

Risk-Based Reliability-Centered Maintenance (RCM3) for Rotating Equipment in a Mature Onshore Steamflood Gathering Station: A Case Study of Duri Field, Indonesia

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Abstract:

Surface facilities in mature steamflood oilfields depend on a comparatively small population of rotating machines whose failure interrupts custody transfer, constrains produced-water treatment, and erodes the economics of aging assets. This paper reports a complete application of Risk-Based Reliability-Centered Maintenance (RCM3) to the rotating equipment of Central Gathering Station Duri Area-1 (CGS-1), a heavy-oil gathering station in the Duri steamflood, Indonesia, where maintenance has historically followed fixed calendar intervals. Equipment criticality analysis over the full rotating-equipment inventory classified 42 units as critical; Pareto screening of OREDA-referenced failure frequencies reduced this population to 30 units for detailed analysis. Weibull fitting of site work-order records for the highest-criticality unit, a high-pressure crude shipping pump, yielded a shape parameter of 1.18 and a characteristic life of 9,910 h, corresponding to 82.2% reliability at the existing 2,500-h preventive interval — well short of the 95% expectation for export-critical machines. Failure-mode Pareto analysis showed five mechanisms accounting for 82.6% of OREDA-referenced failures, dominated by instrumentation faults and external leakage. The RCM3 Information and Decision Worksheets converted 26 failure modes into a program of 13 on-condition, 8 restoration, and 5 failure-finding tasks, reducing assessed risk from predominantly intolerable to tolerable levels. Ten-year costing projects a stable USD 6,552–7,049 annual expenditure for the case-study pump and roughly USD 183,000 per year across all 30 critical units; sensitivity analysis identifies outsourced support services, not labor rates, as the governing cost driver ($\pm 6\%$ versus $\pm 0.5\%$ for $\pm 20\%$ input variation). The study supplies a documented, replicable template for shifting mature onshore facilities from time-based to risk-based maintenance.

Keywords: Reliability-centered maintenance, RCM3, risk-based maintenance, rotating equipment, steamflood, OREDA, maintenance cost.

Author contributions: K. E. Ojango (Conceptualization, methodology, data curation, formal analysis, investigation, visualization, writing original draft); & IGN Wiratmaja Puja (Supervision, methodology, validation, review and editing draft).

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1. INTRODUCTION

Mature oilfields present a maintenance problem that differs in kind, not merely in degree, from that of newer assets. Decades of service leave rotating equipment operating far from its original duty envelope, while the surrounding organization typically retains the calendar-based preventive routines written when the plant was young. The Duri field in Riau, Indonesia - among the largest steamflood enhanced-oil-recovery developments in the world - illustrates the situation. Its central gathering stations process hot, sand-laden, high-water-cut crude through trains of pumps and flotation agitators whose availability directly limits export volume and steam-generation water supply, yet whose maintenance remains predominantly interval-driven.

Reliability-Centered Maintenance (RCM) provides the classical remedy: derive maintenance from functions, functional failures, and failure consequences rather than from elapsed time (Moubray, 1997). Its most recent evolution, RCM3, embeds the analysis in an ISO 31000-aligned risk framework, requiring each failure mode to be characterized by an explicit probability and consequence before a management strategy is chosen (Basson, 2019). Quantitative risk-based maintenance formulations date back at least to Khan and Haddara (2003), and reliability-risk hybrids have been proposed for settings where uncertainty dominates (Selvik & Aven, 2011; da Silva et al., 2023). Nevertheless, documented full-scope RCM3 applications concentrate in refineries, offshore topsides, and individual machine classes such as gas turbines (Darmeim et al., 2023; Nithin et al., 2021) or military vehicle systems (F. Silva et al., 2021). Systematic reviews confirm that onshore gathering infrastructure, and rotating equipment within it, remain underrepresented in risk-based asset-integrity research (Wahono et al., 2025; Ayomoh & Ongwae, 2025).

This paper closes part of that gap. It reports the end-to-end implementation of RCM3 asset hierarchy, equipment criticality analysis (ECA), Pareto screening, reliability analysis, failure-mode prioritization, Information and Decision Worksheets, maintenance-program synthesis, life-cycle costing, and cost sensitivity - across the rotating-equipment population of Central Gathering Station Duri Area-1 (CGS-1). Three questions organize the work: (i) which rotating equipment warrants detailed risk-based analysis; (ii) what reliability behavior and dominant failure mechanisms characterize those units; and (iii) what maintenance program follows from the RCM3 decision logic, and at what cost relative to current practice.

2. RELATED WORK

Three strands of prior work frame the study. The first concerns criticality screening. Pareto-based prioritization has repeatedly shown that a minority of equipment accounts for the majority of failures and cost, whether in offshore components (Nithin et al., 2021) or valve populations assessed with OREDA-derived criteria (Priyanta et al., 2024). Risk-matrix criticality scoring that combines probability and multi-category consequence is

standard in marginal-field applications (Adenuga et al., 2023). The second strand concerns reliability characterization of pumping machinery. Omah & Akaninwor (2024) traced year-by-year reliability decay in multistage export pumps, attributing the decline to recurring seal, bearing, and motor failures - precisely the mechanisms visible in gathering-station work orders.

The third strand is the RCM3 method itself: Basson (2019) formalizes the eight-question sequence, the distinction between evident and hidden failures, and the decision diagram that routes each failure mode to on-condition, restoration, discard, failure-finding, or redesign strategies. What the literature lacks is a case that carries all three strands through a complete onshore steamflood facility and closes the loop with costed, schedule-ready tasks. That is the contribution attempted here.

3. METHODOLOGY

The methodology of this study was designed following the workflow presented in Figure 1 that shows the complete research process from data collection to the development of new maintenance procedures.

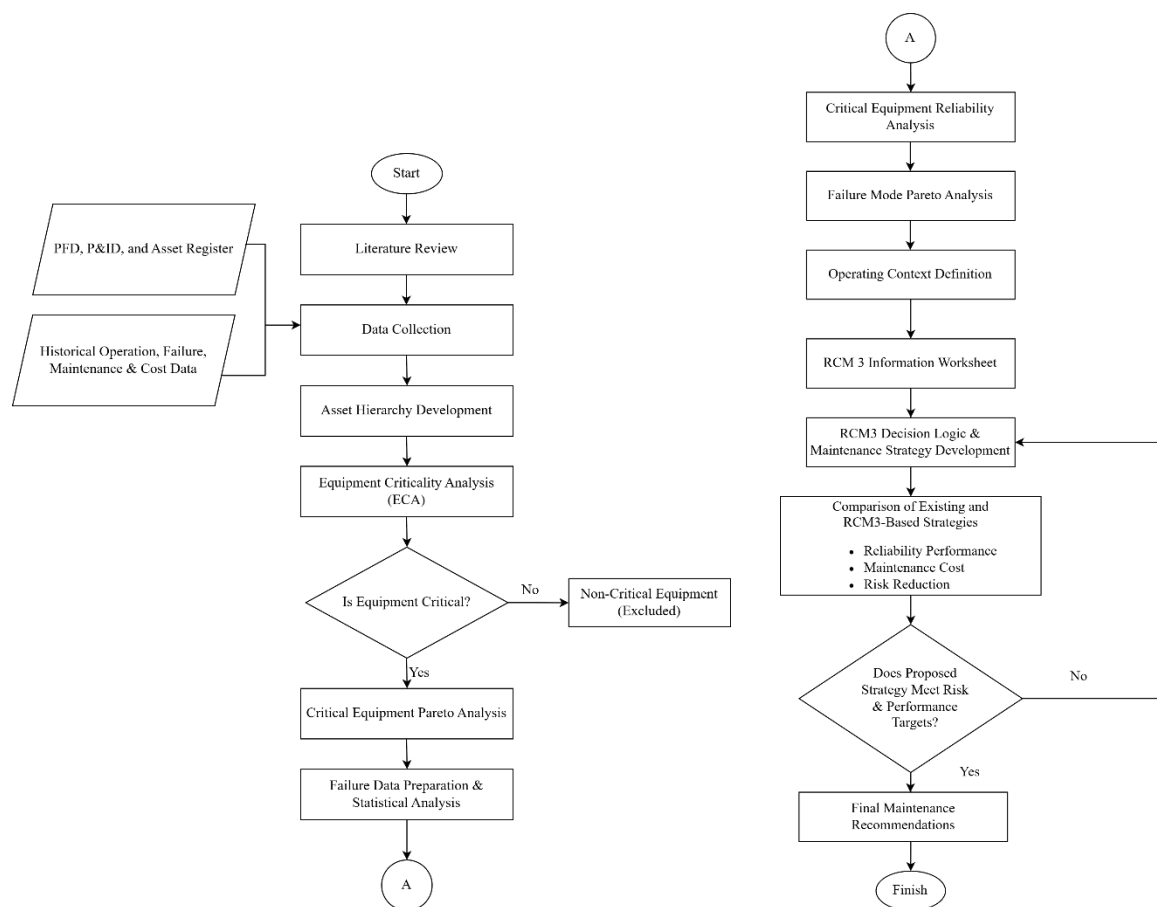


Figure 1 Overall Research Flowchart

The implementation followed nine sequential stages, each feeding the next.

Data Collection

Data were obtained from internal engineering documentation and external reliability databases. Internal data sources included: Engineering documentation including the Process Flow Diagram (PFD) and Piping and Instrumentation Diagram (P&ID), the asset register containing all rotating equipment at CGS-1, and operational and maintenance records including available corrective maintenance histories, and failure logs extracted from the Computerized Maintenance Management System (CMMS). Because historical failure data were not available for a statistically representative reliability analysis, the Offshore Reliability Data (OREDA) Handbook (OREDA, 2015) was used as an external reliability source to provide representative failure rates, failure modes and reliability parameters for the relevant categories of rotating equipment.

Asset hierarchy

All rotating equipment in the station's two plants -the Oil Treatment Plant (OTP) and Water Treatment Plant (WTP) - was organized into an ISO 14224:2016 taxonomy (industry → business category → installation → plant → system → equipment unit, with equipment class and design class), reconciled against process flow diagrams, piping and instrumentation diagrams, and the operator's asset register (ISO 14224, 2016). Pumps were assigned to class PU; the flotation agitators, frequently mislabeled as pumps in legacy registers, were classified as mixers.

Equipment criticality analysis (ECA)

Each unit was scored on a corporate 5×5 matrix as the product of a probability-of-failure rating and the maximum consequence rating across safety, environment, reputation, and business categories, the maximum-consequence convention being deliberately conservative. Units rated High or Medium-High were carried forward.

Pareto screening

Because site work-order records proved too sparse and inconsistently coded for statistically meaningful frequency ranking, OREDA 2015 failure frequencies were assigned by equipment class and service (OREDA, 2015) and accumulated to identify the units contributing the leading share of expected failures.

Reliability analysis

Two complementary treatments were used. Where site data permitted, times to failure extracted from corrective work orders were fitted with a two-parameter Weibull distribution by maximum likelihood; elsewhere, and as a common baseline, the exponential model with OREDA rates supplied reliability estimates at a common 2,500-h evaluation horizon, approximating the plant's recurring 90-day predictive-maintenance cycle under continuous operation.

Failure-mode prioritization, worksheets, and program synthesis

OREDA failure-mode distributions, validated against site work-order narratives, were ranked by Pareto analysis. Functions, performance standards, failed states, failure modes, mechanisms, and effects were then documented in the RCM3 Information Worksheet, with inherent risk scored on a modified 5×5 matrix whose consequence side follows the Level 1 consequence logic of API RP 581 (API, 2016) for safety, environmental, and business categories. The Decision Worksheet applied the RCM3 decision diagram question-by-question to select a management strategy per failure mode and to record the revised risk. Selected tasks were consolidated into a maintenance program with intervals, durations, and resources, costed bottom-up (labor at USD 7 per hour, plus tools, consumables, and support services), projected over ten years, and stress-tested with one-factor-at-a-time $\pm 20\%$ sensitivity scenarios on labor and support-service costs.

4. CASE STUDY

CGS-1 receives hot, high-water-cut heavy crude from the Duri steamflood. The OTP separates and treats the oil through heat exchangers, gas boots, free-water knockout, and wash tanks before custody metering at a LACT unit and export by low-pressure charge pumps feeding five parallel high-pressure shipping (HPS) pumps; the WTP de-oils the separated water through skimming, desanding, chemical conditioning, and mechanical flotation units (MFUs) whose sixteen agitators perform the final polishing before the water returns to steam generation. Two of the five HPS pumps are inactive; the remaining three operate under automatic tank-level sequencing.

The rotating-equipment inventory comprises 98 units (31 OTP, 67 WTP). The unit examined in detail throughout is HPS Pump A (P-0803-A), a horizontal single-stage centrifugal process pump (Goulds Model 3700, size 4×6-16N; 875 US GPM at 810 ft differential head) driven by a 400 HP, 4160 V induction motor - the highest-criticality asset in the station and the last mechanical element of the custody-transfer chain. Work-order histories spanning October 2022 to June 2025 supplied the site failure data.

5. RESULTS

5.1 Criticality and screening

The ECA classified 42 units as critical: the three active HPS pumps rated High (for P-0803-A, probability $4 \times$ consequence $5 = 20$), and 39 further pumps and agitators rated Medium-High as illustrated in Figure 2. Pareto accumulation of OREDA-referenced failure frequencies then concentrated the analysis: in the OTP, the three HPS pumps alone contributed 51.5% of expected failures, and with the low-pressure shipping and recovery-oil pumps the cumulative share crossed the 80% threshold as shown in Figure 3. Across both plants, 30 units - seven in the OTP and twenty-three in the WTP, as shown in Table1, the latter dominated by the sixteen MFU agitators - were selected for full RCM3 treatment.

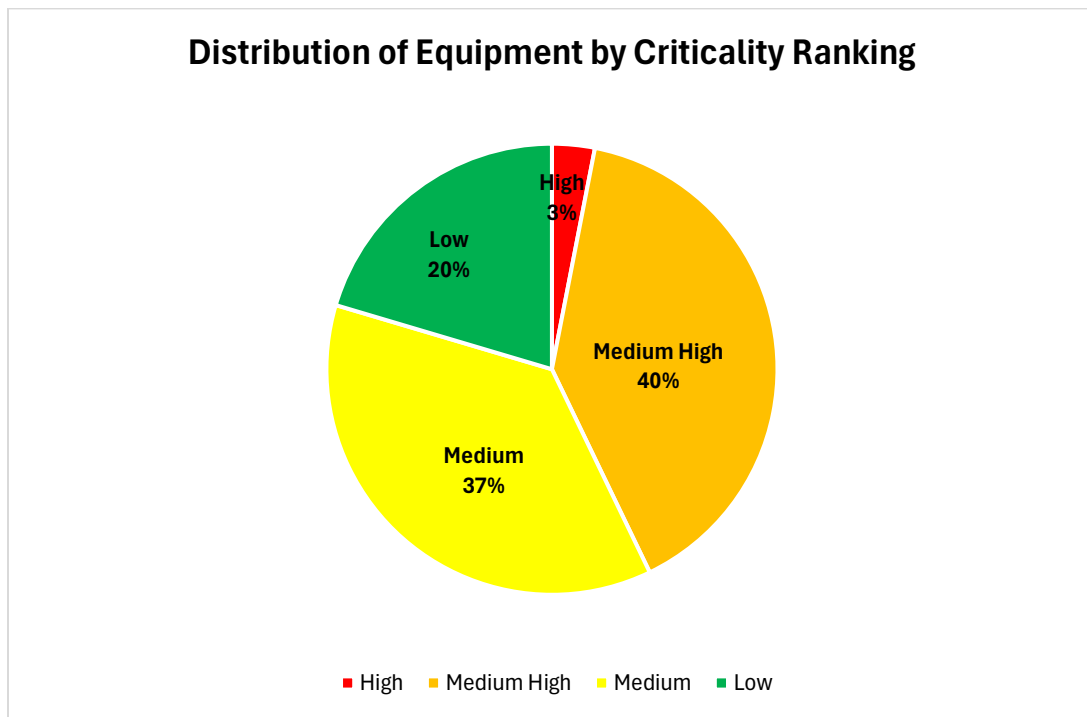


Figure 2 OTP Criticality distribution of the 98-unit population

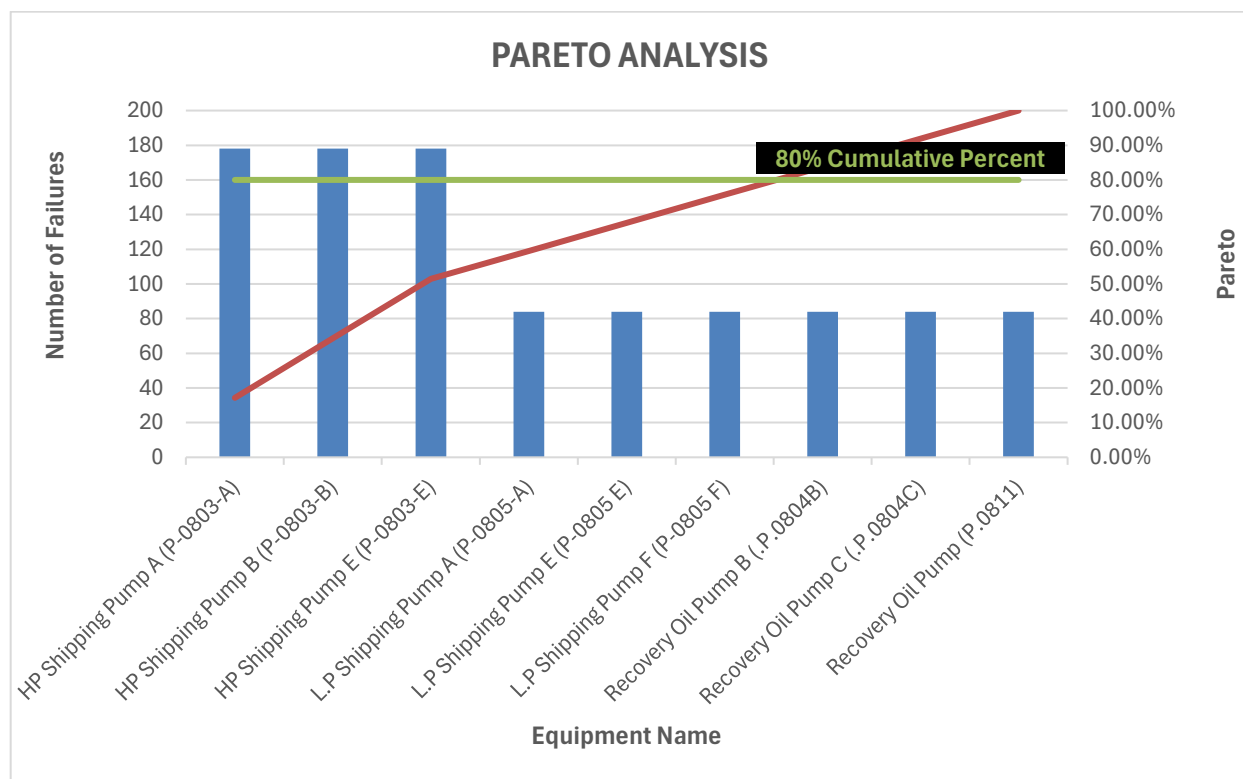


Figure 3 OTP Equipment Pareto chart

Table 1 Critical Equipment Identified at CGS-1 for Further Reliability Analysis

No	Facility	Important Equipment for Further Analysis
1	Oil Treatment Plant (OTP)	HP Shipping Pump A (P-0803-A)
2		HP Shipping Pump B (P-0803-B)
3		HP Shipping Pump E (P-0803-E)
4		L.P Shipping Pump A (P-0805-A)
5		L.P Shipping Pump E (P-0805 E)
6		L.P Shipping Pump F (P-0805 F)
7		Recovery Oil Pump B (.P.0804B)
8	Water Treatment Plant (WTP)	Kill water distribution pump A (P.1212A)
9		Kill water distribution pump B (P.1212B)
10		Kill water distribution pump C (P.1212C)
11		Agitator A, MFU-1 (ZW-1204A)
12		Agitator B, MFU-1 (ZW-1204A)
13		Agitator C, MFU-1 (ZW-1204A)
14		Agitator D, MFU-1 (ZW-1204A)
15		Agitator A, MFU-3 (ZW-1204C)
16		Agitator B, MFU-3 (ZW-1204C)
17		Agitator C, MFU-3 (ZW-1204C)
18		Agitator D, MFU-3 (ZW-1204C)
19		Agitator A, MFU-4 (ZW-1204D)
20		Agitator B, MFU-4 (ZW-1204D)
21		Agitator C, MFU-4 (ZW-1204D)
22		Agitator D, MFU-4 (ZW-1204D)
23		Agitator A, MFU-5 (ZW-1204E)
24		Agitator B, MFU-5 (ZW-1204E)
25		Agitator C, MFU-5 (ZW-1204E)
26		Agitator D, MFU-5 (ZW-1204E)
27		Waste Water MFU feed pump A (P.1211A)
28		Waste Water MFU feed pump B (P.1211B)
29		Wastewater emergency pump A (P.1215A) [Standby]
30		Wastewater emergency pump B (P.1215B)

5.2 Reliability

Nine independent failure events were identified for HPS Pump A after de-duplication and removal of non-failure work orders. Maximum-likelihood Weibull fitting as illustrated in Figure 4 gave a shape parameter $\beta = 1.1835$ and characteristic life $\alpha = 9,909.6$ h (Anderson–Darling 1.643), implying a mean time to failure of 9,356 h and a mildly increasing hazard consistent with progressive seal, bearing, and alignment degradation. At the 2,500-h evaluation horizon, the fitted reliability is 82.2% - materially below the 95% expectation applied to export-critical machinery. Across the thirty units, historically derived reliabilities ranged from 44% to 88%, with none reaching the 95% benchmark; among the shipping pumps, Pump B fitted highest (84.4%) and Pump E lowest (71.2%), the latter reflecting a short, late-onset failure record consistent with standby duty.

Because sample sizes of this order cannot support fleet-wide parametric inference, OREDA-based exponential estimates were adopted as the common reliability baseline for maintenance planning, with the site fits retained as corroborating evidence. Two alternative methodologies were applied to assess the reliability of 19 key equipment items, including 3 HP Shipping (HPS) Pumps and 16 MFU agitators. The historical failure data were analyzed using a Weibull distribution as in Equation (1). The reliability based on OREDA data was evaluated using an exponential distribution model as in Equation (2).

$$R(t) = e^{-\left(\frac{t}{\alpha}\right)^\beta} \quad (1)$$

where $R(t)$ is the reliability at time t , β = shape parameter (failure pattern) and α = scale parameter (characteristic life). λ is the constant failure rate (failures per hour)

$$R(t) = e^{-\lambda t} \quad (2)$$

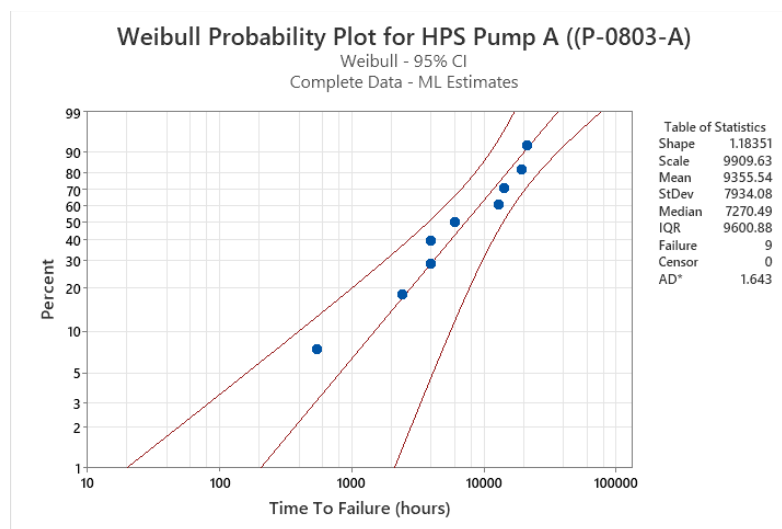


Figure 4 Weibull probability plot, HPS Pump A

The reliability of all 30 critical equipment units was evaluated using the same methodology. The results are summarized and visualized in Figure 5.

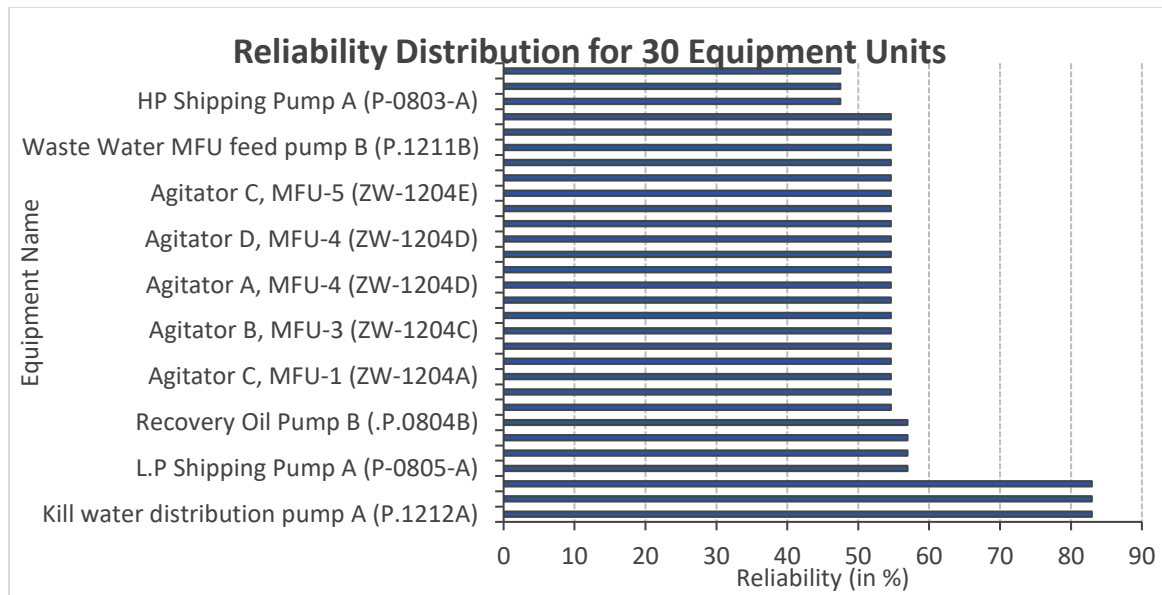


Figure 5 Exponential Reliability Curves for 30 Critical Rotating Equipment Units Based on OREDA Data

5.3 Dominant failure modes

For the shipping-pump class, 178 OREDA-referenced failure events distributed over fifteen failure modes were analyzed as illustrated in Figure 6. Five modes account for 82.6% of the total: abnormal instrument reading (34.3%), external leakage of process medium (19.7%), external leakage of utility medium (15.7%), an unspecified “other” category (6.7%), and plugged/choked flow paths (6.2%). The ordering matches the site work-order narratives, in which vibration-switch failures, transmitter faults, and mechanical-seal leaks recur throughout the record - a convergence that supports transferring OREDA mode structure to this facility.

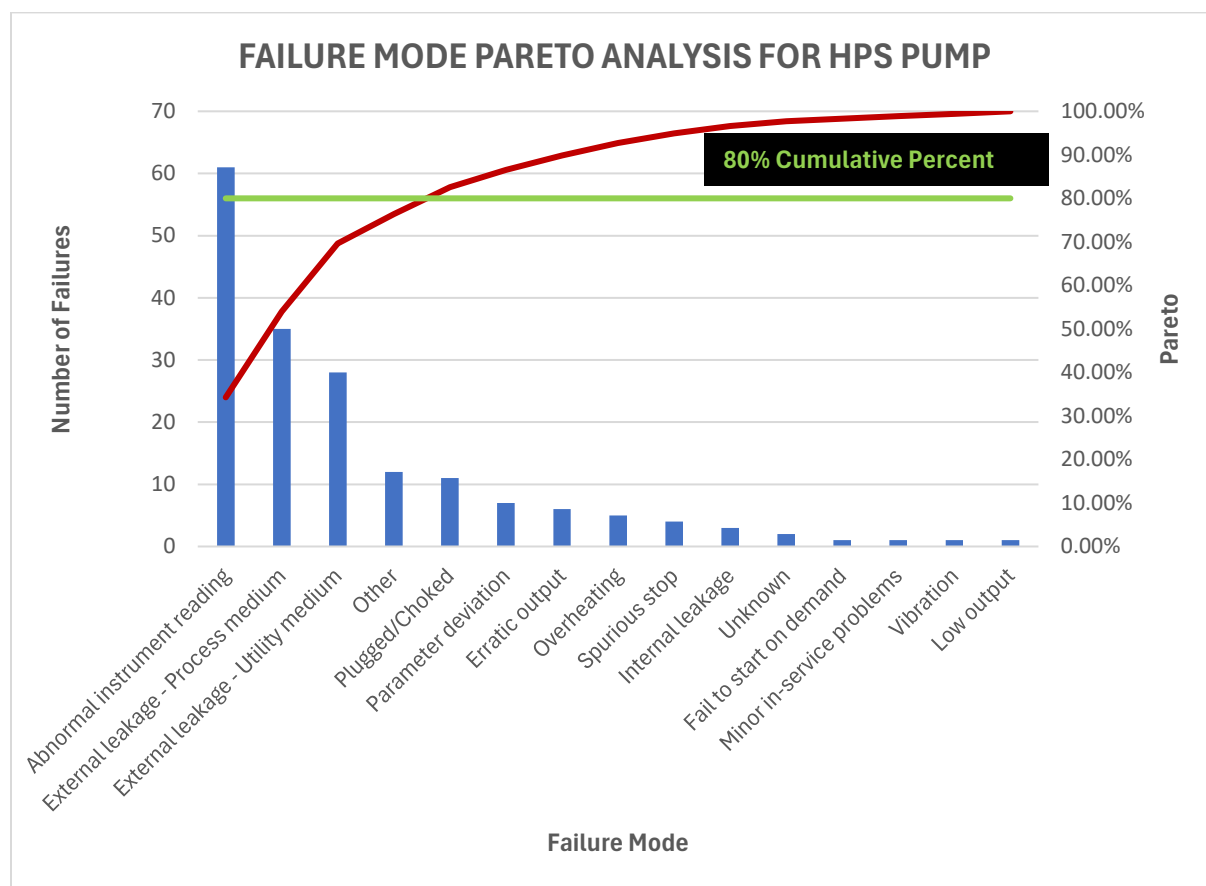


Figure 6 Failure-mode Pareto chart, HPS Pump A

5.4 Worksheets and maintenance program

The Information Worksheet for HPS Pump A defined four functions - pressure boosting of metered crude at 875 US GPM/810 ft, mechanically sound continuous parallel operation, control through the DCS and motor control center, and protective shutdown on abnormal conditions - decomposed into fifteen failed states and 26 failure modes. Inherent risk concentrated in the significant-to-intolerable region of the matrix, with external process-medium leakage scoring highest (21) owing to its combined safety, environmental, and production consequences.

Applying the decision diagram produced a program of 26 tasks: thirteen scheduled on-condition tasks (50%), eight scheduled restorations (31%), and five failure-finding tasks (19%). Continuous DCS monitoring of vibration, temperature, pressure, and flow — supported by daily to monthly manual verification - addresses the progressive mechanisms; annual restoration and calibration address predictable instrument and control-circuit deterioration; and dedicated annual failure-finding tests address the hidden failures of interlocks, trips, and alarms, a category entirely absent from the incumbent program. Revised risk fell to tolerable levels (score 10) for all but one mode; daily leak surveillance holds external process leakage at a revised score of 14 pending seal-

restoration cycles. As a representative example, Table 2 summarizes the proposed RCM3-based maintenance program for HPS Pump A (P-0803-A).

Table 2 Summary of the Proposed RCM3 Maintenance Program for HPS Pump A by Task Type

Maintenance Strategy	Representative Activities	Frequency
Scheduled On-Condition	Continuous monitoring of pressure, flow, vibration, temperature, cavitation, and leakage	Continuous / Daily / Monthly
Scheduled Restoration	Restoration of control loops, instrumentation, motor starters, protective devices, and trip circuits	Annual / Biennial / Four-yearly
Scheduled Failure Finding	Functional testing of interlocks, permissives, protective devices, alarms, and trip signal circuits	Annual

5.5 Cost and sensitivity

Bottom-up costing yields a stable annual expenditure of USD 6,552–7,049 for HPS Pump A, the mild four-yearly peaks reflecting long-interval restoration and certification work; the ten-year total is USD 67,201. On-condition tasks absorb 44.6% of the annual budget, restorations 33.2%, and failure-finding 22.2%, as illustrated in Figure 7 and Table 3. Extended across all thirty critical units, the program projects USD 182,300–184,500 per year - approximately USD 1.83 million over ten years - with the WTP share (~USD 131,700/yr.) dominated by the sixteen agitators as shown in Figure 8.

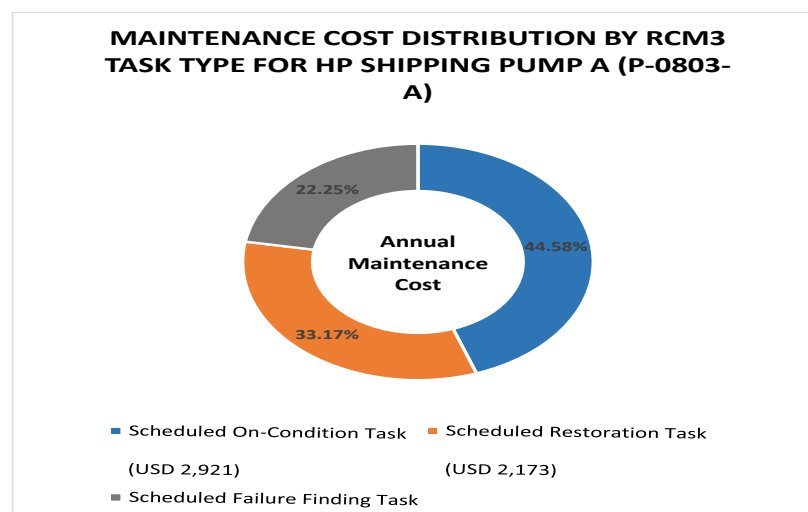


Figure 7 Annual Maintenance Cost Distribution by RCM3 Task Type for HPS Pump A

Table 3 Ten-Year Maintenance Plan and Cost Projection for HPS Pump A

TASK TYPE	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Scheduled On-Condition Task	\$2,921	\$2,921	\$2,921	\$3,189	\$2,921	\$2,921	\$2,921	\$3,189	\$2,921	\$2,921
Scheduled Restoration Task	\$2,173	\$2,402	\$2,173	\$2,402	\$2,173	\$2,402	\$2,173	\$2,402	\$2,173	\$2,402
Scheduled Failure Finding Task	\$1,458	\$1,458	\$1,458	\$1,458	\$1,458	\$1,458	\$1,458	\$1,458	\$1,458	\$1,458
Grand Total	\$6,552	\$6,781	\$6,552	\$7,049	\$6,552	\$6,781	\$6,552	\$7,049	\$6,552	\$6,781

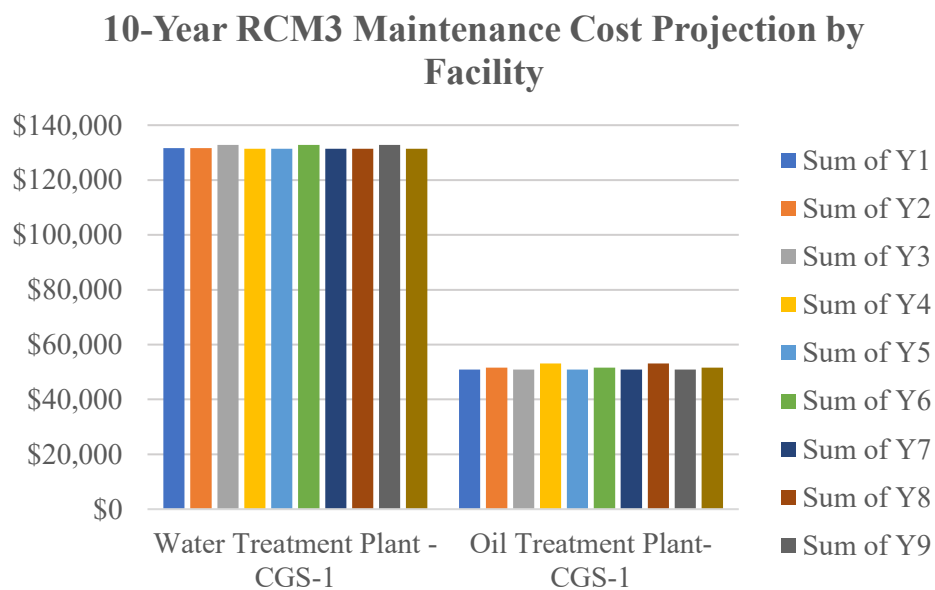


Figure 8 Ten-year cost projection by facility

One-factor sensitivity shows the estimate to be robust: $\pm 20\%$ variation in outsourced support services (calibration, NDT, lifting, specialist contractors) shifts the ten-year cost by $\pm 6.0\%$ ($\pm \text{USD } 4,040$) as illustrated in Table 4 and Figure 9, whereas the same variation applied to the direct per-task labor element shifts it by only $\pm 0.5\%$ ($\pm \text{USD } 364$); combined best/worst cases span $\pm 6.6\%$. Support-service exposure, not wage rates, is therefore the appropriate focus of commercial risk management. It should be noted that the labor element varied here is the per-task labor administration cost; the labor-hour content

embedded in monitoring-execution overheads was held constant, so the labor figure represents a lower bound.

Table 4 Sensitivity Analysis Results for HPS Pump A

Scenario	Labor Cost Adjustment	Support Service Cost Adjustment	Annual Cost (USD)	10-Year Cost (USD)	Change from Base (USD)	Change from Base (%)
Base Case	0%	0%	\$6,552	\$67,201	0	0%
Labor -20%	-20%	0%	\$6,516	\$66,837	-364	-0.5%
Labor +20%	+20%	0%	\$6,588	\$67,565	364	0.5%
Support Services -20%	0%	-20%	\$6,148	\$63,161	-4040	-6%
Support Services +20%	0%	+20%	\$6,956	\$71,241	4040	6%
Best Case	-20%	20%	\$6,112	\$62,797	-4404	-6.6%
Worst Case	+20%	+20%	\$6,992	\$71,605	4404	6.6%

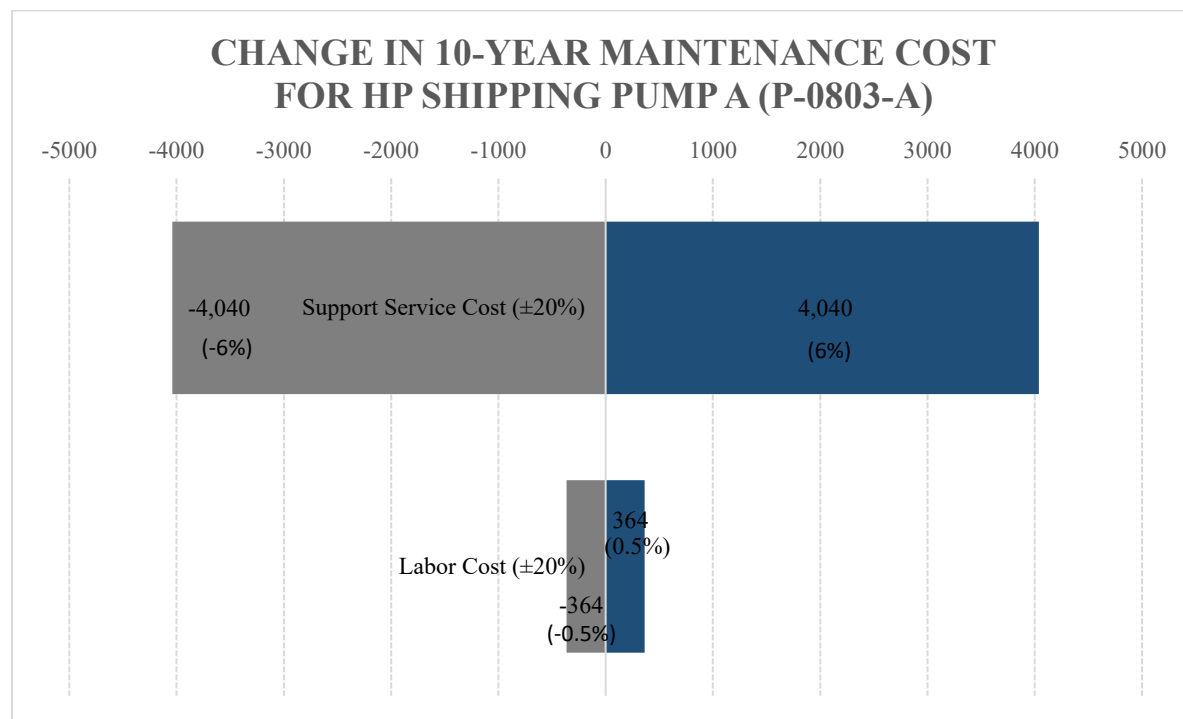


Figure 9 Tornado Chart Showing the Sensitivity of the 10-Year Maintenance Cost for HPS Pump A

6. DISCUSSION AND PRACTICAL IMPLICATIONS

Three findings carry practical weight beyond the case. First, instrumentation - not hydraulics dominates the failure spectrum of the export pumps. More than a third of referenced failures are abnormal instrument readings, and several further modes (spurious stop, erratic output, parameter deviation) are also instrument-borne. A maintenance program conceived around the pump as a mechanical object would miss the largest single source of unavailability; the RCM3 functional decomposition surfaces it naturally through the control and protection functions. Second, the incumbent program contained no failure-finding tasks at all, leaving protective interlocks and trip circuits as unverified hidden functions in a facility where a stuck protection can escalate a routine fault into equipment damage or a loss of containment. The five failure-finding tasks introduced here are arguably the highest-leverage change in the entire program. Third, the cost profile of a risk-based program is flat and forecastable - a property valuable in itself for mature-asset budgeting, where reactive maintenance ordinarily produces erratic expenditure.

For operators of comparable facilities, the transferable elements are the screening arithmetic (criticality $\times$ OREDA-referenced frequency), the reconciliation of legacy registers to ISO 14224 before any analysis, and the use of OREDA mode distributions as scaffolding where CMMS coding is weak - each of which required no proprietary tooling.

7. LIMITATIONS

The study is a planning-level analysis: field implementation and post-implementation validation remain future work. Site failure samples are small (nine events for the case-study pump), so the Weibull parameters carry wide confidence bands and were deliberately subordinated to OREDA baselines for decision-making. OREDA frequencies, while standardized, originate largely from offshore populations and may understate sand-erosion mechanisms specific to steamflood service; the agitators, for which OREDA publishes no dedicated class, required a surrogate. Costing excludes production-loss valuation, discounting, and escalation, and the sensitivity analysis varies only two cost elements one at a time.

8. CONCLUSION AND FUTURE WORK

A complete RCM3 cycle-equipment hierarchy, criticality assessment, screening, reliability analysis, failure-mode prioritization, RCM3 Information and Decision Worksheets, maintenance program synthesis, cost estimation, and sensitivity analysis was implemented for the rotating equipment of a mature onshore steamflood gathering station. Of the 98 rotating equipment units evaluated, 42 were classified as critical, and 30 were selected for detailed analysis. For the highest-criticality export pump, 26 failure modes were translated into a balanced maintenance program comprising scheduled on-condition, scheduled restoration, and failure-finding tasks, reducing the assessed operational risk to tolerable levels while maintaining a stable annual maintenance cost of USD 6,552–7,049. Sensitivity analysis further identified support service costs as the dominant source of lifecycle cost uncertainty. These findings demonstrate that full-scope RCM3 is both technically feasible and economically justifiable for data-limited onshore oil and gas facilities, providing a structured framework for improving maintenance planning and asset integrity management.

Future work should extend the proposed framework by incorporating maintenance interval optimization, real-time condition monitoring data, and predictive analytics to further improve maintenance effectiveness. Validation of the proposed RCM3 program through long-term field implementation and comparison with conventional maintenance practices would also provide stronger evidence of its operational and economic benefits across a broader range of upstream oil and gas facilities.

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