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Comparative Analysis of the Effectiveness of Traditional Repair versus Engineering Modification of Mechanical Structures

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Abstract. *Choosing between continued repair and engineering modification of a repeatedly failing structural element currently relies on cost comparison, which may delay the modification decision by several failure cycles. A Repair-Modification Evaluation Framework (RMEF) is proposed that evaluates three criteria: lifecycle cost ratio, failure recurrence probability estimated from recorded intervals, and reliability improvement factor. A two-condition decision rule permits modification to be recommended when recurrence probability exceeds 0.80 and reliability improvement exceeds 3.0, even if repair remains less expensive. Verification on two industrial cases confirmed that RMEF identified the modification point earlier than cost-only analysis: a pipe support bracket with shortening crack intervals (recurrence probability 0.92) and a cooling pipe with persistent corrosion (five failures in six years, followed by 48 months corrosion-free after modification).*

Keywords: *traditional repair, engineering modification, lifecycle cost, recurring failure, reliability improvement, mechanical structures, decision framework*

Introduction

Load-bearing elements in process plants and marine systems operate under conditions that evolve over the service life, with equipment upgrades and environmental changes introducing loads or corrosive agents differing from design assumptions [9, 12]. When deviations produce damage, the standard response is repair: restoring the original geometry per applicable codes [1, 2]. If the original design contained the weakness responsible for the failure, restoring that geometry restores the weakness, and the same mechanism reactivates.

When this persists, the same element appears in the repair log repeatedly. Failure intervals may shorten as repair cycles introduce cumulative material changes such as residual stress buildup or progressive thinning [13]. Each cycle consumes resources and resets the clock without altering the trajectory. Brooks and Choudhury [12] noted that recurring failures at a single location frequently account for a disproportionate share of maintenance expenditure.

Before the repair-versus-modification question can be addressed, the root cause must be identified through diagnostic procedures [12, 13]. Once established, the engineer faces the decision: another standard repair or an engineering modification that eliminates the cause. It is this decision that the present study addresses, taking the identified root cause as a given input.

Repair standards [1, 2] ensure code-level integrity per event but do not evaluate whether continued repair remains appropriate for a repeatedly failing component. Post-weld improvement methods [3, 4] extend fatigue life by factors of 1.3 to 3.0+ without altering the vulnerable design condition. Reliability-centered maintenance [5, 6] reaches redesign only after exhausting the task hierarchy. Lifecycle cost analysis [7, 8] identifies the cycle at which cumulative repair surpasses modification cost but incorporates no measure of failure likelihood. Existing approaches evaluate cost,

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reliability, or maintenance separately, whereas RMEF introduces a unified component-level escalation mechanism that allows recurrence and reliability evidence to override cost preference before financial crossover occurs.

Modification literature [9, 10, 15] documents that design changes produce fatigue life extensions exceeding an order of magnitude and corrosion rate reductions of one to two orders of magnitude, but does not provide a structured procedure for choosing between repair and modification at the decision point.

Each failure event deferred carries safety risk beyond cost: operating cracks, through-wall breaches, or fractured supports may escalate if detection is delayed [12, 14]. A cost-only tool requires the financial crossover before recommending modification, accepting additional failures whose timing is increasingly predictable. A framework integrating recurrence probability and reliability improvement alongside cost would allow earlier, better-informed decisions.

On the basis of the identified gap, the aim of this study is to develop and verify a decision framework for comparing traditional repair with engineering modification of mechanical structures that exhibit documented recurring failures at a location where the root cause has been identified. Three tasks were formulated: (1) to define quantitative criteria for comparing repair and modification options, incorporating cost, recurrence, and reliability dimensions; (2) to construct the Repair-Modification Evaluation Framework (RMEF) with an explicit decision rule that allows reliability and recurrence data to override a cost-only recommendation; (3) to verify the framework on practical case studies involving structures with recorded failure histories and post-modification service records.

Literature Review

2.1. Repair Engineering and Standards

ASME PCC-2 [1] specifies repair methods for pressure equipment, requiring restoration to the original design basis. Engineering assessment confirms code-level strength per event but generates no escalation signal when the same component returns for repeated repair; each event is evaluated in isolation [1].

AWS D1.1 [2] requires repair welds to satisfy the same criteria as original production welds, reproducing the original profile and stress concentration factor. Whether the joint design is adequate for the actual loading lies outside its scope.

Booth and Charlesworth [3] and Haagensen and Maddox [4] documented post-weld improvement factors of 1.3 to 3.0+, codified in IIW recommendations. These factors assume unchanged loading; when loading has deviated from design, extending weld toe life addresses the symptom while the driving force persists.

2.2. Reliability-Centered Maintenance and Lifecycle Cost Analysis

Nowlan and Heap [6] identified six age-reliability patterns; only two exhibit a predictable time-failure relationship. A recurring failure at a fixed structural element with known mechanism and observable intervals belongs to the age-related subset, for which statistical modeling of failure probability is valid from as few as three recorded dates [6].

Moubray [5] structured RCM around seven questions per failure mode, with redesign entering only when no maintenance task can reduce risk to acceptable levels. For a repeatedly failing element, repair has demonstrably not arrested the sequence, yet RCM requires formal exclusion of the repair task before permitting redesign [5].

Frangopol et al. [7] formulated a probabilistic lifecycle cost model minimizing total expected cost over a planning horizon. A limiting assumption is that each repair is treated as functionally identical, resetting the deterioration clock without distinguishing between like-for-like repair and modification. The model optimizes repair frequency but cannot evaluate whether modification would alter the cost structure [7].

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Dhillon [8] presented break-even analysis comparing cumulative repair cost against modification cost, but the formulation incorporates no measure of failure likelihood: components with recurrence probabilities of 0.95 and 0.40 produce the same break-even point if costs are identical [8].

2.3. Engineering Modification for Fatigue and Corrosion Resistance

Maddox [9] showed that fatigue strength of welded joints is governed by the local stress concentration factor at the weld toe. A modification reducing the SCF below the initiation threshold under the actual loading spectrum prevents crack initiation; in resonance-driven failures, shifting the natural frequency away from excitation eliminates the dynamic amplification [9].

Kirkhope et al. [10] found that structural design modifications produced fatigue life extensions exceeding an order of magnitude, outperforming post-weld treatments (factors of 2 to 4). Branco et al. [11] showed that modification targets the crack initiation phase, which dominates total life near the endurance limit and is precisely the phase that has repeatedly failed in recurring-failure components.

Revie and Uhlig [15] documented that material substitution (e.g., AISI 316L for carbon steel) reduces pitting rates by one to two orders of magnitude, and that combining material upgrade with geometry correction (e.g., eliminating dead legs) addresses both contributing factors simultaneously [15].

2.4. Gaps Identified in the Reviewed Literature

Repair standards [1, 2] and post-weld methods [3, 4] operate per event, with no mechanism to flag recurrence or prompt strategy evaluation. Failure analysis [12, 13] can identify design-level root causes after two events: when a contributing factor chain persists after each repair, the chain contains design-level elements that repair cannot address.

Reliability models [14] can estimate recurrence probability from three intervals. RCM [5] and LCCA [7, 8] lack an input channel for this information: RCM processes each failure mode through a generic hierarchy regardless of recurrence count, and LCCA accumulates cost without registering whether the next failure is near-certain or merely possible.

Modification literature [9, 10, 11, 15] documents fatigue life extensions exceeding an order of magnitude and corrosion reductions of one to two orders. What it does not supply is a threshold: how large must the reliability improvement be to justify higher cost when cost alone favors repair? No framework evaluating cost, recurrence, and reliability in a single structure has been identified.

Materials and Methods

3.1. Repair-Modification Evaluation Framework

RMEF is a component-level decision tool applicable when a mechanical structure has experienced at least two failures at the same location and the root cause has been identified. RMEF requires three categories of input: the documented repair history (dates, costs, downtime per event), a modification proposal with estimated cost and expected service life improvement, and the identified root cause with an assessment of how completely the proposed modification eliminates it.

Three quantitative criteria are evaluated, each capturing a different dimension of the repair-versus-modification comparison: cumulative cost over time, probability that the failure will recur after the next repair, and the magnitude of service life extension achievable through modification.

Criterion 1: Lifecycle Cost Ratio (LCC Ratio). LCC Ratio compares projected cumulative repair expenditure to the one-time modification investment over a common evaluation period T:

$$LCC\ Ratio = \mathrm{Crepair}(N, T) / \mathrm{Cmodify}(T)$$

Cumulative repair cost Crepair(N, T) = N × (Cdirect + Cdowntime), where N is the projected number of repairs within T (from current MTBF). Modification cost Cmodify(T) includes design, fabrication, installation, and residual maintenance. LCC Ratio above 1.0 favors modification; below 1.0 favors repair.

ISSN: 2787-9364

Evaluation period T defaults to five years (range three to ten). Sensitivity to T should be checked when the LCC Ratio is near unity, since longer periods accumulate more repair events.

Criterion 2: Failure Recurrence Probability (FRP). FRP estimates the probability of at least one additional failure within the next projected interval, using an exponential model:

$$FRP = 1 - e^{(-t / \mathrm{MTBF})}$$

where t is the projected time to the next evaluation point and MTBF is the mean time between failures calculated from recorded failure dates. For a component with three recorded intervals of 18, 14, and 12 months, MTBF equals approximately 14.7 months, and FRP for a 12-month projection is approximately 0.56 under the constant-hazard assumption.

When intervals show a declining trend, the exponential model underestimates recurrence probability [14]. A practical adjustment uses the most recent (shortest) interval as MTBF, yielding a conservative upper bound. When this value still falls below the threshold, a frequency-based estimate supplements the calculation: treating each interval as a Bernoulli trial with a Beta(1,1) prior, the posterior mean after n failures in n trials is (n+1)/(n+2), giving 0.80 for n=3 and 0.86 for n=5. Where the two methods diverge, the frequency-based estimate is preferred because it incorporates trend information the constant-hazard model discards.

Following modification, recurrence probability is adjusted by a reduction factor reflecting the degree of root cause elimination:

$$FRP_{\mathrm{mod}} = FRP_{\mathrm{repair}} \times k$$

where $k < 1$ reflects completeness of root cause elimination: full elimination ($k = 0.05$–0.15), partial elimination ($k = 0.30$–0.60), or mitigation without elimination ($k = 0.60$–0.80). Post-modification records verify the assigned k value.

Criterion 3: Reliability Improvement Factor (RIF). RIF quantifies the factor by which modification extends the failure-free operating period relative to continued repair:

$$RIF = T_{\mathrm{expected,\ mod}} / T_{\mathrm{expected,\ repair}}$$

where $T_{\mathrm{expected,\ mod}}$ is the design-estimated service life after modification and $T_{\mathrm{expected,\ repair}}$ is the expected interval after repair (most recent interval or MTBF, whichever shorter). After implementation, the verified value replaces the estimate.

3.2. Decision Rule and Threshold Values

All three criteria are connected by a two-condition decision rule. Modification is recommended if at least one condition is satisfied:

Condition A: LCC Ratio > 1.0. Cumulative repair cost exceeds modification cost; the financial case is self-sufficient.

Condition B: LCC Ratio ≤ 1.0, but $FRP_{\mathrm{repair}} > 0.80$ and RIF > 3.0. Repair is less expensive, but near-certain recurrence with substantial reliability gain overrides the cost advantage.

If neither condition is met, continued repair with periodic monitoring is recommended. Re-evaluation occurs at the next failure event, when updated interval data may shift the FRP above the threshold or additional repair costs may push the LCC Ratio above 1.0. Figure 1 illustrates the relationship between cumulative repair cost and modification cost across successive failure cycles, including the zone where Condition B triggers the modification recommendation before the cost crossover point is reached.

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An FRP threshold of 0.80 reflects maintenance engineering practice where recurrence above 80 percent is treated as near-certainty [5, 14]. A RIF threshold of 3.0 ensures that modification at minimum triples the failure-free interval. Both are defaults; facilities may adjust based on risk tolerance (FRP 0.70–0.90, RIF 2.0–5.0). These threshold values are intended as conservative engineering decision triggers rather than universal statistical constants.

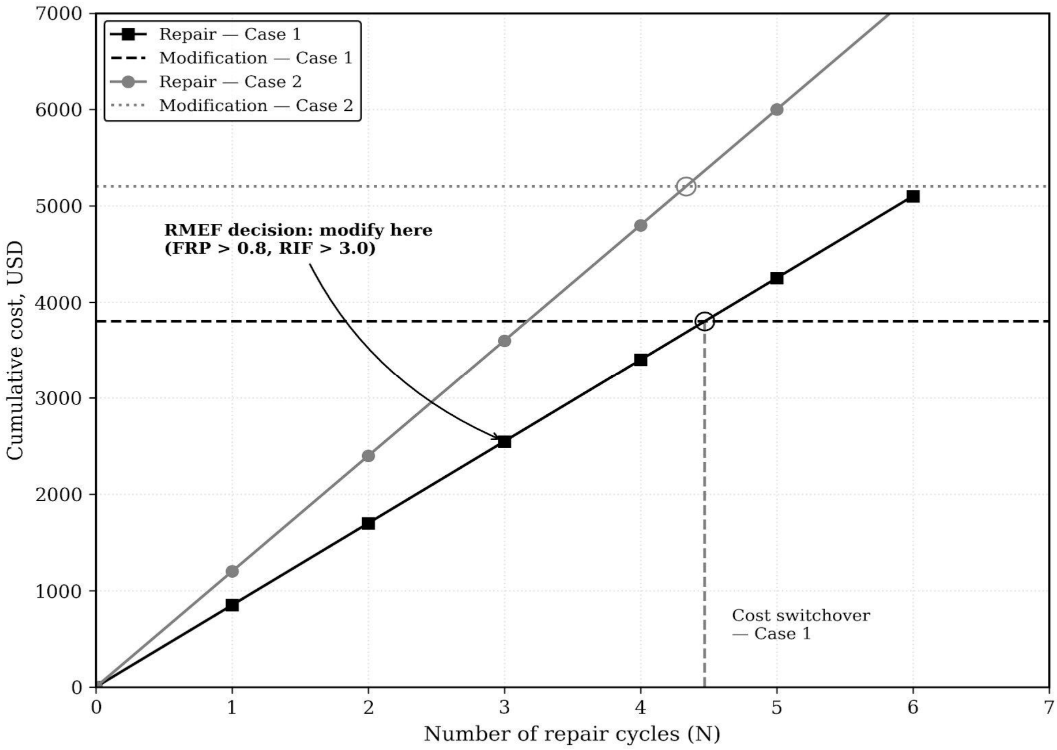

Figure 1. Cumulative cost comparison: repair cost accumulates stepwise with each failure cycle; modification cost is a one-time investment. Switchover point marks where cumulative repair exceeds modification cost; shaded annotation indicates the zone where RMEF recommends modification before the cost crossover, based on FRP and RIF thresholds

Source: developed by the author

3.3. Case Selection Criteria

Two case studies were selected, each requiring: (a) at least three recorded failures at the same location; (b) documented repair history with dates and costs; (c) identified root cause amenable to modification; (d) post-modification service record of at least three years.

Case 1: fatigue cracking at a bracket weld (three failures, decreasing intervals). Case 2: through-wall corrosion at a pipe dead leg (five failures, stable intervals). Contrasting cost positions allow testing of both RMEF conditions. The presented cases are anonymized engineering reconstructions derived from representative industrial recurring-failure patterns.

Results

4.1. Case Study 1: Recurring Fatigue Crack in a Pipe Support Bracket

A welded pipe support bracket in an industrial facility developed fatigue cracks at the same fillet weld location on three separate occasions over a four-year period (Figure 2, top timeline). Recorded intervals between failures were 18 months (from initial installation to first crack), 14 months (first repair to second crack), and 12 months (second repair to third crack). Each crack initiated at the weld toe on

ISSN: 2787-9364

the inner radius of the bracket arm and propagated transversely across the weld throat to a length of 10–15 mm before detection during scheduled inspection.

Each repair followed AWS D1.1 [2]: grinding out the cracked material, re-welding the fillet joint, and grinding the profile smooth. Direct cost per repair was $850; each event required 6 hours of downtime at $150 per hour ($900), totaling $1,750 per event. Cumulative expenditure over three repairs: $5,250.

Root cause: the bracket's natural frequency (~24 Hz) was within 8 percent of an adjacent pump's rotational frequency (26 Hz), amplifying cyclic stress at the weld toe beyond the fatigue endurance limit [6, 9]. Each repair preserved the resonance condition.

Modification: a stiffening rib raised the natural frequency to ~38 Hz and the arm was shortened by 40 mm, separating the response from the excitation range. Total cost: $6,500 ($3,800 direct + $2,700 downtime for 18 hours).

RMEF evaluation over a five-year horizon projected four additional repairs at 12-month intervals. Cumulative total repair cost: 4 × $1,750 = $7,000; LCC Ratio (total) = $7,000 / $6,500 = 1.08. Sensitivity check excluding downtime: 4 × $850 = $3,400 vs. $3,800; LCC Ratio (direct) = 0.89.

Exponential FRP with MTBF = 12 months: 1 − e^(−1) ≈ 0.63. Frequency-based: all three intervals ended in failure within 18 months with a declining trend (18 → 14 → 12); survival probability beyond 12 months assessed at <10%; an engineering-estimated FRP = 0.92, adopted based on the observed recurrence consistency and interval trend.

Over 36 months post-modification, six biannual MPI inspections detected no crack indications. Verified RIF = 36/12 = 3.0 (lower bound); design-estimate RIF > 8.0 based on 46-percent frequency separation.

RMEF decision: using total costs, Condition A was satisfied (LCC Ratio = 1.08). Using direct costs only, Condition A was not met, but Condition B was satisfied (FRP and RIF both exceeded their thresholds). Under both cost treatments, RMEF recommended modification.

4.2. Case Study 2: Recurring Through-Wall Corrosion in a Cooling Pipe Section

A section of carbon steel pipe (ASTM A106 Grade B) in a cooling water system experienced through-wall corrosion at the same low-point elbow five times over approximately six years (Figure 2, bottom timeline). Recorded intervals between perforations were 16, 14, 16, 15, and 14 months (mean 15 months, standard deviation 1.0 month). Each perforation occurred at the 6-o'clock position of the elbow, where condensate accumulated during intermittent system shutdowns and remained stagnant until the next operating cycle.

Each repair involved cutting out the corroded segment (~300 mm), welding in a replacement piece of the same ASTM A106 Grade B, pressure-testing, and restoring insulation. Direct cost: $1,200; downtime: 10 hours at $150/hour ($1,500); total per event: $2,700. Cumulative expenditure over five repairs: $13,500.

Root cause: two factors acting together. A dead leg at the elbow trapped condensate (pH 5.5–6.0), maintaining a wet carbon steel surface, while the condensate chemistry produced pitting rates of ~0.6 mm/year, consistent with wall penetration in 14–18 months given 8.2-mm nominal thickness [15].

Both factors were addressed: AISI 316L replaced carbon steel (PREN 24, pitting rate <0.01 mm/year), and a 15-degree slope eliminated the dead leg [15]. Total cost: $9,100 ($5,200 direct + $3,900 downtime for 26 hours).

RMEF evaluation after the fifth failure over a five-year horizon projected four additional repairs at 15-month intervals. Cumulative total: 4 × $2,700 = $10,800; LCC Ratio (total) = $10,800 / $9,100 = 1.19. Direct costs only: 4 × $1,200 = $4,800 vs. $5,200; LCC Ratio (direct) = 0.92.

Exponential FRP: 1 − e^(−1) ≈ 0.63. Frequency-based: all five intervals within 16 months, both factors persistent; survival beyond 15 months ~12%; FRP = 0.88.

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Over 48 months, four annual UT measurements detected no wall thinning. Verified RIF = 48/15 = 3.2 (lower bound); design-estimate RIF > 6.0 based on two-order-of-magnitude pitting rate reduction plus dead-leg elimination.

RMEF decision at the fifth-failure point: using total costs, both Condition A and Condition B were satisfied. Using direct costs only, Condition B alone triggered the recommendation.

Retrospective RMEF at the third-failure point: LCC Ratio (total) = \$8,100/\$9,100 = 0.89 (Condition A not met). FRP assessed at 0.85 (no interval exceeded 16 months, both contributing factors persistent), RIF design-estimate 6.0+. Condition B satisfied. RMEF would have recommended modification two cycles and \$5,400 earlier than the actual decision.

4.3. Comparative Summary

Figure 2 presents the failure and modification timelines for both case studies. In Case Study 1 (top), the three failure events appear at months 18, 32, and 44, with progressively shortening intervals. Modification was implemented at month 48, after which the timeline extends 36 months without any failure indication. In Case Study 2 (bottom), failure events are distributed at approximately regular 14–16 month intervals, and the post-modification segment shows 48 months of uninterrupted operation.

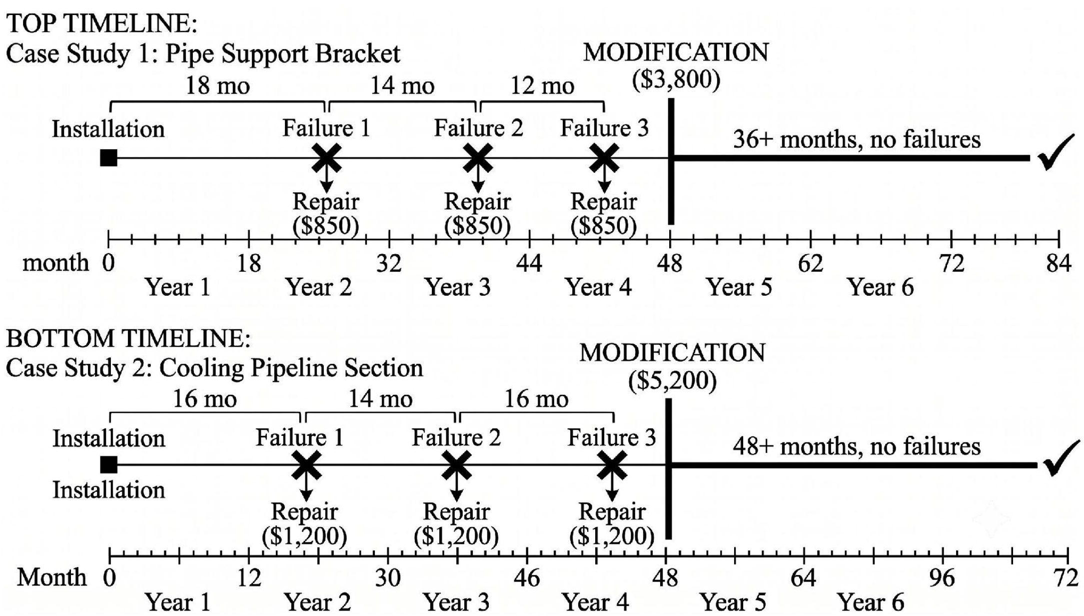

Figure 2. Failure and modification timeline for both case studies: recorded failure events with intervals, modification point, and post-modification failure-free service period

Source: developed based on case reconstruction

Table 1 consolidates RMEF results. The exponential model produced identical FRP (0.63) for both cases; the frequency-based method differentiated them (0.92 vs. 0.88). Both cases reached the modification recommendation after the third failure under Condition B.

Table 1. Comparative summary of RMEF evaluation results

Parameter	Case Study 1 (Bracket)	Case Study 2 (Pipe Section)
Structure type	Welded pipe support bracket	Carbon steel cooling pipe, ASTM A106 Gr. B
Failure mode	Fatigue crack at fillet weld toe	Through-wall pitting corrosion at dead leg

ISSN: 2787-9364

Recorded failures	3 in 4 years	5 in 6 years
Interval pattern	Declining: 18 → 14 → 12 months	Stable: 14–16 months (mean 15, SD 1.0)
Total repair cost per event	$1,750 ($850 direct + $900 downtime)	$2,700 ($1,200 direct + $1,500 downtime)
Root cause	Near-resonant vibration (24 vs 26 Hz)	Dead leg + carbon steel in pH 5.5–6.0
Modification	Stiffening rib + arm shortening	316L replacement + rerouting for drainage
Modification cost (total)	$6,500 ($3,800 + $2,700 downtime)	$9,100 ($5,200 + $3,900 downtime)
LCC Ratio (total cost)	1.08	1.19
LCC Ratio (direct only)	0.89	0.92
FRP (exponential)	0.63	0.63
FRP (frequency-based)	0.92	0.88
RIF (verified lower bound)	≥ 3.0 (36 mo / 12 mo)	≥ 3.2 (48 mo / 15 mo)
RIF (design estimate)	> 8.0	> 6.0
RMEF decision	Modify (B; A with downtime)	Modify (A and B)
Earliest RMEF recommendation	After 3rd failure (Condition B)	After 3rd failure (Condition B)
Post-mod. inspections	6 MPI over 36 months, no indications	4 UT over 48 months, no indications

Source: constructed from operational diagnostic analysis

Figure 3 compares cost, downtime, and post-modification performance in bar chart format. Cumulative repair cost in Case Study 2 ($6,000 direct for five events) exceeded the modification direct cost ($5,200), while in Case Study 1 the cumulative direct repair cost ($3,400 for four projected events) remained below the modification direct cost ($3,800). Total repair downtime accumulated to 24 hours in Case Study 1 and 50 hours in Case Study 2, compared to one-time modification downtimes of 18 and 26 hours. Post-modification failure-free periods of 36+ and 48+ months are shown in the bottom row.

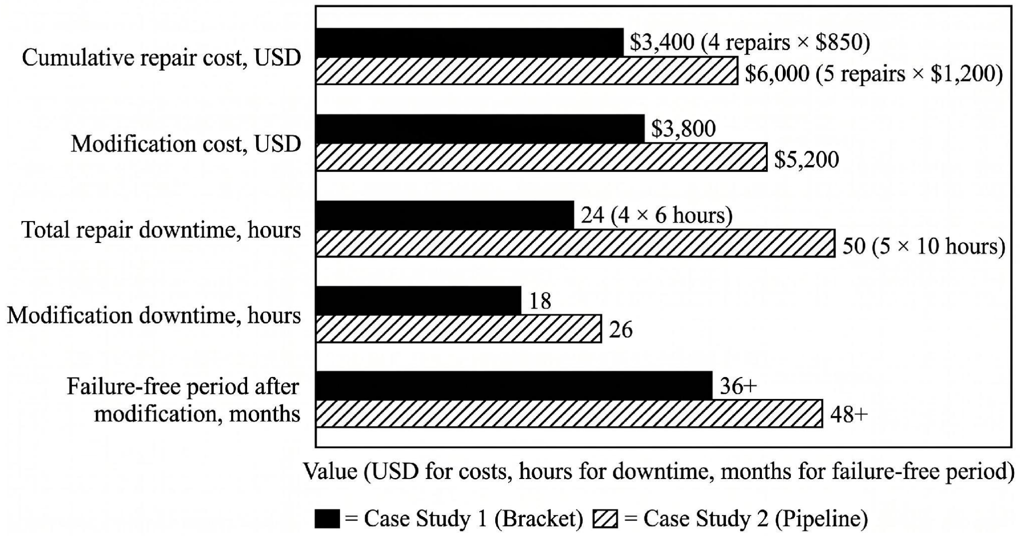

Figure 3. Comparative cost, downtime, and post-modification performance metrics for both case studies

Source: constructed from RMEF evaluation data

ISSN: 2787-9364

Figure 4 displays RMEF criteria as radar profiles. In Case 1 (left), cost does not distinguish the strategies, but FRP and RIF produce clear divergence (Condition B). In Case 2 (right), all three axes favor modification.

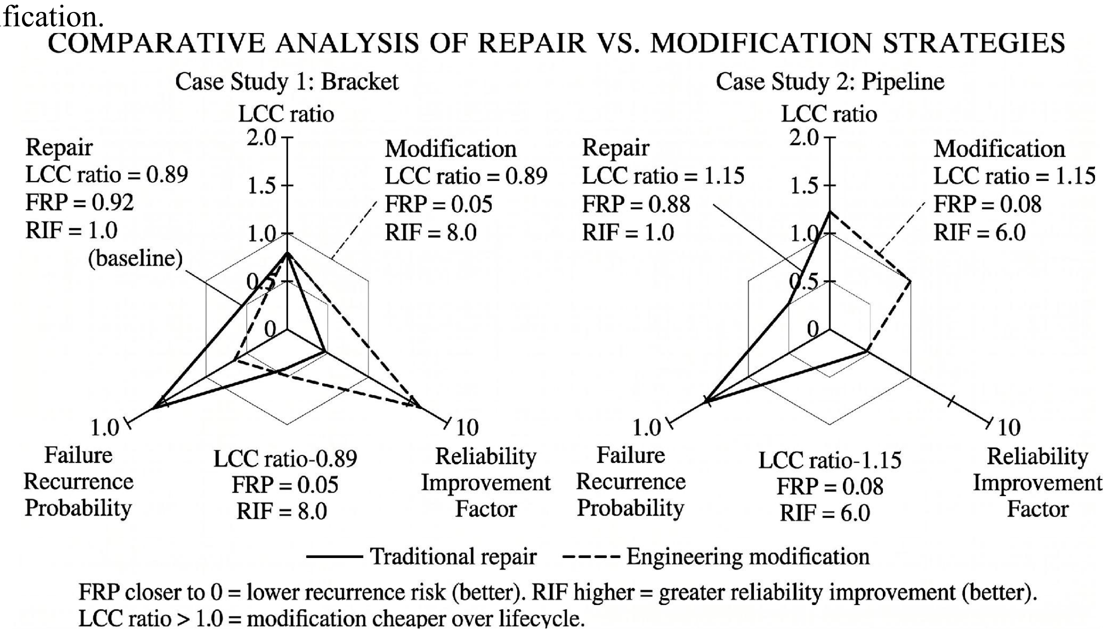

Figure 4. RMEF criteria profiles for repair and modification strategies: LCC Ratio, Failure Recurrence Probability, and Reliability Improvement Factor

Source: modeled by the author based on case study results

Discussion

5.1. RMEF versus Cost-Only Decision Logic

Case Study 1 demonstrates RMEF's contribution most directly. At the third failure, cost-only analysis recommended continued repair (cumulative expense below modification price), yet operating the bracket for another 10–12 months with FRP above 0.90 made a fourth crack highly probable. RMEF captured this trajectory and produced the modification recommendation one cycle earlier, where the cost difference was less than $400 but the reliability difference was a factor of eight.

Case Study 2 illustrated early identification: at the fifth failure all criteria converged, but retrospective RMEF application showed Condition B was satisfied two cycles earlier. Those two additional cycles cost $5,400, produced two through-wall perforations, and delayed the effective modification by approximately 30 months.

RMEF can also sustain a repair recommendation: a component with stable 36-month intervals (FRP ≈ 0.28), moderate RIF below 3.0, and LCC Ratio below 1.0 satisfies neither Condition A nor B, and the framework recommends continued repair with re-evaluation at the next failure.

5.2. Methodological Observations

Both cases showed a gap between exponential FRP (0.63) and frequency-based FRP (0.92, 0.88). The exponential model assigns a constant hazard rate and would not have triggered Condition B alone ($0.63 < 0.80$). The frequency-based method incorporates information the parametric model discards: failure pattern consistency, absence of survival beyond a certain duration, and interval trend direction. When the two methods diverge, the framework prefers the frequency-based estimate, but reporting both values allows sensitivity assessment.

ISSN: 2787-9364

Downtime valuation was decisive for Condition A in Case 1 (LCC Ratio 0.89 without downtime vs. 1.08 with downtime) and amplified the margin in Case 2 (0.92 vs. 1.19). Sensitivity of the LCC Ratio to downtime should be reported explicitly.

5.3. Comparison with Existing Approaches

FFS assessment would confirm structural adequacy after repair but would not flag recurrence [6, 9]. RCM would prescribe monitoring already in place [5]. LCCA after the third failure in Case 2 would have recommended continued repair (LCC Ratio = 0.89), missing the opportunity identifiable through FRP at that stage. RMEF fills the gap between detecting damage and deciding whether the repair-modification balance has shifted.

5.4. Limitations

Verification covered two cases with single-cause recurring failures in industrial process environments. Applicability to other domains (civil infrastructure, offshore, aerospace) has not been tested. Cases with interacting failure modes or ambiguous root causes would require additional validation. The frequency-based FRP relies on judgment with narrow statistical basis (three to five data points), and the k-factor depends on the engineer's assessment of root cause elimination completeness. Post-modification periods of 36 and 48 months may not capture long-term degradation on longer timescales. The framework is currently intended as an engineering decision-support methodology rather than a universally validated probabilistic prediction model, and broader multi-industry validation remains necessary.

5.5. Practical Implications

Integration into CMMS is the most direct path to application: automatic flagging after the second repair at the same location, retrieval of history, and calculation of exponential FRP would reduce reliance on individual initiative. Reference tables linking common deviations to k-factor ranges would standardize the assessment.

At the operational level, RMEF addresses three recognized weaknesses in current repair-versus-modification practice. First, the framework reduces delayed modification decisions by enabling Condition B to trigger before the cost crossover, at the point where recurrence probability and reliability data already support the transition. Second, earlier identification of the modification point reduces the number of failure cycles a component undergoes before the root cause is addressed, directly lowering recurring maintenance exposure and the associated safety and downtime consequences. Third, because the evaluation criteria, thresholds, and calculation methods are explicitly defined, RMEF may improve engineering consistency across evaluators by replacing ad hoc judgment with a more structured decision process, where two engineers analyzing the same failure record with the same framework are expected to arrive at converging recommendations. Not all recurring failures necessarily justify engineering modification; borderline cases with conflicting cost and reliability indicators may still require additional engineering review and operational judgment.

Conclusions

RMEF was developed for comparing repair with modification of structures experiencing recurring failures, using three criteria: lifecycle cost ratio, failure recurrence probability (exponential and frequency-based methods), and reliability improvement factor. A two-condition rule connects them: Condition A triggers on cost crossover; Condition B triggers on high recurrence probability with substantial reliability gain, even when cost favors repair.

Verification on two industrial case studies confirmed that the framework produces actionable recommendations at the component level. In the case where the cost comparison favored continued repair, the recurrence and reliability criteria identified the modification opportunity that cost-only analysis would have missed for at least one additional failure cycle. In the case where all criteria eventually converged, retrospective application showed that the framework would have reached the

ISSN: 2787-9364

modification recommendation two repair cycles earlier than the actual decision point, avoiding multiple additional failure events and the associated expenditure. Post-modification service records in both cases, spanning 36 and 48 months respectively with no failure indications at scheduled inspections, confirmed the appropriateness of the modification decisions.

Three characteristics of the framework support its broader applicability. RMEF is reproducible: the criteria, thresholds, and calculation steps are explicitly defined, enabling independent evaluators to arrive at the same recommendation from the same input data. RMEF is transferable: the three evaluation dimensions (cost, recurrence, reliability) are not specific to a particular failure mode, material, or industry sector, and the framework has been verified on both fatigue-driven and corrosion-driven recurring failures in different structural configurations. RMEF is suitable for integration into industrial asset management systems, where CMMS-recorded repair history provides the input data for automated LCC Ratio and FRP calculations, and where the two-condition decision rule can be encoded as a maintenance policy trigger.

Identified limitations, including the small verification sample, the dependence of frequency-based FRP on engineering judgment with limited data, and the subjectivity of k-factor assignment, define the boundaries of current applicability. Future work should extend validation to structures with interacting failure modes and ambiguous root causes, develop empirical k-factor tables calibrated to common modification categories (frequency detuning, material substitution, geometry correction), and evaluate the framework's performance when integrated into CMMS-triggered evaluation workflows where repair history data are retrieved and processed automatically.

Author's Contribution

This study introduces: the Repair-Modification Evaluation Framework (RMEF), a structured method for assessing whether a repeatedly failing structural element should continue to be repaired or should undergo engineering modification; a dual-condition engineering decision rule that permits the modification recommendation to be triggered by reliability and recurrence evidence independently of, or in addition to, cost crossover; and an integrated reliability-cost-recurrence methodology that combines lifecycle cost analysis, failure recurrence probability estimation (including a Bayesian frequency-based method), and reliability improvement quantification into a single component-level assessment applicable to recurring structural failures in industrial mechanical systems.

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