

# RISK-BASED LIFE CYCLE COST ANALYSIS FOR STRATEGIC MAINTENANCE DECISION-MAKING IN DEEPWATER GAS OPERATIONS

Febri Rio Cahyono<sup>1\*</sup>, Pri Hermawan<sup>2</sup>

<sup>1,2</sup> School of Business and Management, Institut Teknologi Bandung, Bandung 40132, Indonesia

\*Corresponding author: [29324483@mahasiswa.itb.ac.id](mailto:29324483@mahasiswa.itb.ac.id)

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## Abstract

This paper examines why the maintenance cost per barrel at a deepwater gas field operating under a cost-recovery production-sharing contract rose 161% in a single year, climbing from USD 0.41/BOE in the prior year to USD 1.07/BOE, even though plant availability stayed above 97%. A risk-based life-cycle cost (LCC) framework is applied to four maintenance strategy alternatives over an eight-year residual contract horizon (2025 to 2032) using primary operational records for 2021 to 2024, supplemented by sensitivity analysis and the Analytic Hierarchy Process (AHP). The deterministic Net Present Cost (NPC) ranking favors contract restructuring as the least-cost option (A2, USD 72.37M, 10% real discount rate). The multi-criteria evaluation, which integrates risk-cost exposure under the safety, efficiency, flexibility, and cost criteria (weights 0.557, 0.286, 0.100, 0.056, CR 0.003), supports condition-based monitoring investment as the recommended strategy (A3, NPC USD 74.51M, AHP composite 0.438). An expected-value analysis estimates that a CBM-enabled 30% reduction in unplanned-event frequency avoids approximately USD 5.9M of production-loss exposure against a USD 2.14M premium over the cheapest alternative, a ratio of roughly 2.8 times. The recommended strategy targets a return to USD 0.85 to 0.90/BOE within the 2026 to 2028 planning horizon. The findings show that under cost-recovery fiscal structures, the cost-cheapest option is not the value-best option once risk-cost exposure is properly weighted.

**Keywords:** life cycle cost; condition-based monitoring; maintenance strategy; AHP; production-sharing contract; offshore gas

## 1. Introduction

Mature offshore gas assets in regulated upstream environments face a well-documented tension. As fields age, maintenance expenditure tends to grow while production volumes decline, so unit maintenance cost drifts upward even when operational reliability remains high. Under production-sharing contracts (PSCs) with cost-recovery provisions, this tension carries fiscal implications beyond the operator's internal budget, because higher operating costs expand the recoverable cost base, reduce profit gas, and diminish the state's fiscal take even when production is stable. This paper presents a case study of a deepwater gas field (hereafter the case field) operated under a cost-recovery PSC, where the maintenance cost per barrel of oil equivalent (MC/BOE) rose from USD 0.41/BOE to USD 1.07/BOE, a 161% increase in a single year, against a background of stable plant availability and major equipment reliability. The anomaly is structurally important, because it exposes a misalignment between the traditional operational KPI lens, which would declare the year a success, and the unit-cost lens that governs value distribution under the PSC.

Previous work on LCC in offshore and process industries has largely addressed greenfield or early-brownfield assets (Barringer, 1997; Nguyen and Chou, 2019; Patriarca et al., 2025). Decision-analytic applications of AHP to maintenance strategy selection exist for onshore and near-shore settings (Bevilacqua and Braglia, 2000; Ratnayake and Markeset, 2010; Wang et al., 2025), yet their integration with the specific fiscal mechanics of cost-recovery PSCs remains underexplored, particularly the way the economic sign of a maintenance decision differs between contractor and state. This paper makes three contributions. First, it decomposes the MC/BOE spike using a Pareto cost-driver analysis and reliability register data, which establishes that the increase is structural and lifecycle-driven rather than operational. Second, it applies a discounted NPC overlay to an existing technical LCCA so that

four maintenance strategy alternatives can be ranked over the residual PSC horizon. Third, it embeds the NPC result in an AHP framework calibrated to a published oil-and-gas weight reference, generating a recommendation that is robust to weight perturbation and consistent with the cost-recovery fiscal logic. The remainder of the paper is organised as follows. Section 2 reviews the relevant literature. Section 3 describes the methodology. Section 4 presents the results. Section 5 discusses the implications, and Section 6 concludes.

## 2. Literature Review

### 2.1 Asset Management and Life Cycle Cost

ISO 55000:2014 frames physical assets as value-generating systems that require coherent management across their full service life, with decisions weighted by life-cycle cost, risk, and performance rather than short-term budget alone. Life Cycle Costing (LCC) operationalises this view by aggregating all ownership costs, which span initial investment, operations, maintenance, and disposal, and converting future streams into Net Present Cost for strategy comparison (Barringer, 1997; Le Roux et al., 2022). For ageing hydrocarbon assets, LCC provides a principled method for linking maintenance strategy choices to long-run cost exposure that annual budget comparisons cannot supply.

### 2.2 Risk-Based Maintenance

Risk-based maintenance (RBM) prioritises intervention by formally assessing failure likelihood and consequence for each asset element. In oil and gas, RBM and its component framework Reliability-Centred Maintenance (RCM) are standard tools that direct resources to risk-significant items while reducing unnecessary routine work (Bevilacqua and Braglia, 2000). Condition-based monitoring (CBM), one of the strategies evaluated here, extends RBM by replacing fixed-interval inspection with continuous or periodic sensing of degradation indicators, which enables pre-emptive intervention before functional failure. Ratnayake and Markeset (2010) applied AHP to maintenance strategy selection in the Norwegian offshore sector under a safety regulator that is structurally analogous to Indonesia's SKK Migas, which establishes the method's validity for regulated offshore upstream contexts.

### 2.3 Sensitivity Analysis and Scenario Thinking

LCC results are sensitive to assumptions about discount rates, failure rates, and production-loss value. One-way sensitivity analysis tests robustness by varying each parameter across a defined range while the others hold at base values, which produces a tornado diagram that ranks inputs by absolute NPC swing (ISO 15686-5:2017; Kneifel and Webb, 2022). Scenario thinking extends this by testing internally consistent combinations, such as simultaneous upward failure-rate drift and adverse gas-price movement, so that the analyst can identify which strategy remains preferable under plausible future states (Campagna et al., 2025).

### 2.4 AHP for Maintenance Strategy Selection

The Analytic Hierarchy Process introduced by Saaty (1980, 1990) decomposes a decision into objective, criteria, and alternatives, derives criterion weights and alternative scores from pairwise comparison matrices, and supplies a Consistency Ratio that validates judgment coherence. Bevilacqua and Braglia (2000) established AHP as the standard MCDA tool for maintenance strategy selection in process industries. Wang et al. (2025) applied a combined AHP-TOPSIS model to maintenance strategy selection in an oil and gas context and reported a defensible published weight set (Safety 0.586, Efficiency 0.256, Flexibility 0.102, Cost 0.055), which this study uses as an external calibration reference rather than a weight transfer, since the Wang et al. case is a downstream refinery whose recommended strategy and asset context differ from the present setting.

### 2.5 Cost-Recovery PSC Incentives

Under a cost-recovery PSC, the contractor recovers eligible operating and capital expenditure from gross production before the residual profit gas is shared with the state. This creates a bidirectional incentive. Under-maintenance raises failure risk and production loss, both of which harm profit gas, while over-maintenance expands the recoverable cost base, which reduces the profit-gas share for both contractor and state. The maintenance strategy choice is therefore not purely a cost-minimisation problem. It is a risk-adjusted value problem in which the fiscal structure of the contract determines the relative stakes of cost and failure exposure for each party. This fiscal dimension is underrepresented in the existing LCC and AHP maintenance literature, which mostly addresses cost-recovery-neutral settings.

## 3. Research Methodology

### 3.1 Research Design

The study uses a quantitative archival case-study design. Primary data are drawn from the case field's internal operational and financial records for 2021 to 2024, which include SAP PM work orders, monthly performance dashboards, the production disruption register, annual cost actuals, and Work Program and Budget (WP&B) submissions. Secondary sources include SKK Migas regulatory reports, prior LCC study outputs from a ReliaSoft BlockSim model, and the academic references described in Section 2. No formal interviews or surveys are conducted, and informal clarification with field engineers, planners, and finance staff resolves cross-system discrepancies in the primary dataset. The analytical workflow runs in four sequential modules. First, a Pareto cost-driver decomposition identifies and quantifies the contributors to the 2024 MC/BOE spike. Second, reliability metrics, namely failure rate, MTBF, and MTTR, are extracted from the production disruption register. Third, a discounted NPC model evaluates four maintenance strategy alternatives over 2025 to 2032. Fourth, AHP integrates the NPC result with risk, efficiency, and flexibility criteria into a composite ranking. Sensitivity analysis and weight perturbation are embedded in the third and fourth modules respectively.

### 3.2 LCC Model Structure

The NPC model aggregates four cost streams discounted at a 10% real rate over an eight-year horizon, where the sum of discount factors equals 5.868. Planned maintenance covers labour, materials, contracted services, and logistics. Corrective maintenance covers unplanned intervention. Campaign and inspection events cover major overhaul and integrity responses. Risk cost is the expected production-loss value, computed as the product of the annualised failure rate, the production lost per unplanned event in BOE, and the net gas price after cost-recovery treatment:

$$E_{\text{risk}} = \lambda \times \text{LPO\_per\_event} \times P_{\text{gas}}$$

This formulation follows Barringer (1997) and Nguyen and Chou (2019). The company's existing ReliaSoft BlockSim LCCA provides the technical cost basis, while the NPC overlay is a post-processing step that converts projected cost streams into discounted present value, which the original internal model did not do. The 10% real discount rate is used as a decision-economics proxy consistent with oil-and-gas industry practice (Agusyasa and Nainggolan, 2023; McKeown et al., 2024). The four alternatives are the Baseline, which continues the as-is strategy; A1, which strengthens the existing PM and PdM programme through tighter inspection intervals and wider SECE and OCE scope; A2, which restructures the contract portfolio toward long-term service agreements, spares pooling, and contractor-scope rationalisation; and A3, which invests in condition-based monitoring through vibration, thermography, oil-condition, and process-side sensing on critical rotating equipment, integrated with the CMMS, with retirement of redundant time-based PM scope on monitored assets.

### 3.3 AHP Framework

The four criteria are Safety, Efficiency, Flexibility, and Cost. The pairwise comparison matrix is constructed independently by the authors using the Saaty 1 to 9 scale, and the Wang et al. (2025) weight order serves only as an external calibration check rather than a weight source. Alternative scores are derived from four separate pairwise matrices, one per criterion, each anchored in quantitative evidence: NPC results for Cost, RAM and HAZID or HAZOP findings for Safety, projected availability and LPO improvement for Efficiency, and an implementation tractability assessment for Flexibility. The Consistency Ratio is computed for each matrix, and only matrices with CR below 0.10 are accepted. Robustness is tested by varying each criterion weight by plus or minus 10% with the others renormalised, plus two combined Safety and Cost perturbation cases.

## 4. Results and Discussion

### 4.1 Operational KPI and Cost Summary, 2021 to 2024

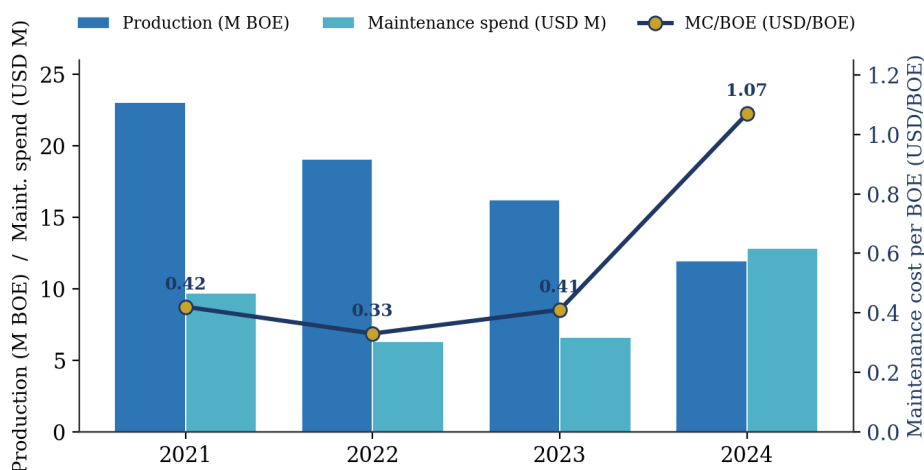
Table 1 summarizes the operational KPI set and the unit-cost trajectory across the study period. The operational indicators show consistent high performance, with plant availability held between 94.4 and 97.3%, major equipment reliability above 99.2%, and PM and PdM completion improving steadily from 97.1 to 99.6%. The cost trajectory diverges sharply. Maintenance expenditure nearly doubled in the final year, rising from USD 6.62M to USD 12.85M, while production fell 26%, from 16.21M to 11.96M BOE. The joint effect drove MC/BOE from USD 0.41 to USD 1.07 in a single year. The maintenance-to-OPEX ratio independently confirms the structural nature of the shift, because it rose from 12.74% to 25.94% in the same year, and this metric is not influenced by the production denominator.

**Table 1.** Operational KPI and maintenance cost summary, 2021 to 2024.

Metric	2021	2022	2023	2024
Plant availability	95.22%	94.38%	97.31%	97.19%
Major equipment reliability	99.99%	99.25%	99.99%	99.98%
PM/PdM completion	97.10%	98.10%	99.14%	99.64%
Maintenance cost (USD M)	9.69	6.31	6.62	<b>12.85</b>
Production (M BOE)	23.07	19.09	16.21	11.96
MC/BOE (USD/BOE)	0.42	0.33	0.41	<b>1.07</b>
Maintenance-to-OPEX ratio	16.56%	13.32%	12.74%	<b>25.94%</b>

Source: Author's analysis from internal performance dashboards and regulatory cost reports.

Figure 1 shows the same divergence visually. The production bars decline year on year while the unit-cost line stays flat through 2023 and then jumps in the final year, which is the signature of a falling denominator combined with a step change in spend rather than a gradual cost creep.



**Figure 1.** Annual production, maintenance spending, and maintenance cost per barrel, 2021 to 2024.

#### 4.2 Cost Driver Decomposition

Table 2 presents the Pareto decomposition of the USD 6.22M year-on-year OPEX increase. Three events account for 84.5% of the total rise. The OPEX portion of a major rotating-equipment overhaul at the 50,000-hour scheduled interval, performed on the export compression train, contributed 51.4%, equivalent to USD 3.20M. Consumable replacement on ageing power generation units contributed 20.9%, or USD 1.30M. A subsea integrity campaign that responded to pipeline inspection findings added a further 12.2%, or USD 0.76M. The remaining 15.5% is dispersed across minor items, none of which exceeds 4% individually. These three events are lifecycle-structural rather than drift-driven. The major overhaul recurs at fixed usage intervals built into the asset's maintenance programme, and the next instance is already scheduled within the residual PSC life. The subsea integrity campaign was triggered by a risk-based inspection finding, so it is a pre-emptive structural intervention rather than an emergency response. This classification matters for the forward-looking strategy, because the cost-control lever is not the unit cost of routine work, which is already well managed, but the frequency and scope of non-routine lifecycle events, which is itself a function of the failure-rate distribution of the safety-critical and operation-critical rotating equipment.

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**Table 2.** Pareto decomposition of the year-on-year maintenance OPEX increase.

Cost driver	Type	Incremental OPEX (USD M)	YoY share	Interpretation
Major overhaul, export compressor (OPEX portion)	Planned lifecycle	3.20	51.4%	Structural, asset maturity
Power generation consumables (turbines, ECP modules)	Materials	1.30	20.9%	Recurring, equipment ageing
Subsea integrity campaign (pipeline freespan)	Integrity campaign	0.76	12.2%	Non-routine, risk-driven
Other dispersed items	Mixed	0.96	15.5%	Dispersed minor items
<b>Total YoY OPEX increase</b>		<b>6.22</b>	<b>100.0%</b>	

Source: Author's analysis from internal cost records and regulatory maintenance reports.

## 4.3 Reliability Metrics

Table 3 reports system-level reliability metrics derived from the production disruption register for 2021 to 2024. The register was filtered to unplanned equipment-failure events in six categories, namely Compressor, Electrical, Instrument and Control, Piping and Valves, Pump, and Well and Reservoir, while planned outages and third-party curtailment events were excluded. MTBF is computed as available operating hours divided by failure count, and MTTR as total unplanned downtime divided by failure count. The reliability profile runs counter to the cost spike. Unplanned equipment failures peaked at 18 in the year preceding the cost escalation, then fell to 10 in the escalation year itself, while MTBF more than doubled from 403 to 874 hours and MTTR collapsed from 83.3 to 4.1 hours per repair. On every reliability dimension, the escalation year was the strongest in the study window, which is direct evidence that the cost increase was caused by scheduled lifecycle work and a declining production denominator rather than by a deterioration of equipment condition. The window-average failure rate of 11.8 events per year anchors the risk-cost stream in the NPC model.

**Table 3.** System-level reliability metrics from the production disruption register, 2021 to 2024.

Reliability metric	2021	2022	2023	2024	Window avg
Unplanned equipment failures	12	7	18	10	11.8
MTBF (hours)	717	1,064	403	874	682
MTBF (days)	29.9	44.3	16.8	36.4	28.4
MTTR (hours per repair)	15.5	187.6	83.3	4.1	66.8

Source: Author's calculation from the production disruption register.

## 4.4 Net Present Cost Results

Table 4 presents the four-stream NPC results for each strategy over 2025 to 2032 at a 10% real discount rate. A2 produces the lowest NPC at USD 72.37M, followed by A3 at USD 74.51M, A1 at USD 80.57M, and the Baseline at USD 80.81M. The USD 2.14M gap between A2 and A3, which is about 3% of A2's total NPC, is the central number in the deterministic ranking. The mechanisms behind the ranking deserve a brief explanation. A1's near-zero gain over the Baseline, only USD 0.24M, reflects a structural limit, because tighter inspection intervals catch degradation marginally earlier but do not alter the underlying failure-rate distribution, so the saving in corrective work is largely offset by the higher cost of a more intensive preventive program. A2's saving of USD 8.44M over the Baseline comes almost entirely from contractor-margin compression across the planned, corrective, and campaign streams, while risk cost is unchanged because failure rates are not affected. A3's saving of USD 6.30M over the Baseline is distributed across all four streams, because the CBM hardware and analytics OPEX, modelled at USD 2.0M over the horizon, raise the planned-maintenance line but are more than recovered by a 30% reduction in

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corrective cost and a corresponding reduction in risk cost, the latter reflecting fewer unplanned production losses on monitored equipment.

**Table 4.** Net Present Cost by maintenance strategy, 2025 to 2032 (USD million, 10% real discount rate).

Strategy	Planned	Corrective	Campaign	Risk cost	NPC total
Baseline	36.40	16.20	13.70	14.51	80.81
A1, PM/PdM strengthening	40.29	13.70	13.70	12.88	80.57
A2, contract restructuring	31.78	14.15	11.93	14.51	<b>72.37</b>
<b>A3, CBM investment (recommended)</b>	41.45	8.10	13.35	11.61	<b>74.51</b>

Source: Author's analysis. Full per-stream derivation in the companion workbook.

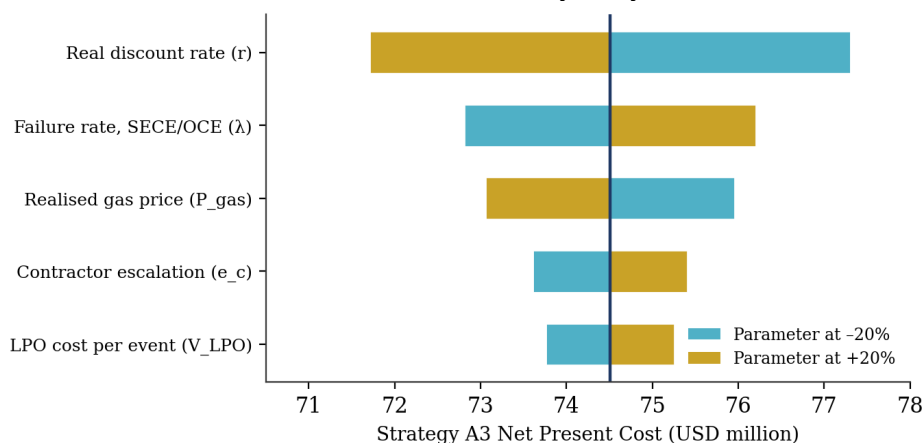
## 4.5 Sensitivity Analysis

Table 5 and Figure 2 show the tornado results for Strategy A3 under plus or minus 20% one-way variation. The discount rate produces the largest absolute NPC swing at USD 5.60M, which is 36.8% of the total, yet this parameter is ranking-neutral, because it shifts all four NPCs in the same direction. The substantively important parameters are the failure rate, with a USD 3.40M swing or 22.4%, and the gas price, with a USD 2.90M swing or 19.1%, both of which enter through the risk-cost stream. Higher failure rates raise A3's risk-cost advantage over A2, and higher gas prices amplify the value of the production that A3 protects. The three top parameters account for 78.3% of the observed NPC swing.

**Table 5.** Sensitivity tornado for Strategy A3 NPC, plus or minus 20% one-way variation (base NPC USD 74.51M).

Parameter	NPC at -20% (USD M)	NPC base (USD M)	NPC at +20% (USD M)	Total swing (USD M)
Real discount rate (r)	77.31	74.51	71.71	<b>5.60</b>
Failure rate, SECE/OCE ( $\lambda$ )	72.81	74.51	76.21	3.40
Realised gas price (P_gas)	75.96	74.51	73.06	2.90
Contractor escalation (e_c)	73.61	74.51	75.41	1.80
LPO cost per event (V_LPO)	73.76	74.51	75.26	1.50

Source: Author's sensitivity analysis.



**Figure 2.** Tornado diagram showing the sensitivity of Strategy A3 NPC to key parameters at plus or minus 20% variation.

The switching-value analysis shows that A3's NPC falls below A2's once the failure rate rises about 14% above the 2024 baseline, which is a plausible threshold given the asset's age profile and the failure-rate patterns observed in the study window. No rank reversal occurs on discount rate, contractor escalation, or gas price

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individually within the test range. Under combined adverse stress, where the failure rate rises 20% and the gas price falls 20%, A3's NPC advantage over A2 grows to about USD 4.8M, which shows that A3's economics improve as the operating environment deteriorates. That property is the defining feature of a robust strategy under cost-recovery fiscal exposure.

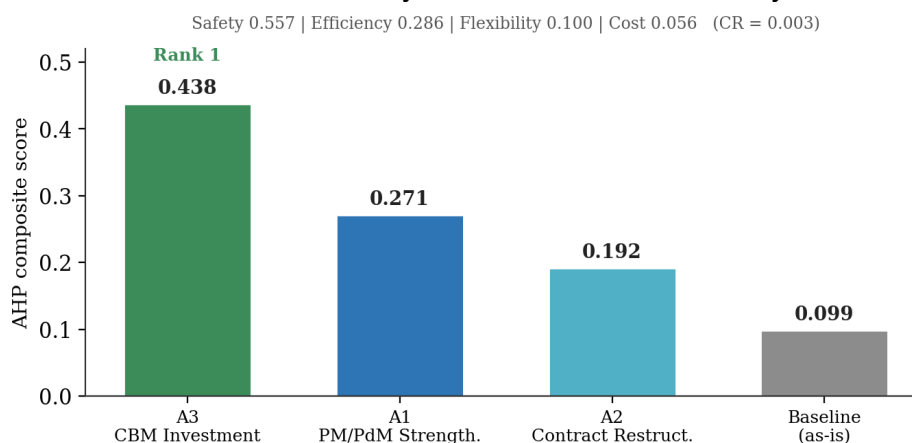
## 4.6 AHP Multi-Criteria Ranking

Table 6 and Figure 3 present the AHP composite scores. The criterion weights, namely Safety 0.557, Efficiency 0.286, Flexibility 0.100, and Cost 0.056 with CR 0.003, reflect the consequence asymmetry of failure in deepwater operations, where a safety-critical equipment breach on an offshore floating unit carries HSE liability, regulatory exposure, and production loss far larger than the cost difference between strategies. Safety dominates cost by nearly 10 to 1 in the weight vector, which is consistent with the Wang et al. (2025) calibration reference.

**Table 6.** AHP composite scoring and ranking. Weights calibrated against Wang et al. (2025) as an external reference.

Strategy	Safety	Efficiency	Flexibility	Cost	Composite	Rank
Baseline	0.088	0.088	0.167	0.141	0.099	4
A1, PM/PdM strengthening	0.272	0.272	0.333	0.141	0.271	2
A2, contract restructuring	0.158	0.158	0.333	0.455	0.192	3
<b>A3, CBM investment</b>	<b>0.482</b>	<b>0.482</b>	0.167	0.263	<b>0.438</b>	<b>1</b>
<b>Criterion weight</b>	<b>0.557</b>	<b>0.286</b>	<b>0.100</b>	<b>0.056</b>	<b>CR 0.003</b>	

Source: Author's AHP analysis. CR denotes the consistency ratio.



**Figure 3.** AHP base-case composite scores by maintenance strategy.

A3 scores highest under both Safety at 0.482 and Efficiency at 0.482, because condition monitoring directly reduces the frequency of unplanned failures, which is the mechanism behind both the safety improvement and the availability gain. A2 scores highest on Cost at 0.455 by the NPC ranking and jointly highest on Flexibility at 0.333 alongside A1. The composite ranking, where A3 reaches 0.438, A1 reaches 0.271, A2 reaches 0.192, and the Baseline reaches 0.099, reverses the NPC order for A1 and A2, because A1's modest PM intensification earns more on safety and efficiency than A2's contractor-only intervention, even though A2 has a substantially lower NPC. The gap between A3 and A1 at 0.167 sits well above the 0.05 threshold conventionally regarded as a decisive margin in AHP rankings. The weight perturbation produced no rank reversal across any of the eleven scenarios tested. A3's composite ranged from 0.433 to 0.444 against a base of 0.438. The recommendation therefore holds across the full perturbation set, including scenarios that raise the cost weight fivefold relative to its base value.

## 4.7 The Cost-Recovery Argument

The USD 2.14M NPC disadvantage of A3 relative to A2 is the most obvious challenge to the recommendation, and the resolution lies in the cost-recovery PSC structure. Under cost recovery, the contractor and the state share both the investment cost and the downside of inadequate maintenance. A2's NPC saving returns to the

recoverable cost pool, which reduces profit gas in the periods it materializes, and that saving is shared in the agreed contractor and state split. If A2's lower-touch posture produces even one major unplanned outage that A3 would have pre-empted, the resulting production loss destroys profit gas for both parties at once. The asymmetry is structural, because cost savings are shared upside while production-loss costs are shared downside, and the magnitude ratio between a deepwater intervention cost and the maintenance premium is roughly 5 to 1. An expected-value calculation makes the point concrete. The Baseline carries a risk-cost NPC of USD 14.51M, which implies an undiscounted annual risk exposure of about USD 2.47M, found by dividing 14.51M by the discount-factor sum of 5.868. A 30% reduction in unplanned-event frequency avoids roughly USD 2.47M multiplied by 0.30 and by 8, which gives USD 5.9M of exposure on an undiscounted basis, or USD 2.90M on a discounted basis, the latter being the difference between the Baseline and A3 risk-cost NPCs. Against the USD 2.14M premium of A3 over A2, the avoided exposure is about 2.8 times the premium on an undiscounted basis. The choice is therefore not between saving USD 2M and spending USD 2M for nothing. It is a choice between saving USD 2M deterministically and spending USD 2M for protection worth roughly USD 5 to 6M of avoided production-loss exposure over the residual PSC life. Under any plausible failure-rate distribution above a long-run minimum, the expected value of the protection exceeds its premium.

## 5. Implications and Implementation

### 5.1 Practical Implications

The study carries three actionable implications for the case field. First, the structural decomposition of the cost spike confirms that the existing maintenance program is not the problem, because operational discipline is strong and the cost escalation is lifecycle-driven. The WP&B narrative should therefore shift from defending the cost increase toward demonstrating that the lifecycle-event clustering is predictable, planned, and mitigated by the proposed CBM transition. Second, the recommended three-phase implementation rolls out over 2026 to 2028 in ascending order of technical complexity and capital commitment. Phase 1 in 2026, at USD 1.2 to 1.5M, deploys vibration, thermography, and oil-condition monitoring on the highest-criticality rotating equipment. Phase 2 in 2027, at USD 2.0 to 2.5M, extends coverage to subsea production equipment and FPU utilities. Phase 3 in 2028, at USD 0.8 to 1.2M, integrates the onshore receiving facility and retires redundant time-based PM scope on monitored assets. Total program CAPEX is USD 4.0 to 5.2M against an expected NPC saving of USD 6.30M over the residual PSC life.

Third, the contract-restructuring elements from A2, namely long-term service agreements and spares pooling, should be embedded within the A3 implementation plan as a logistics enabler rather than pursued as a standalone alternative. This combination captures A2's margin compression alongside A3's risk reduction, which produces a combined posture that outperforms either on its own. The KPI framework recommended for monitoring includes the maintenance cost per BOE, with a target trajectory to USD 0.85 to 0.90/BOE by 2028; the maintenance-to-OPEX ratio, with a target below 18% by 2026 and 15% by 2028; plant availability at or above 97%; major equipment reliability for SECE and OCE assets at or above 99.5%; unplanned downtime attributable to monitored equipment, with a target reduction of 30% from the 2024 baseline by end-2027; and the CBM coverage ratio at or above 80% of SECE and OCE assets by end-2028. The maintenance-to-OPEX ratio is highlighted as a more reliable management signal during production decline, because it is independent of the production denominator.

### 5.2 Theoretical Implications

The study contributes three methodological points to the maintenance-decision literature. First, it demonstrates a tractable approach to integrating an existing engineering LCC model, here a ReliaSoft BlockSim model, with a post-processing NPC overlay and an AHP framework, which makes rigorous decision analysis feasible within the time and confidentiality constraints typical of working-professional research. The approach is replicable in other mature-asset settings where internal reliability models exist but lack a discounted, multi-criteria decision layer. Second, it offers a practical resolution to the weight-provenance critique in AHP applications. The pairwise matrix is constructed independently while its order is calibrated against a published reference, and robustness is then demonstrated through systematic weight perturbation. This combination of calibration with transparency, independence in derivation, and validation through perturbation addresses the most common examiner objection to AHP weight choices. Third, it positions maintenance cost per barrel as a primary decision variable under cost-recovery fiscal structures, which shows that the relative importance of cost against risk changes materially once the fiscal contract is considered. Under a gross-split PSC, where the contractor bears full cost but also captures the full upside of efficiency improvement, the analysis would shift toward cost minimization. Under cost recovery, the shared downside of production loss favors risk reduction above cost compression once the premium sits within the expected

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value of the avoided exposure. This fiscal-structure sensitivity is not captured by existing LCC or AHP frameworks that treat cost as a stable decision criterion.

## 5.3 Limitations

Several limitations qualify the findings. The LCC model is deterministic, and the 30% failure-rate reduction assumed for A3 is derived from the RAM analysis and CBM industry benchmarks rather than from a post-implementation measurement at this specific field. A probabilistic extension that uses Monte Carlo simulation with the failure-rate distributions from the integrated RAM analysis would produce P10, P50, and P90 NPC bands directly comparable to SKK Migas reserves reporting conventions, and that extension is recommended as the natural next step. The production profile and exchange rate are held constant as external constraints, so the combined effect of further decline and unfavorable foreign-exchange movement on the maintenance-to-OPEX ratio is not quantified. The study is a single case under a specific technical configuration and contractual scheme, so the results are analytically transferable to similar deepwater gas assets under cost-recovery PSCs but cannot be statistically generalized to all oil and gas fields.

## 6. Conclusion

This paper set out to explain a 161% rise in maintenance cost per barrel at a deepwater gas field under a cost-recovery PSC and to derive a defensible maintenance strategy for the residual contract life. The cost-driver analysis established that the increase is structural because it is driven by a scheduled 50,000-hour rotating-equipment overhaul and a risk-based subsea integrity campaign against a background of a 26% production decline, rather than by deteriorating maintenance execution. Operational KPIs and reliability metrics confirm that the escalation year was among the strongest on record for equipment performance. The risk-based LCC analysis ranked contract restructuring (A2) as the cost-minimizing option at USD 72.37M NPC and condition-based monitoring investment (A3) second at USD 74.51M. The multi-criteria AHP evaluation, with Safety weighted at 0.557 and Cost at 0.056 and a Consistency Ratio of 0.003, reversed the ranking, because A3 achieved a composite score of 0.438 against A2's 0.192, and the ranking held under all eleven weight-perturbation scenarios. The expected-value analysis showed that the USD 2.14M CBM premium buys approximately USD 5.9M of avoided production-loss exposure over the horizon, a ratio of roughly 2.8 times, which makes A3 cost-recovery-positive once the fiscal mechanism is accounted for. The central methodological finding is that under cost-recovery fiscal structures, the cost-cheapest maintenance option is not the value-best option once risk-cost exposure is properly weighted. This distinction is absent from most existing LCC and AHP maintenance frameworks, and it represents the key contribution of this study to the literature on maintenance decision-making in regulated upstream energy settings.

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## RISK-BASED LIFE CYCLE COST ANALYSIS FOR STRATEGIC MAINTENANCE DECISION-MAKING IN DEEPWATER GAS OPERATIONS

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