

Reliability-Centred Maintenance of Centrifugal Pumps in a Refinery Power Plant: Reliability Assessment, Criticality-based Task Selection and Workload-based Staffing Optimisation

Authors Details

Ngangha Victor Oyama^{1*}

Department of Mechanical Engineering, Faculty of Engineering, University of Port
Harcourt, Nigeria.

E. G. Saturday, Ph. D²

Department of Mechanical Engineering, Faculty of Engineering, University of Port
Harcourt, Nigeria.

Iluno Nzubechukwu Ugochukwu³

Department of Mechanical Engineering, Faculty of Engineering University of Ibadan.

Vincent B. Ikuenayo⁴

Department of Mechanical Engineering, Faculty of Engineering and Technology,
University of Ilorin.

Corresponding Author: Ngangha Victor Oyama

ABSTRACT: Centrifugal pumps in refinery power plants are critical, continuously operated assets, yet maintenance decisions are often made without quantitative reliability evidence. This study applies Reliability-Centred Maintenance (RCM) to five pumps (70CP-1101 to 70CP-1105) in the power plant of the Port Harcourt Refining Company using 2024 failure and repair records (44 failures, 8,256 h available time per pump). Reliability indices were estimated with an exponential model at stated mission times, with 90% confidence intervals. Pump-level MTBF ranged from 714 h (70CP-1103) to 1,352 h (70CP-1104); availability ranged from 95.19% to 98.25%; one-week reliability ranged

from 79.0% to 88.3% and one-month reliability from 36.5% to 58.7%. The between-pump differences in failure rate were not statistically significant ($\chi^2 = 1.87$, $p = 0.76$), so pump ranking is treated as prioritisation rather than proof. FMEA, logic tree analysis and a weighted criticality index identified seven of eight failure causes as high criticality (Group A) for 70CP-1103, leading to condition-directed tasks at weekly and monthly intervals. A workload-based integer programming model was then formulated to size the maintenance workforce. The baseline solution requires three engineers and four technicians (N46.2 million per year) against the current roster costing N189.0 million per year; scenario analysis shows that savings remain at 45–76% for workloads up to six times the baseline. The results indicate that the current roster is not driven by pump maintenance workload alone and should be reviewed with other duties considered.

Keywords: *Reliability-Centred Maintenance; Centrifugal Pumps; Logic Tree Analysis; FMECA; Availability; Integer Programming; Refinery*

1. Introduction

Centrifugal pumps are among the most widely used machines in process industries because of their high flow capacity, simple operation and ability to handle a range of fluids (Singh & Suhane, 2015). In refineries and their power plants, they circulate boiler feed water, cooling water, condensate and process streams, and because they link successive process units a single pump failure can reduce efficiency or stop production (Muhammad et al., 2010). Typical failure sites are seals, bearings, shafts, wear rings and impellers, driven by wear, corrosion, erosion, misalignment and inadequate lubrication (Zhu et al., 2019).

Maintenance can account for 15–40% of production cost (Ikuobase et al., 2016). Fixed-interval maintenance is costly if too frequent and allows excess failures if too infrequent (Navneet & Bhangu, 2018). RCM addresses this by selecting, for each failure mode, the most appropriate strategy (condition-directed, time-directed, failure-finding or run-to-failure) according to its consequences (Afefy, 2010; Geisbush & Ariaratnam, 2023). Logic tree analysis (LTA) and failure mode, effects and criticality analysis (FMECA) are its core decision tools (Ogra et al., 2021).

RCM has been applied to pumps and related equipment in several sectors, but published studies seldom connect three elements in one traceable chain: (i) reliability and

maintainability indices evaluated at explicit mission times with an indication of statistical uncertainty; (ii) criticality-graded task selection; and (iii) an optimisation of the maintenance workforce that is driven by the resulting task workload. The present study builds on the RCM framework of Ogra et al. (2021) and addresses these three elements for centrifugal pumps in a Nigerian refinery power plant. The objectives are to (1) evaluate MTBF, MTTR, failure and repair rates, availability, reliability and maintainability of the pumps; (2) conduct FMEA, LTA and criticality analysis; (3) derive criticality-based maintenance tasks and intervals; and (4) formulate and test a workload-based integer programming model for maintenance staffing.

2. Related work

Table 1 summarises representative studies. Reliability studies of refinery and process pumps have mostly relied on Weibull or exponential models fitted to failure records (Anwar et al., 2002; Muhammad et al., 2010; Ahmed et al., 2016; Zhu et al., 2019), with maintainability addressed by Sijibomi et al. (2020). RCM applications to pumps include Azadeh et al. (2009), who used an FMEA approach for centrifugal pumps, Ega and Sugiyono (2022) for fuel-distribution pumps, and Adu and Ebieto (2023) for a centrifugal pump in a natural gas processing plant. Cost-oriented RCM studies report labour or maintenance cost reductions in steam, brewery, offshore and turbine systems (Afefy, 2010; Ogra et al., 2021; Anu et al., 2021; Darmein et al., 2023), while Viveros et al. (2024) treat preventive maintenance grouping and scheduling as an optimisation problem. Masoomeh et al. (2020) show that successful RCM implementation in the oil and gas sector depends on critical success factors that must be addressed before roll-out.

Table 1. Representative related studies and the gap addressed here

Study	Equipment / setting	Focus
Anwar et al. (2002); Muhammad et al. (2010)	Refinery and petrochemical pumps	Weibull-based time-between-failure and reliability assessment
Azadeh et al. (2009)	Centrifugal pumps, onshore industry	FMEA approach to improve the RCM procedure
Zhu et al. (2019)	Centrifugal pump	Reliability from small-sample data (Weibull with Monte Carlo)
Ega & Sugiyono (2022)	Fuel-distribution pumps	RCM with exponential reliability and root cause analysis

Study	Equipment / setting	Focus
Adu & Ebieto (2023)	Centrifugal pump, gas processing plant	RCM strategy for a pump
Ogra et al. (2021)	Brewery heat exchanger and feed water pump	RCM, FMECA, exponential reliability and labour cost reduction
Afey (2010); Anu et al. (2021)	Steam plant; offshore oil and gas	RCM with cost optimisation
Viveros et al. (2024)	Industrial systems	Optimal grouping and scheduling of preventive tasks
This study	Five refinery power-plant pumps	Mission-time reliability with confidence intervals, criticality-based tasks, workload-driven integer staffing model with sensitivity analysis

Note: only the focus reported in each cited study is summarised.

3. Materials and methods

3.1 System and data

The study covers five centrifugal pumps, 70CP-1101 to 70CP-1105, serving the feed-heater circuit of the Port Harcourt Refining Company (PHRC) power plant. The pump type included Centrifugal pump; circulation water pump, handled fluid (Water), Operating temperature (277°C), Suction pressure (61.42 KG/68.78KG), discharge pressure (70.23 KG/77.59 KG MAX), Motor RPM (1450), 3 phase motor and 750KW. Failure and repair records for 2024 were taken from the plant's power-plant equipment defect records and troubleshooting logbooks (PHRC, 2024): number of failures n , operating time T_{op} , downtime T_{dn} and total available time. Available time is $344 \text{ days} \times 24 \text{ h} = 8,256 \text{ h}$ per pump, as recorded by the plant. Each failure is assumed to be followed by one repair (so the number of repairs equals n). Data are given in Table 2. Staffing and salary data were obtained from the PHRC directory (2024).

Table 2. Failure data of the pumps, 2024 (source: PHRC, 2024)

Pump	Failures, n	Operating time, T_{op} (h)	Downtime, T_{dn} (h)	Available time (h)
70CP-1101	10	7,933.84	322.16	8,256
70CP-1102	8	8,047.06	208.94	8,256
70CP-1103	11	7,858.48	397.52	8,256
70CP-1104	6	8,111.27	144.73	8,256

Pump	Failures, n	Operating time, T_{op} (h)	Downtime, T_{dn} (h)	Available time (h)
70CP-1105	9	8,002.50	253.50	8,256
Total	44	39,953.15	1,326.85	41,280

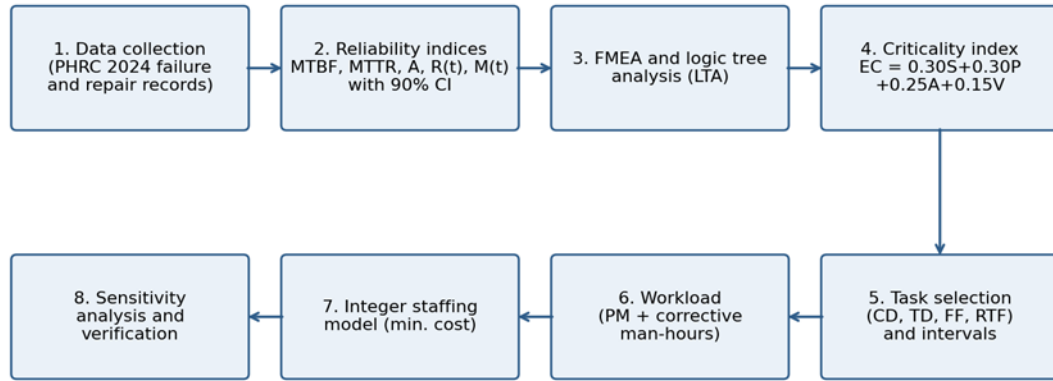


Fig. 1. Methodological workflow.

3.2 Reliability, maintainability and availability

A constant failure rate (exponential model) was adopted, as is common for pump-level records without event-time data (Ega & Sugiyono, 2022; Ogra et al., 2021). For pump i :

$$MTBF_i = T_{op,i} / n_i, \quad MTTR_i = T_{dn,i} / n_i \quad (1)$$

$$\lambda_i = 1 / MTBF_i, \quad \mu_i = 1 / MTTR_i \quad (2)$$

$$A_i = MTBF_i / (MTBF_i + MTTR_i) \quad (3)$$

$$R_i(t) = \exp(-\lambda_i t), \quad M_i(t) = 1 - \exp(-\mu_i t) \quad (4)$$

where t is a stated mission time for reliability and a stated repair-time target for maintainability. Reliability was evaluated for one week ($t = 168$ h) and one month ($t = 720$ h), matching the weekly and monthly maintenance intervals considered; maintainability was evaluated for repair targets of 24 h and 48 h. The time at which reliability falls to a target R^* (here 90%) is

$$t_{R,i} = -\ln(R^*) / \lambda_i \quad (5)$$

For time-terminated observation, two-sided $100(1-\alpha)\%$ confidence limits for MTBF are

$$[2T_{op} / \chi^2_{1-\alpha/2, 2n+2}, 2T_{op} / \chi^2_{\alpha/2, 2n}] \quad (6)$$

with $\alpha = 0.10$. Differences in failure rate between pumps were tested with a chi-square homogeneity test, where expected failures are $E_i = N T_{op,i} / \Sigma T_{op}$ ($N = 44$):

$$\chi^2 = \Sigma (n_i - E_i)^2 / E_i, \quad df = 4 \quad (7)$$

3.3 FMEA, logic tree analysis and criticality

The RCM sequence of system selection, boundary definition, functional description, functional failures, FMEA, logic tree and task selection followed Ogra et al. (2021) and Afefy (2010). Pump 70CP-1103, which recorded the most failures and the lowest MTBF, was selected for detailed analysis. Root causes were traced from failure mode to mechanism to cause. The logic tree asks, for each failure mode: (Q1) is the failure evident to operators during normal duty; (Q2) does it pose a safety or environmental hazard; (Q3) does it cause production loss or outage; and (Q4) does it cause significant economic loss. Modes answering “yes” to Q2–Q4 are classed as critical and carried into the criticality analysis. The criticality index is

$$EC = 0.30 S + 0.30 P + 0.25 A + 0.15 V \quad (8)$$

where S, P, A and V are the safety, production, standby-availability and equipment-value ratings in Table 3 (Ogra et al., 2021). Ratings were assigned from interviews with the plant’s operation and maintenance officers (2 personnel from each team). Groups are A (2.5–3.0, high), B (2.0 to <2.5, medium-high), C (1.5 to <2.0, medium-low) and D (<1.5, low). Task types are condition-directed (CD, inspection or monitoring that detects degradation), time-directed (TD, scheduled restoration or replacement), failure-finding (FF) and run-to-failure (RTF).

Table 3. Criticality rating scales and weights

Criterion	Weight	Rating (3 / 2 / 1)
Impact on safety (S)	30%	3 critical / 2 essential / 1 regular
Impact on production (P)	30%	3 critically important / 2 significant / 1 typical
Standby availability (A)	25%	3 no standby / 2 moderately available standby / 1 fully available standby
Equipment value (V)	15%	3 high value / 2 normal / 1 low value

3.4 Workload-based staffing model

The staffing model sizes the engineering (E) and technician (T) workforce in each discipline d (mechanical M, electrical E, control C) so that the annual maintenance workload can be carried at minimum payroll cost. The annual workload has a preventive and a corrective part:

$$D_{PM} = N_p \sum_j f_j \tau_j c_j, \quad D_{CM} = c_r \sum_i T_{dn,i}, \quad D = D_{PM} + D_{CM} \quad (9)$$

where $N_p = 5$ pumps, f_j , τ_j and c_j are the annual frequency, duration and crew size of preventive task group j (Table 7), and $c_r = 2$ is the assumed crew per repair. The workload of discipline d is $D_d = s_d D$, where s_d is the share of preventive tasks assigned to that discipline in Table 7. The integer program is

$$\min Z = \sum_d (c_E e_d + c_T t_d) \quad (10)$$

$$\text{s.t. } h(e_d + t_d) \geq \varphi D_d, \quad e_d \geq 1, \quad t_d \geq 1, \quad e_d, t_d \in \mathbb{Z} \quad \text{for } d \in \{M, E, C\} \quad (11)$$

where e_d and t_d are the numbers of engineers and technicians, $c_E = \text{₦}750,000$ and $c_T = \text{₦}400,000$ are monthly salaries (PHRC, 2024), $h = 1,800$ productive hours per person-year is an assumed capacity, the lower bounds ensure every discipline retains at least one engineer and one technician, and $\varphi \geq 1$ is a workload multiplier representing an allowance for duties beyond the scheduled pump tasks. The problem was solved by branch and bound and verified by exhaustive enumeration of all integer solutions with $e_d \leq 12$ and $t_d \leq 24$. Because h , c_r and the discipline shares are assumptions, results are reported across $\varphi = 1-6$ and $h = 1,500-2,000$ h.

4. Results

4.1 Reliability indices

Table 4 and Fig. 2 give the reliability parameters. MTBF is highest for 70CP-1104 (1,351.9 h) and lowest for 70CP-1103 (714.4 h); MTTR is lowest for 70CP-1104 (24.12 h) and highest for 70CP-1103 (36.14 h). Availability ranges from 95.19% to 98.25%. The 90% confidence intervals on MTBF are wide and overlap across all pumps.

Table 4. Reliability parameters (MTBF with 90% confidence interval)

Pump	n	MTBF (h) [90% CI]	MTTR (h)	λ (h ⁻¹)	μ (h ⁻¹)	A (%)
70CP-1101	10	793.4 [468–1,462]	32.22	0.001260	0.03104	96.10
70CP-1102	8	1,005.9 [557–2,021]	26.12	0.000994	0.03829	97.47
70CP-1103	11	714.4 [432–1,274]	36.14	0.001400	0.02767	95.19
70CP-1104	6	1,351.9 [685–3,104]	24.12	0.000740	0.04146	98.25
70CP-1105	9	889.2 [510–1,704]	28.17	0.001125	0.03550	96.93

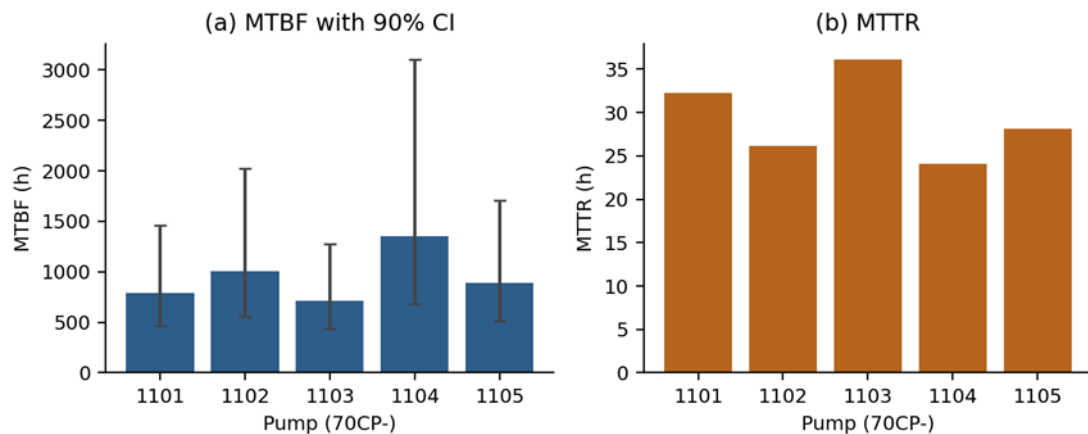
**Fig. 2.** (a) MTBF with 90% confidence intervals and (b) MTTR of the five pumps.

Table 5 and Fig. 3 give reliability and maintainability at the stated times. Over one week the pumps have 79.0–88.3% probability of failure-free operation, falling to 36.5–58.7% over one month. Only 70CP-1104 and 70CP-1102 stay above 90% for longer than about 100 h (t_{90} = 142 h and 106 h); for 70CP-1103 t_{90} is 75 h. The probability of completing a repair within 24 h is 48.5–63.0%, and within 48 h 73.5–86.3%.

Table 5. Reliability and maintainability at stated times

Pump	R (168 h) (%)	R (720 h) (%)	M (24 h) (%)	M (48 h) (%)	t_{90} (h)
70CP-1101	80.9	40.4	52.5	77.5	84
70CP-1102	84.6	48.9	60.1	84.1	106
70CP-1103	79.0	36.5	48.5	73.5	75
70CP-1104	88.3	58.7	63.0	86.3	142
70CP-1105	82.8	44.5	57.3	81.8	94

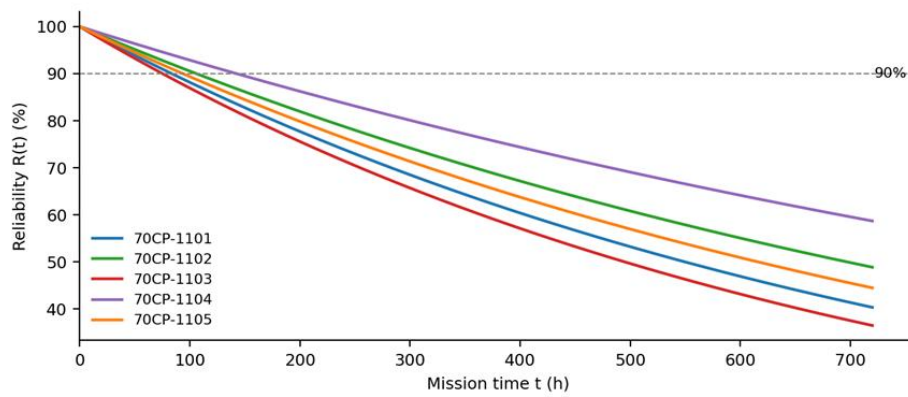


Fig. 3. Reliability functions $R(t)$ of the five pumps.

The homogeneity test does not reject equal failure rates across the five pumps ($\chi^2 = 1.87$, $df = 4$, $p = 0.76$), and the exact binomial comparison of 70CP-1103 (11 failures) with 70CP-1104 (6 failures) is also not significant ($p = 0.23$). The ranking in Tables 4 and 5 is therefore used to prioritise pumps for analysis, not as evidence that the pumps differ intrinsically.

4.2 FMEA, logic tree analysis and root causes

Table 6 gives the FMEA and LTA outcome for the main components of the pumps. The impeller, thrust bearing, coupling and wear ring were classed as critical because their failure leads to a feed-heater trip, shutdown or loss of plant efficiency; shaft deformation and casing leakage were classed as non-critical. Root-cause tracing for 70CP-1103 (Table 7) linked the four dominant failure modes (low discharge pressure, high bearing temperature, causing overheating and low flow) to eight causes.

Table 6. FMEA and logic tree analysis of the pump components

Item	Failure mode	Local effect	System effect	Plant effect	LTA critical
Impeller	Worn impeller	Inefficient pumping, increased dynamic stress, reduced suction force	Feed-heater trip	Plant excursion, power loss, reduced efficiency	Yes
Bearing	Faulty thrust bearing	Excessive vibration, possible motor overload	Feed-heater shutdown	Minimal effect, reduced plant efficiency	Yes
Shaft	Shaft deformation	Inefficient pumping, dynamic stress, increased radial motion, eventual coupling failure	Low heater efficiency	Minor effect, plant excursion	No

Item	Failure mode	Local effect	System effect	Plant effect	LTA critical
Casing	Leaking casing	Loss of pumping performance, corrosion of pump parts	Low heater efficiency	Plant excursion, reduced efficiency	No
Coupling	Faulty shaft coupling	Reduced performance, vibration and noise, possible seal damage, eventual shutdown	Low efficiency, shutdown or trip	Plant excursion, reduced efficiency	Yes
Wear ring	Faulty impeller wear ring	Internal leakage, internal corrosion, large capacity loss	Low efficiency or trip	Power loss, reduced efficiency	Yes

Source: FMEA worksheets prepared by the authors from plant data and discussion with plant staff.

4.3 Criticality analysis and maintenance tasks

Table 7 gives the criticality indices and the resulting tasks for 70CP-1103. Seven of the eight failure causes fall in Group A ($EC = 2.85\text{--}3.00$) and one (elevated fluid temperature, $EC = 2.30$) in Group B. All causes are degradation or condition-related and detectable by inspection or monitoring, so condition-directed tasks were selected; no cause was assigned to time-directed, failure-finding or run-to-failure tasks. Lubrication is the only weekly task, which is consistent with its short interval in the reliability results ($t_{90} = 75$ h for this pump); all others are monthly. Because the pump-level reliability falls below 90% within a few days (Table 5), the monthly inspections should be accompanied by routine operator rounds and, where feasible, bearing-temperature and vibration trending.

Table 7. Criticality analysis and maintenance tasks for pump 70CP-1103

Failure cause	Failure mode(s)	S	P	A	V	EC	Group	Task (type)	Interval	Discipline
Elevated fluid temperature	Low discharge pressure	2	3	2	2	2.30	B	Verify fluid temperature (CD)	Monthly	Control
Bent shaft	High bearing temperature; casing overheating; low flow; low discharge pressure	3	3	3	3	3.00	A	Inspect and repair damaged shaft (CD)	Monthly	Mechanical

Failure cause	Failure mode(s)	S	P	A	V	EC	Group	Task (type)	Interval	Discipline
Worn bearing	As above	3	3	3	2	2.85	A	Inspect and replace worn bearings (CD)	Monthly	Mechanical
Lack of lubrication	As above	3	3	3	2	2.85	A	Apply adequate lubrication (CD)	Weekly	Mechanical
Improper bearing installation	As above	3	3	3	2	2.85	A	Check bearing installation (CD)	Monthly	Mechanical
Motor–pump misalignment	Casing overheating	3	3	3	3	3.00	A	Check alignment by soft-foot test and laser alignment (CD)	Monthly	Electrical
Worn shaft sleeve	Casing overheating	3	3	3	3	3.00	A	Inspect and replace worn sleeve (CD)	Monthly	Mechanical
Loose shaft or damaged impeller	Low flow	3	3	3	3	3.00	A	Check shaft tightness and repair impeller (CD)	Monthly	Mechanical

$EC = 0.30S + 0.30P + 0.25A + 0.15V$. Discipline assignment is used for the workload split (mechanical 6/8, electrical 1/8, control 1/8 of task groups).

4.4 Maintenance workload and optimal staffing

Monthly tasks require $12 \text{ visits} \times 5 \text{ h} \times 2 \text{ persons} = 120 \text{ man-hours}$ per pump per year and weekly tasks $52 \text{ visits} \times 6.15 \text{ h} \times 1 \text{ person} = 319.8 \text{ man-hours}$, giving 439.8 man-hours per pump and $D_{PM} = 2,199.0 \text{ man-hours}$ for five pumps. Corrective repair workload is $D_{CM} = 2 \times 1,326.85 = 2,653.7 \text{ man-hours}$. The total is $D = 4,852.7 \text{ man-hours}$ per year, split as $3,639.5$ (mechanical), 606.6 (electrical) and 606.6 (control).

The current roster for the pump system comprises 13 engineers (4 mechanical, 4 electrical, 5 control) at ₦750,000 per month and 15 technicians (7, 7 and 1) at ₦400,000 per month, a payroll of ₦189.0 million per year (PHRC, 2024). Table 8 shows the optimal integer solution for the baseline workload and for increasing workload allowances. At $\phi = 1$, the

model requires three engineers (one per discipline) and four technicians, at ₦3.85 million per month (₦46.2 million per year), 75.6% below the current payroll. Cost rises linearly with ϕ , because additional workload is met by technicians; even at $\phi = 6$ the annual cost is ₦103.8 million (Fig. 4). Varying h between 1,500 h and 2,000 h changes the baseline annual cost between ₦46.2 million and ₦41.4 million.

Table 8. Optimal staffing for increasing workload allowance

ϕ	Engineers	Technicians	Total staff	Annual cost (₦ million)	Saving vs current (%)
1	3	4	7	46.2	75.6
2	3	6	9	55.8	70.5
3	3	8	11	65.4	65.4
4	3	10	13	75.0	60.3
5	3	12	15	84.6	55.2
6	3	16	19	103.8	45.1
Current	13	15	28	189.0	—

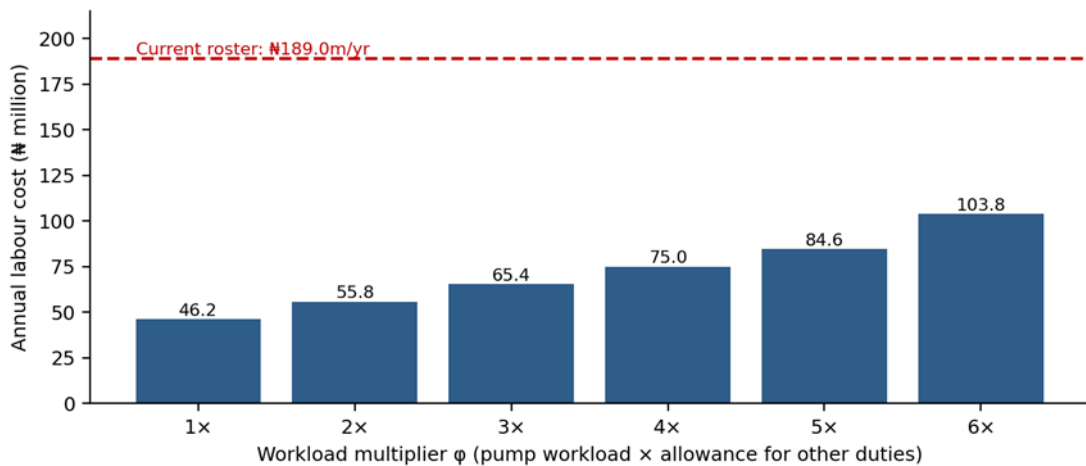


Fig. 4. Annual labour cost of the optimal workforce versus the current roster for increasing workload allowance.

5. Discussion

Reliability. The availability values (95–98%) look high, but the reliability results show that none of the pumps can be expected to run a full month without a failure (R(720 h) of 36.5–58.7%), which supports weekly-to-monthly proactive attention rather than run-to-failure. The wide MTBF confidence intervals and the non-significant homogeneity test mean that a single year of data cannot establish that 70CP-1103 is intrinsically worse than 70CP-1104;

selecting it for detailed analysis is a prioritisation choice. Multi-year records and event-time data are needed to test whether the exponential assumption holds, since ageing or infant-mortality behaviour (Weibull shape) would change the interval recommendations (Anwar et al., 2002; Zhu et al., 2019).

Tasks. Condition-directed tasks dominate because the dominant causes (shaft bending, bearing wear, lubrication, misalignment, sleeve wear and impeller damage) are progressive and detectable. This is consistent with RCM practice in comparable pump studies (Azadeh et al., 2009; Ega & Sugiyono, 2022; Adu & Ebieto, 2023), but intervals here follow plant practice and the reliability benchmark t_{90} rather than a cost-optimal interval derivation, which requires failure cost data not available in the records.

Staffing. The model is a lower-bound estimate: it sizes labour only for the scheduled pump tasks and corrective repairs, plus any allowance ϕ . The finding that seven to nineteen people could carry the pump workload, against a roster of 28, indicates that the current roster is not driven by pump maintenance alone. The remainder may reflect shift coverage, other equipment, supervision and administrative duties, none of which are modelled. The result should therefore be read as a prompt to review roster allocation and redeploy capacity, not as a recommendation to retrench staff. Comparable studies similarly report labour-cost reductions from RCM (Afefy, 2010; Ogra et al., 2021), but these are not directly comparable because of differences in scope and cost basis.

Limitations. (i) One plant, one year and five pumps; (ii) exponential failure model without event-time tests; (iii) MTTR is an aggregate mean and repair-time distributions were unavailable; (iv) tasks derived for 70CP-1103 were applied to all five pumps for workload purposes; (v) criticality ratings come from a small expert panel; (vi) h , c_r and discipline shares are assumptions covered only by sensitivity analysis; (vii) downtime, spare-part and risk costs are excluded; and (viii) no post-implementation data exist to confirm reliability gains.

6. Conclusions

Using 2024 records for five refinery power-plant pumps, MTBF ranged from 714 to 1,352 h, availability from 95.19% to 98.25%, one-week reliability from 79.0% to 88.3% and one-

month reliability from 36.5% to 58.7%; differences between pumps were not statistically significant.

FMEA, LTA and criticality analysis of pump 70CP-1103 identified seven Group A and one Group B failure cause, all addressed by condition-directed tasks at weekly (lubrication) or monthly intervals.

A workload-based integer model gives a baseline workforce of three engineers and four technicians costing ₦46.2 million per year and remains 45–76% below the current ₦189.0 million payroll for workloads up to six times the baseline, indicating that the current roster should be reviewed rather than that staff are redundant.

Future work should use multi-year, multi-plant event-time data to fit Weibull models, derive cost-optimal intervals with downtime and spares costs, and monitor reliability after implementation.

Data availability

The failure data analysed is reproduced in Table 2; the staffing data are reproduced in Section 4.4. Source records are held by the Port Harcourt Refining Company (PHRC, 2024).

REFERENCES

1. Adu, E. C., & Ebieto, C. E. (2023). Effective reliability-centered maintenance strategy for a centrifugal pump in a natural gas process plant. *International Research Journal of Engineering and Technology*, 11(7), 417–441.
2. Afefy, I. H. (2010). Reliability-centred maintenance methodology and application: A case study. *Journal of Engineering*, 2(12), 863–873.
3. Ahmed, H., Kouzou, A., Guemana, M., & Nadji, H. (2016). Reliability analysis using Weibull distribution applied to a booster pump used in oil drilling installations. *Fundamental Sciences and Applications*, 22(7), 20–27.

4. Anu, H. N., Sriramula, S., & Terry, E. (2021). Reliability-centered maintenance and cost optimization for offshore oil and gas components. *Journal of Physics: Conference Series*, 1730(1).
5. Anwar, K. S., Muhammad, Y., & Dahham, M. A. (2002). Weibull analysis of time between failures of pumps used in an oil refinery. *The 6th Saudi Engineering Conference*, Riyadh.
6. Azadeh, A., Ebrahimipour, V., & Bavar, P. (2009). A pump FMEA approach to improve reliability centered maintenance procedure: The case of centrifugal pumps in onshore industry. *WSEAS International Conference on Fluid Mechanics*, Tehran, Iran.
7. Darmein, M., Zuhaimi, F., & Nurlaili, L. (2023). Gas turbine maintenance optimizing using the reliability-centered maintenance method. *Research of Mechanical Engineering – Jurnal Polimesin*, 21(1), 134–139.
8. Ega, S. A., & Sugiyono, M. (2022). Implementation of reliability centered maintenance method for pump on fuel distribution companies. *United International Journal for Research & Technology*, 3(11), 22–31.
9. Geisbush, J., & Ariaratnam, S. T. (2023). Reliability centered maintenance (RCM): Literature review of current industry state of practice. *Journal of Quality in Maintenance Engineering*, 29(2), 313–337. <https://doi.org/10.1108/JQME-02-2021-0018>
10. Ikuobase, E., Rosemary, A. N., & Alan, J. M. (2016). Elements of maintenance systems and tools for implementation within the framework of reliability centered maintenance – A review. *Journal of Mechanical Engineering and Technology*, 8(2), 1–34.
11. Masoomah, Z., Abdoulmohammad, G. C., Eeyhi, A. G., & Jiri, J. K. (2020). Critical success factors of the reliability-centred maintenance implementation in the oil and gas industry. *Symmetry*, 12(10), 1585.

12. Muhammad, M., Majid, M. A. A., & Ibrahim, N. A. (2010). Reliability assessment for centrifugal pumps in a petrochemical plant. In *Engineering Asset Lifecycle Management*. Springer London, 398–404.
13. Navneet, S., & Bhangu, R. S. (2018). Implementation of reliability centered maintenance technique on boiler and accessories in a thermal power plant: A case study. *Journal of Engineering and Economic Development*, 4(2), 1–10.
14. Ogra, O. A., Nkoi, B., & Isaac, E. O. (2021). Using reliability centered maintenance to reduce operational cost of heat exchanger and feed water pump in a brewery. *Journal of Newviews in Engineering and Technology*, 3(3), 20–30.
15. Port Harcourt Refining Company (PHRC) Limited (2024). *Port Harcourt Refining Company Limited: Power Plant Equipment Defect Data*. Port Harcourt Refining Company Limited Directory (accessed May 2025).
16. Sijibomi, A. O., Chukwuemeka, P. U., & Barinyima, N. (2020). Application of reliability techniques to evaluate maintainability of centrifugal pump used for petroleum product delivery. *Journal of Newviews in Engineering and Technology*, 2(3), 11–21.
17. Singh, D., & Suhane, A. (2015). Availability of centrifugal pump on the basis of Weibull analysis. *International Journal of Science and Research*, 4(6), 378–380.
18. Viveros, P., Mena, R., Zio, E., & Campos, S. (2024). Optimal grouping and scheduling of preventive maintenance activities. *Proceedings of the 30th European Safety and Reliability Conference and the 15th Probabilistic Safety Assessment and Management Conference*, Singapore, 2915–2921.
19. Zhu, H., Pei, J., Wang, S., & Huang, X. (2019). Reliability analysis of centrifugal pump based on small scale sample data. *International Journal of Performability Engineering*, 9(4), 423–432.