation of CMP is expressed as the sum of Predetermined CM, Improving CM, and Predictive CM. The term TCPF refers to failures that result in the loss of the primary function of the item under consideration, corresponding to costs associated with corrective maintenance. For each component of the Technical Structure, denoted as element i, where i ranges from 1 to N, the expected frequency of failures per year is defined. This frequency translated to failure per year in each element is taken constant over the life cycle and is ascertained by the following formula, $\lambda(i) = Ni/T$, where Ni stands for the total number of failures of the particular element i and T for the total expected years of useful life. Although this failure frequency is initially considered constant, it is subject to modification based on the Asset Health Index (AHI) assessment, particularly affecting corrective maintenance costs in the final 23 years of the life cycle. The costs relevant to failure of every element are represented as CCi in €/Failure and are as follow Spare Parts Cost, labour cost, profit loss because of production loss and operation influence. The total costs per failure per year are calculated using the expression:

$$TCPF = \sum_{i=1}^{n} CC_i \qquad (3)$$

The corrective cost of element i is broken down into further dimensions as CCi =CMOi+CSI+CLCi where CMOi articulates to labour cost, CSi concerns replacement cost and CLCi relates to loss of profit cost. All of these elements are then computed from specific formulas requiring inputs which are Failure frequency, repair time, Labour rate, cost of spare parts, Downtime, Annual production, and percentage loss of function due to failure. Developing each of the above elements:

$$CMOi = \lambda i \text{ x } TRi \text{ x } RMO \qquad (4)$$
$$CSi = \lambda i \text{ x } CRi \qquad (5)$$
$$CLCi = \lambda i \text{ x } TPi \text{ x } PA \text{ x } PFi \qquad (6)$$

Where:

- $\lambda(i) = \lambda i$ Failure Frequency (No. Failures / Year) of element i
- TRi Repair Time (Hours/Failure) element i
- RMO Labour Ratio (Rate) (Euro / Hour)
- CRi Cost of Spare Parts (Euro / Unit)
- TPi Downtime (Hours / Failure)
- PA Annual Production (Euros / Year)
- PFi % Loss of Function due to Failure

Applying the above elements to the Total Costs per Failure, it is obtained:

$$TCPF = \sum \text{CCi} =$$
$$TCPF = \sum_{i=1}^{n} \lambda i \; x \; (TRi \; x \; RMO + CRi + TPi \; x \; (PEE/CA) \; x \; PFi) \qquad (7)$$

The process of gathering data for the purpose of the LCC of the asset also takes a number of steps. First, an asset or an installation for investigation purposes is selected. The acquisition or investment costs, denoted as IC, form the core of CAPEX. Maintenance costs, both CMP and TCPF, are calculated by identifying the functional location of the plant, obtaining work orders with actual cost values, and repeating the process annually. Actual costs during the elapsed life and projected costs for the remaining life, including any extended life considerations, are obtained. Additionally, CMM maintenance costing and the cost of cessation of activity are calculated. In the spreadsheet used for life cycle cost estimation, certain assumptions and simplifications are adopted. Only the STACK and its associated elements are considered according to the technical structure. Preventive Maintenance costs are based on data from the Maintenance Manual, while Corrective Maintenance costs are derived from the most severe failure mode identified in the Reliability-Centered Maintenance (RCM) analysis. When specific data is unavailable, values from the complete STACK are used. Other assumptions, such as labour rate, cost of spare parts, electricity prices, hours of operation, and annual charge, must be provided or confirmed by the company. Other relevant and needed data involves start-up costs, ongoing costs, and major cost of repairs where necessary.

4. Integration of IoT and Cloud Computing

The utilization of IoT and cloud computing technologies through the dedicated platform supports the automatization of the selected lifecycle cost analysis parameters which are important for calculation and data update. The Asset Health Index (AHI) serves as a methodology for organizing operational, degradation, and maintenance data throughout the asset's lifecycle, with parameterization falling within the scope of the corresponding procedure. The fact that operating conditions are monitored in realtime through integrated sensors and wireless communication modules means that faults and the need for replacement can be detected, an event being automatically recorded in a cloud database. The duration of repair and replacement interventions can be recorded from fault detection to the resumption of operation, facilitated by wireless communication between the equipment and the platform. In addition, the implementation of maintenance management systems within the cloud platform framework allows for the automation of the determination of labour costs proportional to the rates set and actual states of severity and time spent in the system, proposing accurate cost estimates for each intervention. In that case, the equipment performance after each failure or replacement can be evaluated from real-time data stored in the cloud with the percentage loss of function calculated automatically. Smart energy management systems mean timely control of energy utilization or power generation system, where use of energy is controlled in a way that indicates or determines the pattern of consumption or generation in order to reduce the cost of energy. Automation of spare parts stock management through the platform through a system that incorporates RFID or QR code collection makes it possible to update the spare part's price and availability real-time to inform maintenance planning and restocking of crucial spare parts. Realization of these technologies also serves not only the purpose of automating the collection and analysis of critical data for lifecycle cost analysis but also improves the reliability of the calculation and proactively manage maintenance. This approach reduces the operational and maintenance costs while increasing the life cycle of the equipment.

5. AHI Integration to LCC

In order to have controlled failure rate and in order to prevent the rate from surging beyond acceptable levels, preventive maintenance is done frequently and the major maintenance, which is commonly referred as overhaul is done less frequently. These major maintenance activities put the asset in almost as good condition as they were when brand new on their completion. However, as the asset is used throughout its life cycle, it experiences a deterioration process, and even though it undergoes constant corrective and preventive maintenance, a major overhaul is often carried out on the asset to restore it to the required working state so as to meet the desired reliability standard as is defined by the UNEEN 60300. This issue can be fixed by looking at the length of held assets and the related health measurements, and the findings of the study might be used to help solve it. For an asset that is properly maintained, failure rates are expected to remain within acceptable limits as long as the health indicator stays below an Asset Health Index (AHI) of 4.0. The indicator can increase to an AHI of 5.5 in a controlled manner, beyond which the probability of failure begins to rise exponentially. Hence to keep failure rate under control, major maintenance is carried out when AHI touches 5.5 level of Pt100 sensor which requires corrective action. Extension of the interval past this point will cause the failure frequency to rise and eventually hit an exponential growth making the cost of correction as well as preventive maintenance too high to keep reliability within targeted levels. Major maintenance frequencies and tasks, which restore the asset to its original condition, are typically recommended by equipment manufacturers and installers. However, this could mean that real operating conditions are different from the ones assumed by the manufacturer, whereby the condition of assets could be worse than expected before major maintenance leading to more costs in maintenance. In other words, when arriving at the LCC, it is important to take into account how the proclivity for failures vary with age by utilising the AHI and correct the initial rates by a Failure Frequency Correction Factor (Fc). On the other hand, conducting major maintenance earlier can get the asset back to the baseline, and have failure rates that expected again. Subsequently, the UK DNO Standard are applied to integrate the calculation results into the health index, adjusting the failure rates of components in the LCC analysis. In practice, it is advisable to adjust the timing of overhauls to prevent increased failure rates due to premature aging of equipment. The multiplier factor applied to all annual average failure rates is calculated using the formula:

$$F_C = [1 + (C\cdot H) + (C\cdot H)^2/2! + (C \cdot H)^3/3!] \quad (8)$$

where FC is the fault frequency correction factor, C is a constant representing a value where the probability of failure in the worst condition is ten times higher than when the asset is new, and H is determined by H' such that if H' > 4, then H = H', otherwise H = 0. The new failure rates are obtained by multiplying each by the failure frequency correction factor, as expressed by:

$$K_C = K\cdot F_C \quad (9)$$

where K (or lambda) is the standard failure rate of the asset, while KC is the corrected failure rate or frequency, which has been estimated with respect to the condition of the asset presently.

6. Conclusions

This article has dealt with the proposal and implementation of a life cycle cost analysis procedure applied to a power converter. It should be noted that the usefulness of this analysis focuses on relevant aspects such as:

a) Assess Total Cost: Determine the total cost associated with a product or system from acquisition to disposal, including acquisition, operation, maintenance and decommissioning costs.
b) Resource Optimisation: Identify opportunities to reduce costs throughout the product life cycle, optimising the use of resources and improving economic efficiency.
c) Informed Decision Making: Providing a sound basis for strategic and tactical decision making, considering all costs throughout the product life cycle.
d) Comparison of Alternatives: To facilitate the comparison of different design alternatives, materials, and maintenance strategies, assessing their long-term economic impact.
e) Improving Reliability and Maintainability: Identify and mitigate risks associated with failures and maintenance, improving the reliability and maintainability of the product or system.
f) Sustainability and Regulatory Compliance: Ensuring that design and operational decisions comply with sustainability regulations and standards, minimising environmental impact and the costs associated with regulatory compliance.

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