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Balancing Cost and Reliability: A Sustainable Framework for Engineering Project Decision-Making

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Abstract: As we are facing our new reality, the biggest cost driver in engineering project planning over the past years system reliability is urgently trying to be balanced off with sustainability. Conventional methods often focus on cost reduction or reliability improvement, largely missing the interdependent nature of environmental and social factors in the success of projects over time. We, therefore, introduce a sustainability centric decision-making framework integrating cost, reliability and sustainability measures for engineering project planning. The framework employs multi-criteria decision assessment tools, such as Analytic Hierarchy Process (AHP), to assess trade-offs in a methodological approach leading to optimal strategies. A case study application to a simulated engineering project illustrates the usefulness of the proposal in obtaining minimum life cycle cost with acceptable failure-free performance, along with fulfilling sustainability targets. The findings underscore the need for an integrated approach that is in agreement with both financial and technical economic perspectives, as well as environmental objectives. This work adds to the practice of sustainable engineering by creating an organized, repeatable process for evidence-based decision-making and sets up an opportunity for further iterative improvement from field experiences.

Keywords- Cost optimization, System reliability, Sustainable engineering, Decision-making framework, multi-criteria analysis

1. INTRODUCTION

1.1 Background on Distributed Temporal Databases and Concurrency Control

Distributed temporal databases play a pivotal role in managing time-evolving data across multiple, often geographically distributed, nodes. Such databases are used in applications that demand precise tracking of historical states and temporal relationships, including financial transaction systems, health records, supply chain monitoring, and real-time analytics. Ensuring concurrency where multiple transactions execute without interfering with each other and temporal consistency is central to their reliability and performance. In distributed environments, this task becomes significantly more complex due to network latency, data replication, and asynchronous updates[1].

1.2 Limitations of Traditional Timestamp-Based Methods

Historically, concurrency control mechanisms have relied on timestamp-based strategies to maintain consistency. Logical clocks (like Lamport timestamps) and physical clocks (wall clock time) are widely used to establish the ordering of events and transactions. However, these methods suffer from inherent limitations in distributed settings. Logical clocks lack real-world synchronization, while wall clocks are vulnerable to skew and drift, particularly in the absence of precise synchronization protocols. These deficiencies can result in stale or conflicting reads, unnecessary aborts, and reduced throughput, especially when nodes operate asynchronously or under high transactional loads[2].

1.3 Introduction of System Change Number (SCN): Motivation and Industry Adoption

In distributed database systems, maintaining a reliable and consistent view of the system state across multiple nodes is one of the most critical challenges. Traditional concurrency mechanisms often rely on timestamps either logical or physical—to impose order among transactions. However, these timestamps can be imprecise or inconsistent due to issues such as clock skew, unsynchronized time sources, or latency in message propagation. As a result, these methods often lead to concurrency anomalies or degraded performance in real-world scenarios. To address these limitations, commercial database systems such as Oracle have adopted the System Change Number (SCN), a logical, monotonically increasing identifier that reflects the exact point in time when a transaction is committed. Unlike timestamps that depend on external synchronization, SCNs are internally generated and incremented in a strictly ordered manner. This guarantees that each committed transaction is associated with a unique and strictly increasing SCN, providing a deterministic ordering of changes across the system.

The motivation for using SCN lies in its ability to simplify concurrency validation and recovery. Since SCNs are tightly coupled with commit operations, they inherently encode causal dependencies between transactions. This makes them suitable for identifying read-write conflicts, maintaining consistent snapshots for queries, and ensuring repeatable reads. In Oracle, SCNs form the foundation of features such as flashback queries, read-consistent views, and incremental backups. Despite their proven utility in enterprise-grade systems, SCNs have not been widely adopted or formalized in academic models for distributed concurrency control—especially within the context of temporal databases where time dimensions add further complexity. This gap motivates the integration of SCN into a hybrid concurrency control framework that can capitalize on its determinism and efficiency, while addressing the unique demands of distributed temporal data management.

1.4 Research problem

In distributed temporal databases, maintaining concurrency and consistency across time-evolving data is a highly complex task. Each transaction may read or write data with temporal constraints, and concurrent access by multiple users can lead to anomalies such as lost updates, write skews, or inconsistent temporal snapshots. These challenges are amplified in geographically distributed systems, where network latency, asynchronous communication, and partial failures further complicate concurrency control. Traditional concurrency control mechanisms such as Two-Phase Locking (2PL), Optimistic Concurrency Control (OCC), and Multi-Version Concurrency Control (MVCC) attempt to address these issues using timestamp-based ordering and versioning. However, these approaches often fall short in distributed temporal environments. Timestamp-based methods can suffer from clock skew, network delays, and ambiguous transaction ordering, resulting in false conflict detection, unnecessary transaction aborts, or weakened consistency guarantees[3].

Furthermore, while versioning helps provide historical access, it does not inherently resolve the ordering ambiguity between concurrent operations. As a result, existing solutions frequently involve a trade-off between strict consistency and high throughput particularly under high-concurrency workloads or partitioned network conditions. There is a lack of robust, scalable, and efficient mechanisms to accurately validate concurrent transactions in distributed temporal databases, especially under asynchronous and high-load conditions. Current models often fail to capture the causal and commit-time relationships between transactions, leading to either over-conservative conflict detection or reduced data integrity.

1.5 Objective

This research proposes a System Change Number (SCN)-based hybrid concurrency control model that augments traditional timestamp and version-based mechanisms with SCN-driven validation. By leveraging the deterministic and monotonically increasing nature of SCNs, the proposed model aims to:

- Improve the accuracy of conflict detection in concurrent transaction validation
- Enhance throughput and reduce abort rates in distributed settings
- Maintain strong temporal consistency without compromising system performance
- Provide a scalable and resilient concurrency control mechanism suitable for modern distributed temporal databases

This SCN-enhanced approach bridges the gap between theoretical models and industry practices, providing a more effective framework for concurrency control in time-sensitive, distributed applications.

2. LITERATURE REVIEW

2.1 Existing work on cost optimization and reliability

Cost optimization and reliability are two important engineering project planning strategies that have long been recognized as opposing objectives. The research in cost optimization is mainly concentrated on lifecycle costing, value engineering, lean manufacturing, life cycle cost analysis and optimization algorithms such as linear programming; genetic algorithms and multi-objective optimization model[4]. Concurrent activities on reliability focus on the dilution of fluctuation in system behavior, i.e., to have a system performing at a level laid down for specified operating conditions, typically based on Fault Tree Analysis (FTA), Failure Modes and Effects Analysis (FMEA), Reliability-centered Maintenance (RCM) techniques. Results in power systems, aerospace, civil infrastructure and manufacturing show that although cost or reliability are widely studied topics they are typically investigated separately[5]. For example, cost minimization in construction may result in poor material quality (although this is not always the case; luxury and long-term reliability do not normally go hand in hand there either). While cost-reliability tradeoffs have been studied in few quantitative models, e.g. using stochastic probabilistic methods; and they are often limited to provide either costs or reliability and do not consider sustainability related long-term environmental aspects[6].

2.2 Gaps in integrated approaches

Reliability and cost have been deeply investigated, but there are not many integrated models of decision-making that consider both dimensions along with the third dimension of sustainability. Unfortunately, cost optimization studies often ignore long-term effects on system robustness & solutions that are cost-effective but operationally brittle in the long run. And studies that focus on reliability are often at the cost of considering economic constraints, leading to costly designs which are reliable but practically not feasible. In addition, traditional models usually do not include environmental and social considerations more emphasis is placed on technical and financial factors. So, their scalability is somewhat limited: as their application to engineering optimization problems becomes more and more diverse, the applicability of a particular methodology gets less and less. A second important gap is the lack of effective overall evaluation metrics that can evaluate system cost, reliability and sustainability simultaneously[7].

2.3 Need for a sustainable decision-making model

Modern engineering projects operate in a complex environment where economic efficiency, technical performance, and sustainability must be balanced simultaneously. There is a growing demand for decision-making frameworks that embed triple bottom line principles economic, environmental, and social into cost reliability trade-offs. Such models should leverage multi-criteria decision-making (MCDM) techniques, such as Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), or VIKOR, to systematically evaluate competing objectives[8]. They must also enable transparent, data-driven, and reproducible evaluations for diverse stakeholders. Additionally, the framework should be scalable, adaptable, and applicable across various industries, ensuring that sustainability is not treated as an afterthought but as an integral component of engineering project planning[9].

3. PROBLEM DEFINITION

Engineering projects face a persistent challenge in balancing cost optimization and system reliability while also meeting sustainability targets. Achieving low costs often leads to compromises in reliability, whereas high-reliability designs can significantly inflate project expenses. This imbalance can have substantial operational, financial, and environmental consequences. The problem becomes more complex when considering the broader sustainability requirements in modern engineering, which demand integration of environmental and social impacts alongside economic and technical performance[10][11].

3.1 Key trade-offs between cost and reliability

The relationship between cost and reliability in engineering projects is often described as a conflicting duality. Reducing costs can lead to choices such as:

- Using lower-grade materials or components that wear out faster.
- Designing with minimal redundancy, increasing vulnerability to single-point failures.
- Cutting down on quality control, inspection, and testing phases[12].

These decisions, while lowering initial capital expenditure, can increase the frequency of breakdowns, shorten system lifespan, and raise maintenance costs in the long run. On the other hand, increasing system reliability requires:

- Investment in higher-grade, durable materials.
- Incorporation of redundant systems and fail-safes.
- Implementation of robust quality assurance protocols and preventive maintenance schedules.

These measures, though improving uptime and operational stability, can significantly raise both initial and operational costs. Without a structured framework, organizations often make these trade-offs based on short-term budget constraints rather than long-term performance optimization, leading to suboptimal outcomes[13].

3.2 Real-world impact of imbalance

The absence of a balanced approach between cost and reliability has tangible consequences across industries

- Infrastructure: Bridges or roads built with minimal investment in reliability measures may require frequent repairs, disrupt transportation and increase lifecycle costs.
- Manufacturing: Production lines with cost-driven equipment choices may face repeated downtime, leading to loss of productivity and contractual penalties.
- Energy Sector: Power plants designed with low reliability may face outages, affecting energy supply security and public trust[11].

The impact is not just technical or financial—reliability failures can lead to safety hazards, legal liabilities, and reputational damage. Moreover, such imbalances can undermine sustainability goals. For example, frequent equipment replacement increases material consumption and waste, while unreliable systems may consume more energy and resources during their lifecycle. Thus, the lack of integrated cost–reliability decision-making has both micro-level (project-specific) and macro-level (environmental and societal) repercussions.

3.3 Statement of the research problem

Existing decision-making approaches for engineering projects often focus narrowly on optimizing either cost or reliability, with sustainability addressed as a secondary consideration, if at all. These approaches are typically:

- Fragmented: Designed for specific industries or project types, making them difficult to generalize.
- Reactive: Addressing issues after they occur rather than incorporating preventive design strategies.
- Limited in scope: Excluding comprehensive sustainability metrics from the evaluation process[14].

The central problem, therefore, lies in the absence of a comprehensive, scalable, and adaptable decision-making framework that can simultaneously optimize cost and reliability while embedding sustainability into the core of the decision process. This leads to the guiding research question that How can engineering project planners develop and implement a sustainable decision-making framework that optimizes both cost and reliability while ensuring environmental and social sustainability across diverse industries? By addressing this question, the research aims to contribute to a new generation of project planning methodologies that are technically sound, economically viable, and socially as well as environmentally responsible. Such a framework would not only improve project performance but also align with the global push toward sustainable development goals (SDGs)[15].

4. PROPOSED FRAMEWORK

4.1 Sustainable decision-making framework

A sustainable decision-making framework for engineering projects integrates life-cycle cost analysis (LCCA) which captures not only upfront capital expenses but also long-term operation, maintenance, and disposal costs with triple-bottom-line cost–benefit analysis (TBL-CBA), extending traditional cost-benefit evaluation to include quantified environmental and social impacts alongside financial returns[16]. This approach is complemented by multi-criteria decision-making (MCDM) methods such as AHP and TOPSIS, which enable systematic weighting and comparison of trade-offs among cost, reliability, environmental, and social factors. Anchored in life-cycle engineering (LCE**)** a sustainability-oriented engineering methodology that evaluates technical, economic, and environmental implications throughout a product's entire life cycle this framework supports cradle-to-grave optimization by aligning functional reliability with sustainable objectives. By combining rigorous cost modeling with holistic impact assessment and structured decision analysis, this framework empowers engineering teams to select solutions that deliver reliable performance, economic prudence, and environmental resilience[17].

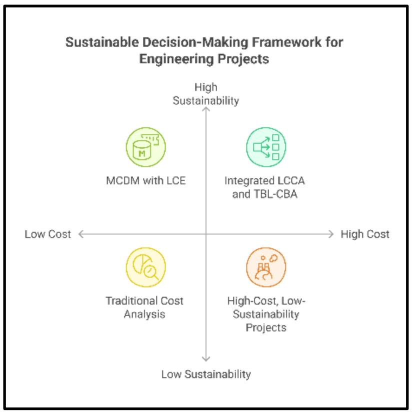

Fig 1. Conceptual Model of the Sustainable Decision-Making Framework Integrating Cost, Reliability, and Sustainability Metrics

4.2 Criteria for evaluation

When evaluating engineering project options under a sustainable decision-making framework, three core criteria drive analysis. Cost assessment typically incorporates life-cycle cost analysis (LCCA), which includes initial capital investment, operation, maintenance, disposal, and residual values, often expressed through net present value or return on investment especially when combined with broader triple-bottom-line cost–benefit analysis (TBL-CBA) that monetizes environmental and social impacts alongside financial outcomes. Reliability is measured through indicators such as failure probability, system uptime, maintenance cost, safety indices, or staff acceptance, ensuring functional performance and uptime under real-world conditions. Sustainability metrics draw from life-cycle sustainability assessment (LCSA), which combines environmental measures (e.g. GHG emissions, pollution), economic outcomes (e.g. LCC, net present value), and social aspects (e.g. social acceptability, work environment, local community impacts) to support holistic evaluation

Table 1. Evaluation Criteria for Sustainable Engineering Projects.

Criterion	Examples of Metrics/Indicators	Purpose
Cost	- Life-cycle cost (LCC) - Net present value (NPV), ROI, payback period - TBL monetized externalities	Quantifies full economic impact including upfront and long-term costs and benefits
Reliability	- Failure probability - Maintenance cost - Uptime metrics - Safety index - Staff acceptance	Ensures system dependability, safety, and operational effectiveness
Sustainability	- Environmental: GHG emissions, pollution - Economic: LCC, NPV - Social: social acceptability, work conditions, community impact	Evaluates environmental footprint, social well-being, and sustainable value

4.3 Tools and Techniques

- **Analytic Hierarchy Process (AHP):** AHP allows decision-makers to break down complex decisions into a hierarchy of objectives, criteria, and alternatives. Pairwise comparisons between criteria yield numerical weights and priorities that produce a rational ranking of alternatives. It's widely used across sectors such as government, industry, and engineering[18].
- **Fuzzy AHP:** This variation of AHP incorporates uncertainty and expert ambiguity by using fuzzy logic in pairwise comparisons. It’s particularly helpful when criteria or judgments are imprecise—for example, in structural system evaluations where cost, safety, and aesthetics may be subjectively assessed[19].
- **TOPSIS** (Technique for Order Preference by Similarity to Ideal Solution) ranks alternatives based on their distance to an ideal solution—commonly applied where quantitative, measurable criteria are available, though sensitivity to input weights must be checked[20].
- **PROMETHEE** is also used in sustainable infrastructure selection, such as bridge materials and construction methods.
- **VIKOR** emphasizes compromise—striking a balance when multiple conflicting criteria must be considered.
- **Cost–Benefit Analysis (CBA)**: CBA remains a foundational tool: it systematically compares the costs and benefits of alternatives—both tangible and intangible—to determine the most economically justified option.

4.4 Framework flowchart or model diagram

This sustainable decision-making framework begins with defining project objectives—balancing cost efficiency, reliability requirements, and sustainability goals (environmental and social). Next, generate viable design alternatives through value engineering. Stakeholder engagement and expert input inform criteria weighting, often using methods like AHP or fuzzy AHP to quantify relative importance. Each alternative is then evaluated against criteria, integrating life-cycle cost analysis (LCCA), reliability metrics (e.g., failure probability, uptime), and sustainability measures (e.g., GHG emissions, social impact). MCDM techniques such as TOPSIS, VIKOR, or weighted product model then rank alternatives based on weighted criteria. The framework includes an iterative review—if results fail to meet thresholds, revisit objectives or adjust alternatives. Finally, select the optimal solution, document the rationale, and implement while planning for ongoing monitoring and feedback to inform future decisions.

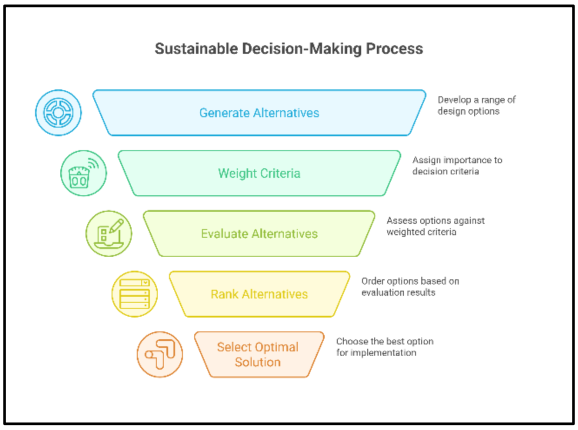

Fig 2. Process Flow of the Sustainable Decision-Making Framework from Criteria Definition to Implementation.

Table 2. Stepwise Framework for Sustainable Decision-Making in Engineering Projects.

Step	Description
1. Define Objectives & Criteria	Establish goals: cost, reliability, sustainability (economic, environmental, social).
2. Generate Alternatives	Develop options via value engineering or design iterations.
3. Weight Criteria	Use AHP or fuzzy AHP to determine importance of each criterion.
4. Assess Alternatives	Measure each alternative using LCCA, reliability metrics, and sustainability indicators.

5. Multi-Criteria Decision Analysis	Apply MCDM methods (e.g., TOPSIS, VIKOR, weighted product model) to rank alternatives.
6. Evaluation & Iteration	Review results; if unsuitable, adjust criteria or alternatives and re-evaluate.

5. CASE STUDY AND APPLICATION

5.1 Application of the framework to a real or simulated engineering project

In a compelling real-world study from the Indian manufacturing industry, engineers examined a band-saw cutting machine using an integrated framework that combined reliability analysis with life-cycle cost optimization The process began with gathering operational data from both the manufacturer and end-users. Engineers applied Weibull-based reliability modeling via tools like ReliaSoft's Weibull++ to estimate failure distributions and pinpoint critical failure-prone subsystems such as the band wheel bearing, guide roller, limit switch, hydraulic cylinder oil seal, control panel components, and the solenoid valve Next, the team conducted a life-cycle cost breakdown, which accounted for acquisition, operating, failure, support costs, and also considered net salvage value By overlaying the reliability insights with cost drivers, they implemented targeted design modifications. These changes yielded impressive results: a 15.85% improvement in overall reliability alongside a 22.09% reduction in life-cycle costs Additionally, the reliability analysis informed more effective maintenance scheduling, enabling a shift from reactive to proactive interventions. This study exemplifies how a structured framework merging Weibull-based reliability modeling and comprehensive life-cycle cost analysis can yield tangible benefits: higher performance, lower total cost, and more sustainable operations[4].

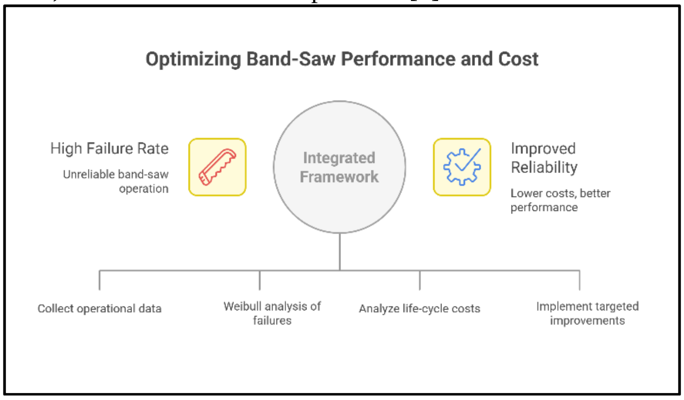

Fig. 3. Reliability and Cost Optimization Process for the Band-Saw Cutting Machine Case Study.

5.2 Analysis of results: cost-efficiency vs. system reliability

In engineering projects, the cost–reliability trade-off often follows a classic Pareto-style pattern: early investments in reliability yield substantial gains for modest cost increases, but pushing reliability beyond a threshold leads to sharply increasing expenses with diminishing returns. For example, studies in electro-optical system design have developed multi-objective models that simultaneously maximize system reliability and minimize lifecycle costs, using techniques such as goal programming to guide subsystem reliability allocation effectively From a maintenance perspective, optimal maintenance theory offers a structured way to balance costs and reliability by modeling the interplay between failure costs, downtime losses, preventive maintenance, and corrective interventions[21]. The goal is to determine maintenance schedules or actionable thresholds that minimize total lifecycle cost while sustaining acceptable reliability levels. Another key technique is Pareto analysis, used to identify the few high-impact failures or cost drivers. By ranking failure types according to their frequency and cost, engineers can target improvements on the most critical issues, yielding disproportionately large benefits in reliability and cost-efficiency. These approaches consistently reveal fundamental insights: while basic reliability improvements are cost-effective, further enhancements especially via redundancy or high-complexity designs often face steep costs for relatively smaller gains. The optimal strategy typically involves pinpointing high-leverage components via Pareto analysis and applying well-calibrated maintenance and reliability enhancements[22].

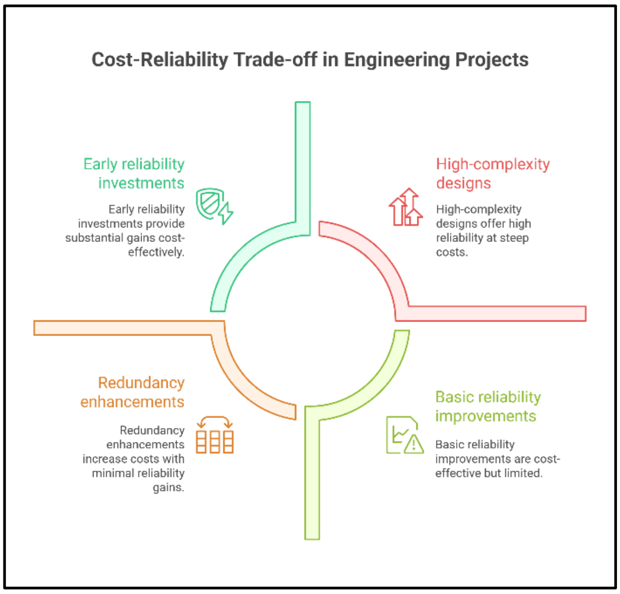

Fig. 4. Pareto Curve Illustrating the Trade-Off between Reliability Improvement and Cost Escalation.

Table 3. Summary of Reliability–Cost Trade-Off Analysis and Optimization Techniques.

Early-Stage Concept Trade-Off Modelling	Incorporating reliability estimates early (e.g., using Monte Carlo simulation) prevents underestimation of LCC and avoids investing in infeasible designs
Life-Cycle Cost (LCC) Integration	Incorporates acquisition, operation, failure, support costs, minus salvage value; ensures long-term cost vs reliability balance
Optimal Maintenance Interval	Cost-minimizing intervals may yield moderate reliability (e.g., 82%), while pushing for higher reliability (e.g., 98–99%) incurs exponential costs—highlighting diminishing
Pareto Analysis in Reliability	Identifies the vital few failure causes (often 20%) that contribute to most problems (around 80%), enabling focused cost-effective reliability improvements
Reliability Improvement Impact	Enhancements (e.g., materials, redundancy, design optimization) improve reliability but add to upfront cost; optimal trade-offs needed
Reliability-Cantered Maintenance (RCM)	Uses structured FMECA analysis to prioritize maintenance tasks that yield the most reliability gains per unit cost

5.3 Evaluation of sustainability outcomes

Table 4. Sustainability Outcomes and Associated Evaluation Approaches in Engineering Applications.

Metric / Approach	Sustainability Outcome
Triple Bottom Line Cost–Benefit Analysis	Integrates financial, environmental, and social impacts into a unified decision basis, enabling sustainable investment choices with quantified NPV and intangible benefits
Life-Cycle and Life-Cycle Engineering (LCE)	Considers full cradle-to-grave environmental, economic, and social impacts. Supports optimization that reduces waste, resource use, and lifecycle environmental burdens
Sustainable Return on Investment (S-ROI)	Provides a more holistic ROI evaluation by monetizing externalities like emissions avoided, health improvements, and community benefits—adding depth to sustainability analysis

Hybrid Energy Systems (Rwanda Case Study)	A solar–diesel hybrid mini-grid reduced costs by up to 32% and emissions by up to 83% in refugee camp electrification—illustrating powerful sustainability gains with balanced design.
Green Building Retrofit (Indonesia)	Integrating Value Engineering with LCCA showed that adding ~7% to construction cost for green retrofitting yielded a payback period around 4 years.
Structural System Evaluation (Italy)	Constructed wetlands delivered benefit–cost ratios (BCR) significantly >1 and ROIs up to 9 when ecosystem services were valued—demonstrating environmental, social, and economic viability
MCDM-Based Design Assessment	In aircraft fuselage panel evaluation, combining environmental LCA, cost LCC, and performance via MCDM consistently identified thermoplastic CFRP as the most sustainable option

- **Holistic Evaluation**: Approaches like TBL-CBA, LCE, and S-ROI help quantify not just direct costs and reliability, but also environmental and social benefits, providing a comprehensive sustainability assessment.
- **Quantified Trade**-offs: Evaluations show that sustainable engineering solutions like hybrid energy systems or retrofitted green buildings can deliver substantial environmental gains without compromising reliability, and often yield strong financial returns over time.
- **Methodological Rigor**: Incorporating MCDM frameworks enables the balancing of multiple criteria (cost, environmental metrics, performance), ensuring decision-makers select truly sustainable solutions all backed by robust, data-driven rankings.

6. CONCLUSION AND FUTURE WORK

Balancing cost-efficiency and system reliability within a sustainable engineering framework is essential for addressing modern challenges in infrastructure, energy systems, and manufacturing. By integrating methodologies such as Life-Cycle Cost Analysis (LCCA), Life-Cycle Engineering (LCE), Multi-Criteria Decision-Making (MCDM), and Triple Bottom Line Cost–Benefit Analysis (TBL-CBA), engineers can make informed decisions that optimize economic, environmental, and social outcomes. The adoption of emerging technologies like Artificial Intelligence (AI), Machine Learning (ML), and the Internet of Things (IoT) can further enhance system reliability through predictive maintenance, optimized design, and improved performance. While challenges such as high initial costs, technological barriers, and resistance to change remain, these can be overcome through collaboration among stakeholders, supportive policies, and increased education and awareness.

The proposed framework advances sustainable engineering planning by ensuring projects are financially viable, environmentally responsible, and socially beneficial. Future improvements include integrating Value-Based Engineering for ethical alignment, Design for Manufacturability to reduce production costs, Lean Construction to minimize waste, Alternatives Assessment for better decision-making, and Adaptive Management to handle uncertainty. By embedding these strategies into engineering practice, the framework promotes solutions that are not only cost-effective and reliable but also contribute to long-term sustainability, resilience, and societal well-being.

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