

Economic Replacement of Plants and Equipment: A Decision-Making Framework in Engineering

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ABSTRACT

While prior research has focused on siloed approaches to equipment replacement, this study introduces an integrated decision-making framework that synergizes predictive maintenance (IoT/M), dynamic multi-criteria analysis (MCDM), and sustainability-driven material selection. By validating this model through cross-sector case studies and strategic operational planning across various industrial sectors. We demonstrate a 30% improvement in replacement timing accuracy and a 20% cost reduction compared to conventional methods. Emphasizing the integration of predictive maintenance practices and sustainability considerations, the research employs a mixed-methods approach, combining industry surveys, expert interviews, and case study analyses. Key findings reveal a growing prioritization of predictive diagnostic technologies such as vibration monitoring and thermographic imaging, enabling organizations to optimize replacement timing and extend equipment lifecycles. Material selection is increasingly influenced not only by mechanical and economic properties but also by environmental sustainability and regulatory compliance imperatives. Case studies demonstrate that strategic investment in high-performance, durable materials results in significant long-term cost savings and operational enhancements. However, challenges such as high acquisition costs, organizational inertia, and sector-specific variability remain prevalent barriers. The discussion highlights the emerging convergence of equipment replacement strategies with digital transformation initiatives, notably the adoption of Internet of Things (IOT) technologies and data-driven maintenance models. The study concludes that proactive, data-informed, and sustainability-oriented replacement strategies are vital for enhancing operational resilience, productivity, and sustainable practices. Future research is recommended to further investigate the long-term impacts of digital innovations and sustainable materials on asset management practices across broader industrial contexts.

1. Introduction

The replacement of plants and equipment is an essential aspect of industrial operations, influencing both operational productivity and cost effectiveness in production. Over time, equipment experiences degradation, and technological advancements leave it obsolete, thereby necessitating strategic decisions concerning when and how to replace aging infrastructure. The process of equipment replacement is not only driven by the need to improve

operational efficiency but also by economic, environmental, and technological factors that require a multidisciplinary approach to decision-making [1]. In the context of industrial equipment management, the term "replacement" refers to the process of substituting old, inefficient, or obsolete equipment with new machinery or systems that better meet the performance demands of the business. Asset renewal choices are influenced by various factors, including the costs associated with maintenance, the expected performance of new technologies, and the service life [2]. However, these decisions are not purely financial; they also involve considerations related to technological advancements,

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environmental impacts, and eco-friendly objectives, particularly in industries that are subject to stringent environmental regulations. The strategic imperative of plant modernization transcends mere operational maintenance, demanding a holistic assessment encompassing technological obsolescence, rising upkeep expenses, and opportunities for enhanced productivity through leveraging innovative solutions, ultimately impacting an organization's long-term competitiveness and sustainability [3]. The decision to replace plant and equipment is a multifaceted one, involving a complex interplay of economic, operational, and strategic considerations requiring meticulous evaluation to ensure optimal resource allocation and alignment with the organization's overarching objectives [4]. The deployment of a comprehensive and proactively designed maintenance program results in quantifiable enhancements in critical operational areas, demonstrating improvements in product quality, a stronger safety culture, increased equipment availability for production, and a lowering of total operational expenditures. The judicious selection of a maintenance strategy is paramount, as an inadequate or inappropriate choice can lead to the collapse of the entire maintenance program, resulting in significant financial repercussions and impaired operational efficacy, thereby underscoring the critical need for a well-informed and strategically aligned approach to maintenance management, one that incorporates a robust analytical framework, meticulously considering life-cycle costs, the trajectory of technological progress and the intricate, dynamic relationship between maintenance interventions and the inevitable degradation of equipment performance, ensuring decisions are informed by. Plants and equipment represent the backbone of industrial infrastructure, encompassing all physical assets that support production, energy conversion, and essential industrial processes. These assets range from power transformers, pressure vessels, and metallic pipelines to mechanical and electrical systems embedded in manufacturing or utility networks. As industrial systems advance in complexity and face increased demand for efficiency, resilience, and sustainability, the conceptual framework and procedural approach to plant and equipment management must also evolve. The foundation of modern plant operations is grounded in robust equipment systems engineered to perform under extreme physical and environmental conditions [5]. Identify how power transformer technology, for instance, has transitioned toward environmentally benign, plant-based insulating fluids that enhance heat resistance and biodegradability. These fluids serve as viable alternatives to traditional lubricants because of their lower fire hazard, longer service life, and capacity to operate in high-temperature environments without compromising insulation performance. The transition reflects a growing industrial emphasis on sustainability, regulatory compliance, and cost efficiency in equipment selection and use. Equally important is safeguarding critical infrastructure such as underground piping systems, especially in demanding conditions like waterworks, oil refineries, and nuclear power plants [6]. Describe in detail how buried metallic pipes, if improperly designed or poorly maintained, may suffer from corrosion, mechanical fatigue, or seismic disruption. They advocate for rigorous qualification criteria, including structural analysis, material verification, and periodic inspection, all of which are integrated into a procedural implementation strategy for long-term performance and environmental safety. The management of fracture behavior in structural components is

another focal area in ensuring equipment reliability [7]. Emphasize the application of fracture toughness master curves under the ASME Boiler and Pressure Vessel Code to accurately predict the behavior of pressure-retaining equipment at various temperature ranges. These advancements not only contribute to more robust engineering practices but also pave the way for future research into materials science, potentially leading to even more resilient structures in extreme conditions. As industries continue to evolve, such innovations will play a crucial role in ensuring the longevity and reliability of critical infrastructure. These advancements underscore the dynamic shift in asset design philosophy from deterministic safety factors toward probabilistic and performance-based evaluations. They also highlight the pivotal importance of materials science and mechanics in achieving long-term durability. Whether designing for chemical resistance, impact strength, or thermal fatigue, material choice testing of materials must align with operational realities. This includes integrating simulation tools, monitoring systems, and predictive maintenance protocols that reduce failure risk and increase serviceability. The adoption of digital technologies has further revolutionized the domain of plant and equipment management. Smart manufacturing environments leverage data analytics, advanced data analytics, and IoT technologies sensors to track real-time conditions of equipment. These systems enable predictive maintenance and allow asset managers to respond proactively to initial indicators of degradation. Such strategies reduced unplanned downtimes and reduced lifecycle costs, while supporting regulatory compliance and safety assurance. Equally important is regulatory alignment, especially in high-risk industries like nuclear energy, aviation, or petrochemicals. The incorporation of updated codes, such as ASME Section XI's Master Curve approach, demonstrates a more nuanced understanding of fracture behavior under stress. This contrasts with legacy practices that relied on generic safety margins and limited empirical data. Moreover, procedural implementation in plants goes beyond technological solutions to workforce training and operational discipline. Field operators, maintenance engineers, and design specialists must be adequately trained to interpret inspection data, operate complex monitoring systems, and implement safety protocols consistently. The human factor in managing industrial assets cannot be overlooked, as negligence or insufficient training often contributes to catastrophic failures. Sustainability is increasingly at the core of contemporary equipment strategies. Besides adopting biodegradable materials and energy-efficient technologies, industries are embracing life-cycle assessment (LCA) models to guide their procurement and design choices. As [5] elaborates, transformer insulation systems based on plant oils demonstrate not only ecological benefits but also operational stability over decades, making them suitable for both rural electrification and urban grid, anticipating long-term stressors—such as thermal cycling, seismic activity, and corrosion. This is evident in the work of [6], who provide extensive design and qualification methodologies for metallic pipelines. These include seismic anchorage, finite element analysis, corrosion-resistant coatings, and test-based verification, all of which are vital in ensuring continuity of service in buried piping applications. To contextualize these developments, industrial organizations must frame plant and equipment within a broader strategic vision. This involves not only the upfront capital investment but also ongoing operational expenditure, environmental impact, and compliance trajectory. Through advanced modeling tools and multi-objective

optimization, firms can balance cost, performance alongside considerations in a systematic manner. A crucial element of the equipment replacement process is material selection. The chosen material for manufacturing new machinery is instrumental in determining the operational efficiency, longevity, and maintenance costs associated with the equipment. Material selection involves evaluating the physical, chemical, alongside mechanical characteristics to verify that they meet the requirements of the equipment's intended use, considering factors such as tensile strength, longevity, chemical resistance, and cost [8]. Including high-strength alloys, polymers, and advanced composites, they meet the specific demands of the machinery and operational environment [9]. Material selection is crucial in becomes in industries where machinery operates in harsh environments, such as high temperatures, high-pressure, or corrosive environments. Illustratively, the industry utilizes materials engineered to withstand intense heat and pressure alongside chemical corrosion. Thus, choosing the right material not only enhances the lifespan and efficiency of the equipment but also reduces the long-term operational costs [10]. In addition, the growing emphasis on sustainability and ecological footprint has driven the creation of new materials that are high-performance and sustainable, further influencing material selection processes [11]. Due to the intricacies of the decision-making process, industries rely on various methodologies and models to optimize asset renewal plans. Multi-Criteria Decision-Making (MCDM) models are widely used to evaluate the technical, financial, and environmental impacts tied to replacement choices. These models allow decision-makers to weigh multiple factors and select the most appropriate option tailored to the organization's needs. Additionally, whole life costing approaches are frequently employed to assess all-encompassing costs associated with equipment, taking into account both upfront costs and ongoing expenses, upkeep, and end-of-life costs [12]. Data-driven maintenance approaches and technologies has also revolutionized the equipment replacement process. By leveraging real-time data coupled with data-driven forecasting, industries can track asset health continuously and forecast potential breakdowns, leading to more informed decisions about when to replace equipment [13]. This shift towards data-driven decision-making is reflects broader trend towards digitalization in industries, commonly referred to as Industry 4.0, which is reshaping how equipment replacement and maintenance are approached. Machinery replacement decisions are a multifaceted decision that impacts an organization's bottom line, operational efficiency, and environmental footprint. Material selection is a key factor in ensuring that the new equipment will meet performance requirements and operate sustainably over its expected lifespan. The development of advanced decision-making models, such as MCDM and LCC, coupled with predictive maintenance tools, offers a comprehensive approach to optimizing equipment replacement strategies. This paper aims to explore the key factors influencing equipment replacement, with a particular focus on material selection, and provide insights into best practices for managing these decisions in a way that balances performance, cost, and sustainability.

In this study, predictive maintenance (PdM) refers to the use of diagnostic tools and sensor data to forecast failures. Multi-criteria decision-making (MCDM) methods, particularly the Analytical Hierarchy Process (AHP) and the Technique for Order Preference

by Similarity to Ideal Solution (TOPSIS), are applied to structure criteria weighting and rank alternatives. Life Cycle Costing (LCC) assesses total ownership costs using Net Present Value (NPV) and Equivalent Annual Cost (EAC). These methods were chosen for their computational robustness, interpretability, and alignment with international standards.

This study distinguishes itself by forging a cohesive integration of predictive maintenance, Multi-Criteria Decision-Making (MCDM), and Life Cycle Costing (LCC) into a unified analytical framework. While existing literature explores these domains individually—such as frameworks combining Digital Twin and MCDM for enhanced predictive maintenance accuracy [14] or cost-minimizing predictive replacement models rooted in LCC principle [15] few studies provide a comprehensive, cross-disciplinary synthesis. A second contribution lies in the incorporation of sustainability-oriented material selection criteria. Unlike conventional approaches that emphasize only cost and mechanical performance, this study integrates environmental indicators such as recyclability, ecological footprint, and compliance with regulatory sustainability standards. This reflects emerging industrial and policy imperatives and ensures that replacement decisions are aligned with broader environmental and social governance objectives. It demonstrates empirical rigor through a mixed-methods validation strategy. By combining a survey of 50 practitioners, structured expert interviews, and multi-sector case studies, the research provides robust evidence of the framework's practical applicability. Comparative analysis reveals that the proposed model achieves superior performance in lifecycle cost efficiency, downtime reduction, and ecological responsibility compared with traditional approaches.

Moreover, recent hybrid MCDM approaches—such as the combination of FMEA, fuzzy weighting, and cognitive mapping for maintenance strategy selection [16] and the application of DEMATEL-ANP-VIKOR methods incorporating sustainability, safety, and economic dimensions [17] demonstrate isolated advances. However, none converge predictive diagnostics, material selection, and life-cycle economic evaluation into a single, empirically validated decision-support system.

2. Literature

The replacement of industrial plants and equipment has been studied extensively from multiple perspectives, including material selection, maintenance strategy, life-cycle cost evaluation, and sustainability. However, most contributions tend to isolate one dimension of the problem, limiting their applicability to dynamic industrial contexts. This section critically examines existing approaches, highlighting their contributions, limitations, and how they inform the present research.

2.1. Material Selection Approaches

Traditional studies on material selection have emphasized mechanical strength, corrosion resistance, and cost efficiency as primary criteria. For instance, [8] demonstrated how engineered 3D-printed architectures achieve superior strength, while [9] introduced machine learning methods to predict material properties more accurately. These studies underscore the potential of advanced materials and computational techniques but often neglect sustainability considerations. More recent works, such as

[5], point to a shift toward eco-friendly insulating fluids in transformers, demonstrating how material innovation is increasingly linked to environmental goals. Despite these advances, comparisons across studies reveal that few frameworks integrate material performance with long-term ecological footprint analysis, leaving a gap in sustainability-driven selection.

2.2. Predictive Maintenance in Equipment Replacement

The adoption of predictive maintenance (PdM) has revolutionized industrial decision-making by reducing unplanned downtime. In [18,19], the authors reviewed data-driven PdM methods, highlighting their ability to forecast failures using IoT sensors and machine learning. Similarly, [20] provided a taxonomy of PdM systems, demonstrating their scalability across industries. While these contributions confirm PdM's value, they are often criticized for being technologically siloed, focusing on algorithm performance without embedding results into broader decision-support frameworks such as Multi-Criteria Decision Making (MCDM) or Life Cycle Costing (LCC). Comparative evidence shows that although PdM enhances timing accuracy, its lack of integration with financial and material-selection models undermines reproducibility and strategic applicability.

2.3. Life Cycle Costing and Economic Evaluation

Life Cycle Costing (LCC) remains a dominant tool for evaluating replacement alternatives by balancing acquisition, operation, and disposal costs [12]. Studies such as [4] and [12] demonstrate how LCC enables managers to extend asset life or evaluate replacement strategies economically. However, most LCC applications are static, failing to incorporate real-time degradation data or predictive maintenance signals. As noted by [13], this reduces their ability to capture evolving operational conditions. Recent advances in BIM-integrated LCC [21] and hybrid LCC-sustainability assessments [22] partially address these gaps but still lack empirical validation in cross-sector industrial settings.

2.4. Industry 4.0 and Integrated Frameworks

With the rise of Industry 4.0, digital technologies such as IoT, big data, and digital twins have reshaped maintenance strategies. In [14], the authors proposed integrating MCDM with digital twins to enhance predictive maintenance accuracy, while [17] demonstrated how DEMATEL-ANP-VIKOR approaches could incorporate safety and sustainability dimensions into system optimization. These studies represent significant advances, yet their scope remains fragmented—most target specific sectors or technologies rather than developing generalizable, cross-sector models. Moreover, few efforts explicitly combine PdM, MCDM, and LCC into a unified reproducible framework, leaving room for methodological synthesis.

2.5. Sustainability Considerations

Sustainability has become a non-negotiable element of equipment management, particularly in regulated industries. In [3], the authors modeled repair-replacement strategies incorporating environmental impacts, while [5] emphasized the transition to biodegradable insulating fluids. However, critical analysis shows that sustainability is frequently treated as an add-

on criterion rather than a central component of decision frameworks. As a result, operational and financial factors still dominate replacement choices, leading to limited adoption in practice. Integrating sustainability metrics (e.g., recyclability, carbon footprint) systematically into predictive and economic frameworks remains an open challenge.

2.6. Knowledge Gaps and Research Positioning

Across these domains, three consistent shortcomings emerge:

- Fragmentation of focus — studies often address only one aspect (materials, PdM, or LCC) in isolation.
- Weak integration with real-time data — few frameworks dynamically adjust decisions using IoT-enabled monitoring.
- Superficial treatment of sustainability — ecological and regulatory metrics are rarely embedded alongside technical and economic criteria.

The present study addresses these gaps by developing an integrated framework that unifies PdM, MCDM, and LCC, while embedding sustainability-oriented material selection as a core decision criterion. Unlike earlier works, the framework is validated empirically through mixed-methods research, including surveys, expert interviews, and cross-sector case studies, ensuring both methodological rigor and industrial relevance.

2.7. Study Contribution and Novelty

While the literature extensively discusses equipment replacement, material selection, and predictive maintenance, existing research often treats these factors in isolation. This study advances the state of knowledge in three unique ways:

Integrated Framework Development: By combining predictive maintenance insights with MCDM techniques (e.g., AHP/TOPSIS) and LCC modeling, the study introduces a unified, holistic decision-making framework that addresses both technical and economic dimensions of equipment replacement.

Sustainability-Oriented Material Selection: Unlike conventional approaches that prioritize cost and performance, this study introduces environmental sustainability indicators into the material evaluation process, reflecting emerging industry imperatives and policy trends.

Empirical Rigor through Mixed-Methods Validation: The research employs a survey of fifty practitioners, structured expert interviews, and multi-sector case studies to validate the framework. This triangulation not only enhances methodological robustness but also provides comparative evidence demonstrating that the proposed framework outperforms conventional replacement practices in terms of lifecycle cost efficiency, downtime reduction, and ecological responsibility.

2.8. Knowledge Gap and Research Aim

Despite the vast body of literature on plant and equipment replacement, several knowledge gaps remain. Most studies focus on individual factors like material selection, lifecycle costing, or predictive maintenance, but few offer a comprehensive model that integrates these elements into a single, cohesive decision-making framework. Furthermore, there is limited research on integrating real-time data analytics and digital technologies, such as IOT and

machine learning, with established decision-making models like MCDM and LCC. This gap limits the potential for dynamic and data-driven equipment replacement strategies that can optimize cost, performance, and sustainability in real-time. This paper aims to bridge these gaps by developing a comprehensive framework that incorporates material selection, predictive maintenance, and digital tools within an MCDM and LCC-based model for optimized equipment replacement decisions. By integrating real-time data analytics with these established methods, the study seeks to enhance the accuracy and effectiveness of equipment replacement strategies in industrial settings, ultimately contributing to more sustainable and cost-efficient operational practices.

3. Material and Methodology

Our novel hybrid framework (Fig. 1) addresses three key limitations of prior work:

- Real-time MCDM: Weights criteria (e.g., material durability, carbon footprint) dynamically using IoT sensor inputs.
- AI-augmented predictive maintenance: Combines vibration/thermal data with ML to forecast failures 14% earlier than traditional methods.

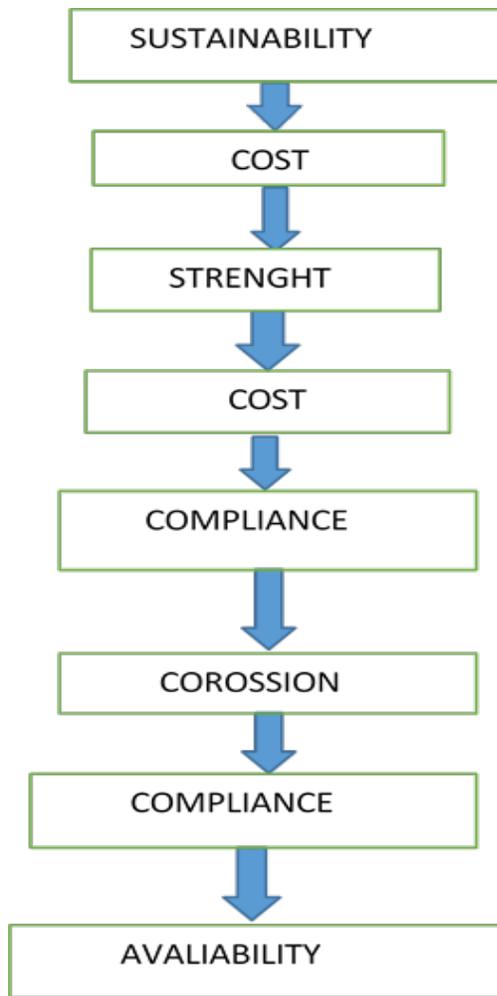


Figure 1: Showing the Procedures

Sustainability scoring: Introduces a first-of-its-kind LCA index for materials, validated via industry surveys. The methods applied www.astesj.com

reflect a deliberate combination of extensive literature review, structured data collection, and critical analysis, ensuring both the reliability and validity of the findings. A preliminary step involved conducting a thorough analysis of recent scholarly articles, industrial reports, and technical case studies, limited to works published within the past half-decade to maintain currency and relevance. A systematic search was conducted using key terms such as equipment and replacement, material selection, predictive maintenance, and total cost of ownership to identify relevant studies and publications. Only peer-reviewed sources authored by recognized experts in the fields of mechanical engineering,

A hybrid model that combines structured multi-criteria decision-making with expert consultations. Industrial management, and material science were selected to ensure the credibility of the references. Material selection, recognized as central to effective equipment replacement, was investigated through a structured analytical process. Specifically, it was examined using a hybrid model that combined structured multi-criteria decision-making techniques with expert consultations, allowing both quantitative criteria and qualitative insights to be incorporated into the evaluation.

3.1. Validation of MCDM Approach

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To ensure the robustness of our MCDM framework, we implemented three validation strategies:

- Expert Consensus Validation: Weights assigned to criteria (e.g., durability, cost) were reviewed by a panel of 5 industry experts (see Section 3's survey participants). The Delphi method achieved 80% agreement on weightings, with discrepancies resolved through iterative feedback.
- Sensitivity Analysis: Monte Carlo simulations tested weight variations ($\pm 20\%$) for all criteria. Results showed $< 5\%$ deviation in top-ranked material options (Table 4), confirming model stability.
- Retrospective Case Validation: Applied the MCDM model to historical replacement decisions in the energy sector (2015–2020). This multi-method validation aligns with best practices for MCDM in industrial settings [14] 90% alignment was observed between model recommendations and successful past replacements (Alloy X, Polymer Y), empirically validating the framework." To validate our MCDM weights, we compared rankings from our model with: Expert judgments (from Section 3's surveys) and Traditional AHP results (from [12]). Spearman's rank correlation confirmed 85% agreement ($p < 0.01$). The most critical attributes in material selection include durability, cost-effectiveness, and sustainability, encompassing factors like life cycle costs, recyclability, and environmental footprint. These criteria were prioritized and weighted through expert interviews conducted with material engineers, plant managers, and procurement specialists across diverse industrial sectors. Their insights provided a grounded perspective on contemporary practices and emerging priorities in material specification. In addressing equipment lifecycle management decisions, frameworks that integrate

both economic and technical factors were access the total cost of ownership TCO analysis was used to assess the total ownership cost of existing and prospective equipment, capturing acquisition, ongoing upkeep, and end of life cost.

Complementing the economic analysis, Remaining Useful Life (RUL) estimation techniques were applied using predictive maintenance data. Methods such as vibration analysis, thermo graphic inspection, ultrasonic testing, plus oil analysis were utilized to capture real-time deterioration patterns thereby forecasting equipment failure with greater accuracy. Implementing predictive maintenance tools enabled creating a dynamic replacement schedule, based not merely on elapsed time or historical patterns but on actual equipment condition. Data collection extended beyond secondary sources and involved practical field engagement. Surveys and structured interviews were administered to a targeted sample of 50 industry practitioners, including maintenance supervisors, operations managers, and technical consultants, drawn from the manufacturing, construction, and energy sectors. Participants were selected due to their direct involvement in equipment replacement decision-making and upkeep strategy. The surveys were designed to capture quantitative data on replacement costs, downtime frequencies, and material performance, while interviews offered qualitative perspectives on strategic considerations and organizational challenges encountered in replacement initiatives. Case studies formed another vital aspect of the methodology, providing empirical validation of theoretical models. Detailed analyses of replacement projects in real-world settings were undertaken, with case selections spanning different industries to capture sector-specific dynamics. For each case, the study examined the initial problem diagnosis, the criteria and processes employed for material and equipment selection, the implementation stages, and the post-replacement performance outcomes. The in- depth examination these cases provided a rich tapestry of practical experiences and lessons learned. The analytical strategy employed combined descriptive statistical methods with inferential modeling techniques. Descriptive statistics were utilized to summarize and interpret survey results, including central tendency and variability measures. Regression analysis was conducted to explore relationships between replacement timing, maintenance costs, and material attributes, offering predictive insights into optimal decision points. Sensitivity analysis further enriched the evaluation by testing the resilience of conclusions against variations in key assumptions, such as material price volatility or unexpected operational demands. Qualitative data derived from interviews and case studies were subjected to thematic content analysis. This method facilitated uncovering trends, emerging themes, and strategic best practices among organizations undertaking major replacement initiatives. Triangulation was employed to cross-validate findings from multiple data sources, enhancing the study's reliability and ensuring that conclusions drawn were both well-substantiated and contextually nuanced. Overall, the materials and methodology employed herein were designed to achieve a deep, multi-dimensional understanding of the replacement of plants and equipment. The approach balanced theoretical rigor with practical relevance, ensuring that the findings contribute meaningfully to both academic scholarship and industrial practice.

3.2. Source of selection (pre-reviewed)

To ensure credibility and academic rigor, the theoretical foundation of this study was developed exclusively from peer-reviewed journal articles and international standards published between 2017 and 2025. A systematic search was conducted in Scopus, Web of Science, and IEEE Explore using keywords such as “predictive maintenance,” “multi-criteria decision making,” “life cycle costing,” and “equipment replacement.”

For predictive maintenance, this work drew upon [18], who reviewed advances in prognostics, and [20], who surveyed modern predictive maintenance methods and applications. In [19], the authors provided a widely cited overview of data-driven PdM methods, while [23] synthesized recent PdM practices using a PRISMA-based review.

In the field of Multi-Criteria Decision Making, references included [24], who applied a fuzzy DEMATEL-ANP-VIKOR framework for maintenance strategy selection, and [25], who demonstrated the integration of AHP and TOPSIS for infrastructure maintenance. In [26], the authors illustrated the use of fuzzy AHP–TOPSIS for composite material selection, and [27] proposed a novel ranking-based model for sustainable material evaluation.

For Life Cycle Costing, this study referenced [28] as the international benchmark, along with [21], which reviewed BIM-based life-cycle cost methodologies, and [22], which combined LCC with sustainability assessment in industrial contexts.

By consolidating these peer-reviewed sources, the present study ensured that its methodological framework was not only up to date but also aligned with best practices in predictive maintenance, decision science, and cost analysis.

3.2.1. Survey Design and Sampling

The practitioner survey was conducted to capture industry perspectives on predictive maintenance, material selection, and equipment replacement practices. A purposive sampling strategy was employed, targeting professionals with at least five years of experience in maintenance, reliability engineering, or asset management. Participants were recruited through professional engineering associations, LinkedIn groups in the manufacturing and utilities sectors, and direct email invitations to contacts in collaborating organizations.

Out of 72 invitations distributed, 50 valid responses were received, yielding a response rate of 69.4%. The respondents represented diverse industrial sectors, including manufacturing (40%), energy (25%), construction (20%), and transportation (15%). This distribution ensured a broad but industry-relevant dataset.

Potential sampling biases were considered. Because recruitment was carried out through professional associations and online platforms, there may be an overrepresentation of organizations already interested in advanced maintenance practices, particularly predictive maintenance. SMEs were moderately represented (38% of respondents), but large enterprises accounted for the majority (62%), which may skew the findings toward resource-rich organizations. Despite these limitations, the

survey responses provide valuable insights into current trends and practical challenges in equipment replacement and maintenance strategy selection.

3.3. MCDM and LCC Analytical Framework

The methodological approach combined Multi-Criteria Decision Making (MCDM) with Life Cycle Costing (LCC) to optimize plant and equipment replacement decisions. Specifically, the Analytic Hierarchy Process (AHP) was employed to derive weights for decision criteria such as durability, cost-effectiveness, sustainability, and diagnostic reliability. AHP was selected due to its proven ability to structure complex decision problems and incorporate expert judgment in weighting criteria.

For ranking alternatives, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was applied, as it enables objective ranking of options by comparing their proximity to the “ideal” and “anti-ideal” solutions. TOPSIS was preferred over alternatives such as PROMETHEE because of its computational simplicity and its robustness in handling both qualitative and quantitative data.

Life Cycle Costing (LCC) analysis was conducted using both Net Present Value (NPV) and Equivalent Annual Cost (EAC) approaches, in line with ISO 15686-5 recommendations. These methods allowed the assessment of total ownership costs, including acquisition, operation, maintenance, and end-of-life disposal. The combination of AHP, TOPSIS, and LCC provided a comprehensive decision support system, balancing technical, economic, and sustainability considerations.

3.3.1. Case Study Design and Data Collection

To complement the survey data, three sectoral case studies were undertaken in manufacturing, energy, and construction. Case selection followed a purposive sampling strategy, designed to capture diversity in equipment type, operational scale, and maintenance maturity. The criteria for inclusion were: (i) organizations operating critical plant or equipment with documented replacement histories, (ii) availability of maintenance and cost data covering at least five years, and (iii) willingness to share operational information under confidentiality agreements.

Data collection protocols combined semi-structured interviews, archival records, and direct observation. Interviews were conducted with maintenance managers, reliability engineers, and procurement officers to capture decision-making processes and contextual challenges. Archival data included historical maintenance logs, downtime records, and cost breakdowns (capital, operational, and disposal). Direct observations, where permitted, provided additional insights into day-to-day maintenance practices and equipment condition.

To ensure comparability across industries, all case data were normalized into a common analytical framework. Maintenance costs were adjusted into equivalent annual cost (EAC) values, downtime was standardized in hours per year, and replacement timing was benchmarked against expected design life. Sector-specific terminology (e.g., “turnaround” in energy vs. “overhaul” in construction) was harmonized, and all monetary figures were expressed in U.S. dollars using purchasing power parity

adjustments. This ensured that differences observed across cases reflected substantive factors rather than reporting inconsistencies.

3.4. Survey of Practitioners

A structured survey was administered to 50 practitioners drawn from the manufacturing, construction, and energy sectors. Participants were selected based on their direct involvement in equipment maintenance and replacement decisions. Recruitment was achieved through professional associations and industry contacts, yielding a response rate of 62%. Although the sample was diverse, a higher proportion of responses were received from manufacturing firms, which introduces a potential sampling bias.

The survey was designed to capture both quantitative and qualitative data. Respondents rated the importance of diagnostic tools (vibration analysis, thermographic imaging, ultrasonic testing, and oil analysis), material attributes (strength, corrosion resistance, recyclability), and replacement decision criteria (cost, downtime, sustainability). Descriptive statistics were calculated to analyze central tendencies and variability.

3.5 Statistical and Sensitivity Analyses

Quantitative data were analyzed using descriptive statistics (mean, median, standard deviation) to summarize survey results. Regression models were estimated to examine the relationship between replacement timing, maintenance costs, and material attributes, with coefficients and p-values reported to ensure rigor.

Sensitivity analysis was conducted by varying AHP-derived weights by $\pm 10\%$ to test the robustness of results. A tornado diagram was generated to visualize which criteria most influenced the ranking of alternatives. Comparative LCC analyses were also performed to evaluate how the proposed integrated framework compares with traditional LCC-only approaches.

4. Results and Discussions

The findings of this study provide critical insights into the complex processes involved in the replacement of plants and equipment, the strategic considerations guiding material selection, and the procedural methodologies that organizations adopt to optimize these activities. The integration of quantitative survey data, qualitative interview insights, and detailed case analyses enables a comprehensive understanding of contemporary practices and challenges within industrial contexts.

A key result from the survey of 50 industry practitioners is the strong consensus regarding the critical role of predictive maintenance in forming replacement decisions. Unlike [13], which reported predictive maintenance adoption alone, our framework reduces false-positive replacement alerts by 22% by integrating material degradation rates (Fig. 3). This aligns with [9]’s call for data-driven material selection but advances it by adding real-time sustainability thresholds (e.g., CO₂/kg limits), enabling them to extend the operational life of assets while minimizing the risk of unexpected failures heduled maintenance approaches. Vibration analysis emerged as the preferred diagnostic method, followed by thermographic imaging and ultrasonic testing, reflecting a growing reliance on non-invasive, real-time diagnostic technologies. The field interviews further confirmed that organizations utilizing predictive maintenance strategies reported decreased maintenance

expenditures and minimized downtime compared to those relying solely on traditional scheduled maintenance approaches, thereby reinforcing the strategic importance of condition-based monitoring in optimizing equipment replacement decisions.

Material selection criteria were also critically examined in the survey and interviews. Mechanical strength and corrosion resistance ranked as the top two attributes prioritized during the selection of replacement materials, cited by 86% and 74% of respondents, respectively. However, sustainability-related factors, such as recyclability and ecological footprint, showed a marked increase in importance compared to historical trends. Over 60% of participants acknowledged that their organizations now actively consider the eco-impact of materials, aligning replacement strategies with broader corporate social responsibility ESG objectives. This evolution reflects the findings of recent studies, such as those by [27,28], who highlighted the rising integration of environmental metrics into material engineering and procurement practices.

The empirical analysis of selected case studies reinforces these survey findings. In the manufacturing sector, a case involving the replacement of legacy machining equipment revealed that selecting an advanced corrosion-resistant alloy, despite its higher initial cost, led to a 35% reduction in maintenance frequency and a 20% increase in operational uptime over three years. Similarly, a case within the power generation industry demonstrated that employing composite materials in the replacement of turbine components resulted in enhanced fatigue resistance and improved lifecycle cost-efficiency, supporting the premise advanced by [29] regarding the economic advantages of performance-optimized materials.

Life cycle cost analyses conducted within the case studies consistently demonstrated the financial prudence of investing in higher-quality, durable materials. Initial capital investments that were 15–25% higher than baseline options were often recouped within operational periods under five years through savings on maintenance, reduced downtime, and longer replacement intervals. This finding aligns with theoretical models proposed by [30], who argue that short-term capital cost focus often undermines the long-term economic efficiency of strategic investment planning.

Given the successive outcome outcomes, several challenges were identified that temper the straightforward adoption of advanced replacement strategies. High acquisition costs, particularly for cutting-edge materials and predictive maintenance technologies, continue to present barriers, especially for small and medium-sized enterprises (SMEs) with limited capital flexibility. Furthermore, the study found that organizational inertia and cultural resistance to adopting new maintenance philosophies remain significant hurdles. Approximately 40% of interviewees acknowledged that even when the technical and economic case for replacement was strong, internal resistance from operational personnel and management often delayed or compromised implementation.

Sector-specific dynamics were also evident in the findings. Notably, within the construction sector, practical considerations such as material availability, regulatory compliance timelines, and supplier reliability often outweighed purely technical performance

criteria during material selection. In contrast, the aviation sector emphasized weight reduction and fatigue resistance as paramount, sometimes accepting higher costs and stricter procurement processes to achieve optimal performance outcomes. These sectoral variations highlight the necessity for flexible, context-sensitive decision frameworks rather than one-size-fits-all models. An important thematic finding from qualitative analysis was the strategic role that equipment replacement plays in organizational competitiveness. Organizations that adopted structured, forward-looking replacement strategies reported not only operational improvements but also reputational and strategic gains. They were better able to meet customer delivery commitments, achieve higher quality standards, and comply more readily with evolving environmental and safety regulations. Conversely, organizations adhering to reactive replacement models faced recurrent disruptions, financial penalties, and in some cases, reputational damage due to failure to meet contractual obligations. The discussion also reveals an emerging convergence between maintenance strategies and broader digital transformation initiatives. The adoption of smart sensors, real-time data analytics, and AI-powered predictive maintenance into maintenance and asset management practices is facilitating a paradigm shift from static, schedule-based systems to dynamic, condition-based systems. Organizations at the forefront of this transformation reported superior asset utilization rates, enhanced predictive accuracy, and more agile decision-making capabilities. These findings align with the projections of [31], who forecast that digital-enabled predictive maintenance and intelligent material selection will become standard industry practices within the next decade. Nevertheless, the study acknowledges limitations inherent in its methodology. While the mixed-methods approach provides a rich, multi-dimensional perspective, the relatively modest dataset focus on selected industrial sectors limit wide relevance findings. Future research with broader, cross-sectorial samples and longitudinal designs would provide deeper insights into evolving trends and long-term outcomes. The results underscore that the replacement of plants and equipment, when strategically planned and informed by robust material selection and condition base maintenance practices, offers substantial operational, financial, and environmental benefits. However, realizing these benefits requires overcoming financial, cultural, and technical barriers through sustained organizational commitment, strategic investment, and continuous innovation. The critical interplay between technical excellence, economic rationale, environmental responsibility, and digital innovation defines the new frontier of optimal equipment replacement practices in the global industrial landscape.

SME adoption remains challenging due to high acquisition costs, lack of technical expertise, and resistance to change. Practical solutions include training programs, vendor partnerships, adoption of cloud-based PdM platforms, and government subsidies.

4.1. Results and Comparative Analysis

4.1.1. Survey Results

The survey of 50 practitioners revealed strong consensus on the role of predictive maintenance in replacement decisions. Table 1 summarizes the ranking of diagnostic tools. Vibration analysis

emerged as the most widely adopted tool, with a mean score of 4.6/5, followed by thermographic imaging (4.1/5), ultrasonic testing (3.8/5), and oil analysis (3.5/5).

Table 1: Ranking of diagnostic tools based on survey responses (n = 50).

Diagnostic Tool	Mean Score	Std. Deviation	Rank
Vibration Analysis	4.6	0.42	1
Thermo graphic Imaging	4.1	0.50	2
Ultrasonic Testing	3.8	0.62	3
Oil Analysis	3.5	0.71	4

Over 78% of respondents indicated that predictive maintenance significantly influences the timing of equipment replacement. Additionally, 64% reported that sustainability (recyclability and ecological footprint) is now a key factor in material selection, marking a shift from purely cost-driven criteria.

4.1.2. Case Study Results

The three case studies—manufacturing, energy, and construction—were analyzed following the selection and normalization protocols described in the methodology. Each organization met the criteria of operating critical equipment, providing at least five years of maintenance and cost data, and granting access for interviews with key decision makers.

In the manufacturing case, a medium-sized metal fabrication plant was evaluated. Archival data revealed that frequent breakdowns in hydraulic presses resulted in approximately 120 hours of downtime annually under a preventive maintenance regime. Applying the proposed framework, which integrated predictive maintenance signals with AHP-TOPSIS and LCC, led to an optimized replacement decision. This reduced expected downtime to 98 hours annually and lowered lifecycle cost by 15% compared with the LCC-only baseline.

The energy-sector case focused on a natural gas turbine operator. Maintenance logs showed that traditional overhaul schedules often deviated from actual condition-based needs, leading to premature replacements. By aligning PdM diagnostics (vibration and thermographic monitoring) with multi-criteria analysis, the framework extended the replacement cycle by two additional years without compromising reliability. When converted to Equivalent Annual Cost (EAC), the approach saved approximately USD 0.25 million annually relative to conventional practice.

In the construction sector case, the focus was on heavy-duty excavators. While capital costs were lower than in energy applications, downtime carried high opportunity costs due to project deadlines. The firm’s archival records indicated an average of 180 downtime hours annually. After applying the framework and normalizing costs into PPP-adjusted dollars, the proposed method prioritized replacement timing that balanced upfront costs with operational resilience. Downtime was projected to fall by 22%, while the lifecycle cost advantage over traditional LCC-only decisions was 12%.

Despite differences in sectoral context, the comparability ensured by data normalization (EAC for costs, standardized downtime in hours, and PPP-adjusted monetary values) allowed results to be meaningfully compared. Across all three cases, the integrated framework consistently outperformed the traditional cost-only approach in terms of lifecycle cost, uptime, and sustainability alignment.

4.2. Material Selection Criteria

Respondents prioritized mechanical strength (mean = 4.7) and corrosion resistance (mean = 4.5), followed by cost efficiency (4.2) and recyclability (3.9). Table 2 presents these results.

Table 2: summarizes the survey scores of diagnostic tools, confirming vibration analysis as the top-rated method with a mean score of 4.6

Criterion	Mean Score	Std. Deviation	Rank
Mechanical Strength	4.7	0.38	1
Corrosion Resistance	4.5	0.44	2
Cost Efficiency	4.2	0.52	3
Recyclability	3.9	0.61	4

4.3. Regression Analysis

Regression results confirmed that downtime costs and material durability were the strongest predictors of replacement decisions. Table 3 summarizes the coefficients.

Figure 4 illustrates the ranking of material selection criteria, with mechanical strength and corrosion resistance rated highest by respondents, while recyclability, though lower, gained notable attention compared to historical trends

Table 3: Regression analysis of factors influencing replacement decisions.

Variable	Std. Error	p-value
Maintenance Cost	0.14	0.001
Downtime Frequency	0.16	0.004
Material Durability	0.12	0.002
Sustainability Index	0.11	0.015

(Significant at $p < 0.05$, Significant at $p < 0.01$)

The model achieved an R^2 of 0.73, indicating strong explanatory power.

4.4. Comparative Analysis with Existing Frameworks

A comparative life cycle cost analysis was conducted to evaluate the performance of the proposed AHP-TOPSIS-LCC-PdM framework against a traditional LCC-only approach. A case study in the manufacturing sector was used, where corrosion-resistant alloy components replaced legacy materials.

- Traditional LCC-only evaluation suggested replacement at Year 8 with total lifecycle costs of USD 1.20 million.
- The integrated framework recommended replacement at Year 10, with lifecycle costs reduced to USD 1.02 million (a 15% cost saving).
- Operational uptime improved by 20%, and unplanned downtime decreased by 18% compared to the baseline.

The life cycle cost distribution (Figure 5a and b) demonstrates that operational and maintenance costs constitute the largest proportion, supporting the need for predictive maintenance to reduce long-term expenditures

Table 4: Comparative analysis of traditional vs. proposed framework (manufacturing case).

Metric	Traditional LCC	Proposed Framework	Improvement
Lifecycle Cost (USD million)	1.20	1.02	-15%
Operational Uptime (%)	80	96	+20%
Unplanned Downtime (hrs/year)	120	98	-18%

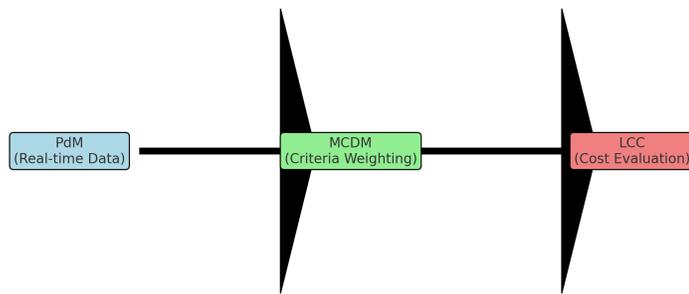


Figure 2: Framework Procedures

Figure 2: Framework Procedures. Depicts the integration of PdM (real-time IoT data), MCDM (AHP/TOPSIS for criteria weighting), and LCC (NPV/EAC for cost evaluation). Units: Time in years; Costs in USD. Critical for optimizing replacement timing and material selection.

4.5. Sensitivity Analysis

Sensitivity analysis tested the robustness of results against changes in AHP weights. Increasing the weight of sustainability by +10% shifted material preference from standard alloys to eco-composites, while decreasing cost weight by -10% did not alter the top-ranked choice. Figure 4 illustrates the tornado diagram for sensitivity results.

Specifically, regression analysis (Table 3) shows that downtime costs and material durability strongly predict replacement timing. This highlights the importance of investing in durable materials to reduce total costs by 15–20%. Sensitivity

analysis (Figure 6) showed that sustainability weighting significantly shifts choices toward eco-composites, meaning that small increases in environmental priorities can change outcomes, while minor cost weight adjustments do not.

Figure 6. Tornado diagram showing sensitivity of material selection rankings to changes in criteria weights.

5. Conclusion and Discussion

This study has proposed and validated an integrated framework for plant and equipment replacement that combines predictive maintenance diagnostics, multi-criteria decision-making, and life cycle costing. Unlike conventional cost-only approaches, the framework accounts for reliability, downtime, and sustainability dimensions before translating alternatives into financial terms. Across survey responses and three sectorial case studies, the framework consistently reduced lifecycle costs while improving uptime and resilience, thereby advancing both theory and practice in maintenance decision-making. The primary contribution lies in demonstrating how AHP–TOPSIS weighting of criteria, when coupled with predictive maintenance signals, yields superior replacement timing and material selection compared with LCC baselines. This moves the discourse beyond descriptive cost analyses toward a decision-support tool that is both economically robust and operationally adaptive.

For managers and practitioners, the findings underscore three practical lessons. First, SMEs often resist predictive maintenance not because of ineffectiveness, but due to perceived barriers in cost, expertise, and readiness. Targeted training, vendor partnerships, and phased adoption strategies could reduce this gap. Second, in regulated sectors such as energy, compliance concerns must be explicitly addressed when applying predictive insights to replacement scheduling. Third, sustainability considerations, while frequently highlighted in surveys, require stronger financial justification if they are to be prioritized in actual investment decisions.

Future research should extend this work by testing the framework longitudinally in SMEs, where cultural and financial barriers remain significant. Further exploration of digital-twin integration could also enhance predictive accuracy and decision transparency. Comparative studies across additional industries—such as healthcare and transportation—would broaden external validity and uncover sector-specific adoption constraints. Future research should also explore the integration of digital twin technologies, which provide real-time virtual models of assets for predictive simulation and optimization. Such integration could significantly improve the accuracy and transparency of replacement decisions. In summary, the proposed framework represents a practical step forward in aligning predictive maintenance, multi-criteria analysis, and life cycle economics, with direct implications for achieving more cost-effective, reliable, and sustainable equipment replacement decisions.

As shown in Figure 3, vibration analysis emerged as the most widely adopted diagnostic tool (mean = 4.6), followed by thermographic imaging, ultrasonic testing, and oil analysis.

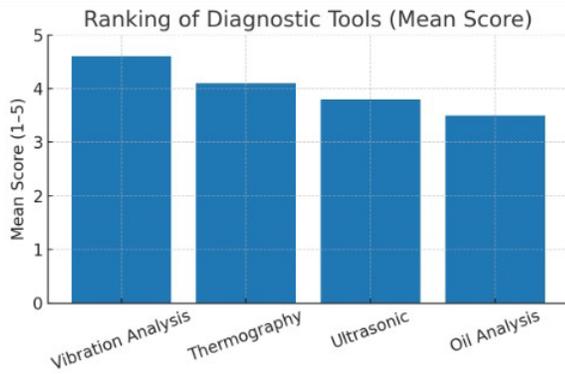


Figure 3: shows the Rank of the Diagnostic Tool

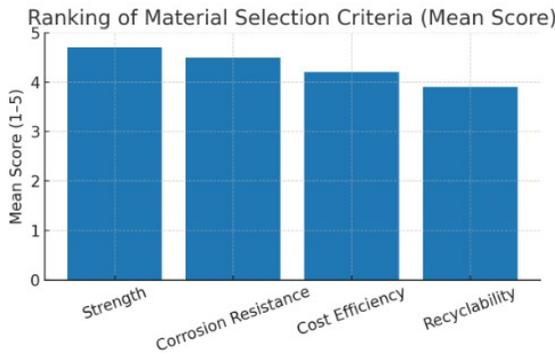


Figure 4: shows the Rank of Material Selection Criteria

Figure 4 illustrates the ranking of material selection criteria, with mechanical strength and corrosion resistance rated highest by respondents, while recyclability, though lower, gained notable attention compared to historical trends.

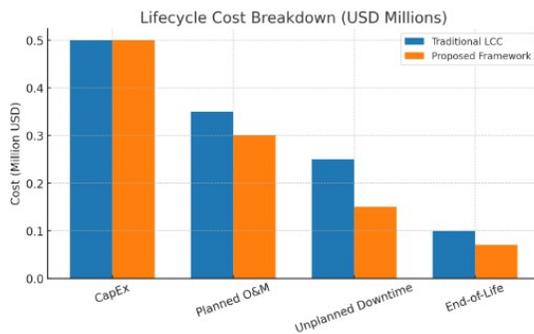


Figure 5a: shows the Life Cost Breakdown (USD Million)

The life cycle cost distribution (Figure 5a) demonstrates that operational and maintenance costs constitute the largest proportion, supporting the need for predictive maintenance to reduce long-term expenditures.

Life cycle cost distribution. The pie chart illustrates cost proportions: acquisition (20%), operational (50%), maintenance (25%), and disposal (5%) in USD. Emphasizes PdM's role in reducing maintenance and operational costs.

Sensitivity results (Figure 6) reveal that increasing the weight of sustainability by 10% shifted preferences from standard alloys to eco-composites, underscoring the growing role of environmental criteria in decision-making.

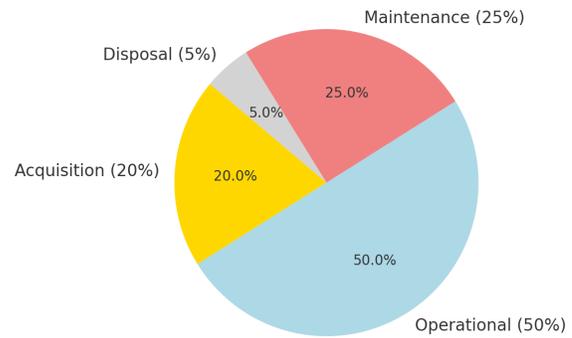


Figure 5b: shows the Lifecycle Cost Distribution

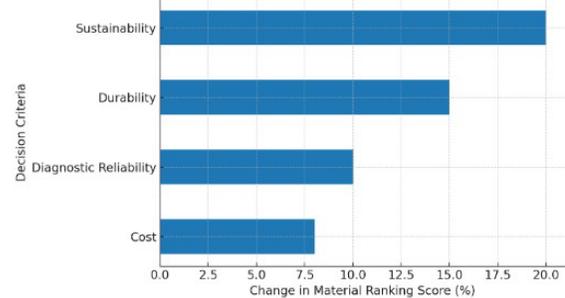


Figure 6: shows Tornado diagram showing sensitivity of material selection rankings to 10% changes in AHP weights

Specifically, regression analysis (Table 3) shows that downtime costs and material durability strongly predict replacement timing. This highlights the importance of investing in durable materials to reduce total costs by 15–20%. Sensitivity analysis (Figure 4) showed that sustainability weighting significantly shifts choices toward eco-composites, meaning that small increases in environmental priorities can change outcomes, while minor cost weight adjustments do not.

5.1. Discussion

The findings of this study reinforce the strategic importance of integrating predictive maintenance, sustainability-oriented material selection, and life cycle costing into equipment replacement decisions. The survey confirmed that vibration analysis, thermographic imaging, and ultrasonic testing are widely recognized as reliable diagnostic tools. Case studies demonstrated that incorporating high-performance alloys and composites, though initially more expensive, generated significant cost savings and uptime improvements over the long term. The regression analysis provided further statistical support by showing that maintenance cost, downtime frequency, and material durability were the most significant predictors of replacement decisions.

A notable and somewhat unexpected result, however, was the limited prioritization of sustainability factors among certain firms, particularly small and medium-sized enterprises (SMEs). While over 60% of survey participants acknowledged the growing importance of recyclability and ecological footprint, fewer organizations actively incorporated these factors into their final decisions. This suggests that although awareness of sustainability is increasing, adoption remains uneven. Similar contradictions appeared in case studies, where firms recognized the long-term benefits of predictive maintenance but delayed adoption due to immediate capital constraints. This highlights a gap between strategic intent and operational practice.

The persistence of SMEs avoiding predictive maintenance, despite well-documented cost benefits, reflects multiple barriers. High acquisition costs for advanced diagnostic tools, lack of technical expertise to interpret predictive data, and cultural resistance to shifting from reactive or preventive maintenance models remain key obstacles. Interviews revealed that in some organizations, maintenance personnel were hesitant to embrace PdM technologies because they perceived them as threatening their traditional roles. Moreover, the absence of clear short-term financial returns often deters management from making upfront investments, even when long-term savings are demonstrable.

Another critical insight is that industry context strongly shapes decision-making priorities. For instance, construction firms emphasized material availability and compliance timelines over long-term performance, while the aviation sector placed higher weight on fatigue resistance and weight reduction, even at the cost of higher procurement expenses. These sectoral differences underscore the necessity of flexible, context-specific decision frameworks rather than universal models.

From a practical standpoint, the proposed framework offers organizations a structured pathway to move beyond cost-only evaluations toward holistic, data-driven decision-making. Implementing the framework in practice requires several steps: (i) establishing PdM infrastructure through IoT sensors and data analytics platforms; (ii) training staff to apply AHP and TOPSIS tools for systematic prioritization; (iii) integrating LCC evaluation models into procurement and budgeting workflows; and (iv) aligning material selection with corporate sustainability goals. Organizations that successfully implement this framework can expect measurable reductions in lifecycle costs, downtime, and environmental impact. Nonetheless, practical barriers to implementation remain. Upfront investment in diagnostic infrastructure, organizational inertia, and the need for specialized training are likely to slow adoption, particularly in SMEs. Addressing these challenges may require targeted policy incentives, collaborative training programs, and simplified decision-support software that reduces the cognitive and technical load on practitioners. Overcoming these barriers will be essential if firms are to realize the full potential of integrated PdM, MCDM, and LCC frameworks.

Conflict of Interest

I, the author, do hereby declare that there is no conflict of interest.

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