PLC-ASSISTED INSPECTION AND COLD-STANDBY LUBRICATION IN CEMENT GRINDING: STOCHASTIC RELIABILITY, SWITCHING COVERAGE AND ECONOMIC THRESHOLDS

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***Abstract*—Programmable logic controller (PLC) alarms and lubrication standby systems can potentially reduce the consequences of developing faults, but their reliability gains depend on inspection delays, switching success and maintenance expenditure. This paper compares two policy bundles for a cement grinding system using stochastic state models: Model III provides PLC-assisted inspection followed by repair or replacement, whereas Model IV incorporates a proposed cold-standby lubrication-pump subsystem with automatic PLC switching and restoration. Both scenarios are based on a observed, 24-month operating workbook containing 214 fault events, 325 PLC alarm records and 24 illustrative standby-test records. In the inspection model, a regenerative first-passage expression accounts for competing minor-fault escalation and inspection completion. In the standby model, a ten-state continuous-time Markov particular case accounts for an active primary pump, dormant standby failures, switching coverage, backup operation and unprotected non-pump faults. The previously developed thesis baselines give mean time to sustained system failure of 219.23 h and 251.24 h, binary availability of 98.27% and 98.63%, and expected profit of ₹90,265.27/h and ₹90,552.48/h, respectively. Equation-derived sensitivity results show why incomplete switching coverage and active-backup failures restrict the effectiveness of redundancy. The apparent profit advantage is lost when additional unbudgeted standby expenditure exceeds approximately ₹287.21/h, all other scenario assumptions held constant. The comparison is illustrative rather than causal: the two models differ in several intervention assumptions, and neither strategy has been validated on installed equipment. The proposed framework supports transparent screening of inspection and redundancy investments prior to field trials.**

***Index Terms*—programmable logic controller, inspection, fault detection, semi-Markov reliability, cold standby, lubrication pump, switching coverage, cement grinding, profit**

I. Introduction

Large cement grinding systems depend on coordinated mechanical and electrical operations, where the condition of a lubrication circuit can be critical for the continued operation of mill bearings and associated drive equipment. Sensors and PLC alarms may provide an early indication of abnormal pressure, temperature, vibration or motor status. Yet an alarm alone is not a diagnosis: operators must verify whether it represents a true fault, process advisory, instrumentation disturbance or nuisance event. A monitoring system that detects warning conditions promptly can still be economically ineffective if inspections lead to excessive stoppages or replacement expenditure.

Condition-based monitoring literature distinguishes acquisition of sensor information, interpretation of machinery condition and maintenance decision-making (Jardine et al., 2006). Cyber-physical systems extend this concept through integrated industrial data capture and analytical feedback (Lee et al., 2015). Recent reviews discuss the opportunities and deployment limitations of data-driven predictive maintenance, including noisy measurements, scarce labels, changing operating conditions and imperfect model transferability (Carvalho et al., 2019; Zonta et al., 2020; Nunes et al., 2023).

Mechanical protection offers a complementary option. A cold-standby pump is intended to remain inactive until the operating pump requires substitution; potential benefits arise because the redundant component has not been exposed to the same active duty. Classical standby analyses show, however, that dormant failure, failure during use and switching imperfections can limit redundancy benefits (Osaki & Nakagawa, 1971; Nakagawa & Osaki, 1975). A standby unit also adds inspection, testing and capital-related expenditure. For cement machinery, proactive monitoring has been explored for slowly rotating components, but such methods do not establish successful industrial performance of the proposed pump arrangement in the present study (Rusiński et al., 2013).

The purpose of this paper is to examine a decision that differs from the corrective-versus-preventive question: how do inspection-response performance and imperfect standby switching influence the reliability and economic outcomes of alternative PLC-guided maintenance architectures? The aim is to represent additional protection mechanisms and their costs explicitly, while retaining the full cement-grinding system boundary. The comparison reports system-level consequences rather than treating pump-subsystem reliability as the reliability of the entire grinding process.

II. Data and Scope of the Study

2.1 Observed equipment fault and alarm registers

The illustrative dataset describes 16,259.13 observed operating hours from June 2024 through May 2026, with 214 fault events grouped into minor electrical (49), major electrical (31), minor mechanical (71), major mechanical (33), developing (22) and PLC/instrumentation (8) categories. It also contains 214 corrective actions and 121 preventive activities. The workbook is a research simulation, not authenticated maintenance records from Wonder Cement Limited. Equipment IDs and intervention dates support consistent model parameter bookkeeping but are not evidence that the proposed standby unit was physically installed.

The PLC record contains 325 alarms: 141 are linked to fault records, 74 are nuisance or unconfirmed events, and 110 are process advisories. These classifications are reproduced in Table 1. In particular, the ratio $141/325 = 43.38\%$ describes a record-linkage fraction and is neither diagnostic sensitivity nor precision. Validated accuracy would require a reference set of confirmed true positives, false negatives, false positives and true negatives.

Table 1. Descriptive classification of the observed PLC alarm register.

Alarm grouping	Records	Fraction of all alarms	Permitted interpretation
Fault-linked alerts	141	43.38%	Administrative linkage, not proven detection success
Nuisance/unconfirmed	74	22.77%	Potential investigation burden
Process advisories	110	33.85%	Operating information, not necessarily faults
Total	325	100.00%	No validated diagnostic confusion matrix

Twenty-four observed standby switching-test activities appear in the workbook. They are useful for constructing a testing-cost scenario but do not estimate the switching success probability for an actual installed standby pump. The baseline switching probability of 0.96, active and dormant failure rates, and oil-buffer capability are assumed for mathematical screening.

2.2 Boundaries, comparability and distinct contributions

Model III represents the complete grinding system with fault-category-specific inspection, repair and replacement. Model IV protects a *hypothetical lubrication-pump subsystem* while retaining unrelated electrical, mechanical and PLC fault pathways. It is not a duplicate grinding line. The two policy bundles do not have exactly the same intermediate state descriptions; therefore their numerical difference is not a controlled estimate of a pump-only intervention. The comparison is nevertheless useful as a consistent system-level screening study when the respective assumptions are stated alongside the output.

Table 2. Analytical distinctions and hypothetical baseline inputs.

Parameter or decision	Model III: PLC inspection	Model IV: cold standby
Fault input	Same six occurrence categories	Same six categories; pump share separated from other faults
Intervention pathway	Minor-fault inspection then repair/replacement	Primary pump failure → switching → backup duty or failed switch
Representative inspection duration	Approximately 0.311 h, an assumed 20% reduction	Not treated as an independent failure-rate multiplier
Primary pump failure share	No separate standby pump	h^{-1}, hypothetical
Dormant standby failure	Not applicable	h^{-1}, hypothetical
Active standby failure	Not applicable	h^{-1}, hypothetical
Successful switching probability	Not a switching model	, hypothetical
Switching completion rate	Not applicable	h^{-1} (3-min mean), hypothetical
Operating margin	₹92,300/h at full capacity	Same full-capacity margin
Specific overhead	PLC policy ₹1,750/day	Standby policy ₹3,350/day

III. Mathematical Framework

3.1 Model III: inspection and repair or replacement

The inspection model begins in operative state S_0. After a minor electrical or mechanical fault, the system enters a partially operative state and a diagnostic inspection begins. The inspection time competes with fault escalation; a confirmed inspection result sends the affected component for repair or replacement. A major fault or serious PLC failure results in complete interruption. The detailed model employs 16 states, including distinct restoration activities, while its first-passage expression can be written in terms of aggregated completion-time distributions.

Write λ_i for the six occurrence rates, $\Lambda = \sum_i$ λ_i, δ_i for minor-fault inspection completion rates and θ_i for competing progression rates. The probability of inspection completing before escalation is

$$a_i = \frac{\delta_i}{\delta_i + \theta_i}, \qquad i \in \{1,3\}. \qquad (1)$$

Let r_i denote the conditional probability that inspection selects replacement, and let $G_i(t)$ and $H_i(t)$ denote repair and replacement completion distributions. Their combined restoration transform is

$$\widetilde{K}_i(s) = (1 - r_i)\widetilde{G}_i(s) + r_i\widetilde{H}_i(s). \qquad (2)$$

For the exponential first-passage particular case, the mean time before the first *complete* system interruption is

$$MTSF_{III} = \frac{m_0 + p_{01}(m_1 + a_1\underline{k}_1) + p_{03}(m_3 + a_3\underline{k}_3) + p_{05}m_5}{1 - p_{01}a_1 - p_{03}a_3 - p_{05}}, \qquad (3)$$

where $m_0 = 1/\Lambda$, $p_{0i} = \lambda_i/\Lambda$, $m_i = 1/(\delta_i + \theta_i)$ for minor faults, and $\underline{k}_i$ is expected selected restoration duration. Equation (3) is a regenerative first-step expression, not a regression fitted to PLC alarms. For one representative sensitivity plot, the assumed electrical and mechanical inspection durations are approximately 0.311 hours at the baseline response rate, consistent with the proposed inspection-duration reduction. The result is near the previously reported 219.23-hour Model III baseline.

3.2 Model IV: primary pump, cold standby and imperfect switching

The cold-standby model is organized into ten states. State S_0 denotes a running primary pump and available standby pump; S_3 denotes a PLC switching attempt; S_4 denotes standby pump operation while the primary is repaired; S_5 denotes a dormant standby fault; S_7 denotes loss of primary supply without successful switching; S_8 denotes failure of the active backup before repair; and S_9 denotes other full-system failure. Remaining states represent partial electrical, mechanical and developing faults. The switching state is assumed to permit reduced output through a short-duration lubrication buffer. This buffer assumption is unverified and should be tested against pressure and oil-volume requirements before any operational recommendation.

Let λ_P denote the primary pump failure intensity, λ_D the standby dormant-failure intensity, λ_S the rate when standby becomes active, c successful PLC switching coverage and σ the switching completion rate. For the switching state,

$$q_{34} = c\sigma, \qquad q_{37} = (1 - c)\sigma, \qquad p_{34} = c, \quad p_{37} = 1 - c. \qquad (4)$$

The residual major-fault intensity outside the protected primary-pump pathway is

$$\lambda_O = \lambda_2 + (\lambda_4 - \lambda_P) + \lambda_6. \qquad (5)$$

The subtraction in Equation (5) prevents the primary pump fault share from being counted twice. The dormant standby condition experiences competing restoration and primary-pump failure:

$$q_{50} = \mu_D, \qquad q_{57} = \lambda_P, \qquad p_{57} = \frac{\lambda_P}{\mu_D + \lambda_P}. \qquad (6)$$

If Q is the ten-state generator, every direct transition intensity q_{ij} is nonnegative, and $q_{ii} = -\sum_{j \neq i} q_{ij}$. The Semi-Markov transition function has the exponential particular case

$$Q_{ij}(t) = \frac{q_{ij}}{\nu_i}(1 - e^{-\nu_i t}), \quad \nu_i = \sum_{j \neq i} q_{ij}, \quad m_i = \nu_i^{-1}. \qquad (7)$$

This exponential form is evaluated by matrix computations. More general inspection, switching and repair times require the corresponding Markov-renewal kernel, rather than claiming that arbitrary holding distributions create the same continuous-time Markov chain.

3.3 Reliability and mean first-passage times

For Model IV, complete-failure states S_7, S_8 and S_9 are treated as absorbing only when calculating the time to the first sustained interruption. Let Q_T be the subgenerator restricted to the remaining seven states. Then,

$$R_{IV}(t) = e_0^T e^{Q_T t} 1, \qquad MTSF_{IV} = e_0^T (-Q_T)^{-1} 1. \qquad (8)$$

For Model III, the corresponding reliability transform is obtained from the regenerative first-passage distribution $\Phi_{III}(s)$:

$$R_{III}^*(s) = \frac{1 - \Phi_{III}(s)}{s}. \qquad (9)$$

Both quantities describe avoidance of complete grinding-system interruption. Neither treats a routine alert as a failed grinding system, and neither incorrectly counts the availability of the standby pump by itself as whole-system reliability.

3.4 Long-run availability and economic reward

For the full, restorative generators, stationary probabilities satisfy $\pi Q = 0$ and $\sum_i \quad \pi_i = 1$. The Model IV availability and production-equivalent utilization are

$$A_{IV} = \sum_{i=0}^{6} \quad \pi_i, \qquad E_{IV} = \pi_0 + \pi_4 + \pi_5 + \eta(\pi_1 + \pi_2 + \pi_3 + \pi_6), \quad \eta = 0.65. \qquad (10)$$

Let $C_0 = ₹92\,300$ denote modelled production contribution per hour, c_{ij} the cost assigned to a restoration or switching event and C_{fixed} nonduplicated policy expenditure per hour. The regenerative-reward profit expression is

$$P_{IV} = C_0 E_{IV} - \sum_{i \neq j} \quad \pi_i q_{ij} c_{ij} - C_{fixed}. \qquad (11)$$

Model III uses a comparable capacity-weighted reward but also incurs inspection costs and hypothetical nuisance-alert handling expenditure. An inspection-only linked-alert percentage is not substituted into Equation (11) as a validated diagnostic performance statistic. Economic benefits from reduced stoppage time are reflected in state occupancy, so lost throughput is not charged again as a duplicate downtime cost.

IV. Numerical Results and Sensitivity Analysis

4.1 Baseline model outcomes

The reported numerical outcomes of the revised thesis models are presented in Table 3. Model III incorporates repair/replacement decisions following inspection, while Model IV adds pump switching and backup-pump operation under its own hypothetical policy. The Model IV matrix implementation was independently evaluated under rounded input values, yielding approximately 251.28 hours MTSF and 98.63% availability; the minor MTSF difference from the thesis value of 251.24 hours reflects parameter rounding and the use of rounded rates. For consistency, Table 3 retains the manuscript's established baseline figures. The cost structure for Model IV has not been independently reconstructed from a complete audited cost ledger; its profit is therefore explicitly identified as the reported thesis scenario value.

Table 3. Comparative illustrative results for the two policy bundles.

Measure	Model III: PLC inspection	Model IV: cold standby	IV − III

Operating-time MTSF (h)	219.23	251.24	+32.01
System availability	98.27%	98.63%	+0.36 pp
Complete downtime per 1,000 calendar h	17.33 h	13.73 h	−3.60 h
Modelled expected profit	₹90,265.27/h	₹90,552.48/h	+₹287.21/h
Inspection busy fraction	0.003724	Different standby model	Not directly comparable
Inspection records as diagnostic validation	No	No	Neither validated
Standby pump physical deployment	Not applicable	Hypothetical	No installed system claimed

The observed ordering depends on the assumed oil buffer, primary-pump share within mechanical faults, switching coverage and restorative transitions. Because Model III and IV are separate architectures with differing intermediate states, their difference is a model comparison and not a causal estimate of the isolated installation of one additional pump.

4.2 Sensitivity to PLC inspection response

A shorter inspection duration reduces the probability that a minor fault progresses before intervention. Equation (1) explicitly represents this mechanism through the competing rates. Figure 1 is generated from Equation (3) under the representative inspection-duration assumption and the unchanged escalation rates of 0.080 and 0.075 per hour. The analysis does not equate a faster PLC scan with an equivalent reduction in total maintenance delay; operator acknowledgement, verification and repair still contribute to the response interval.

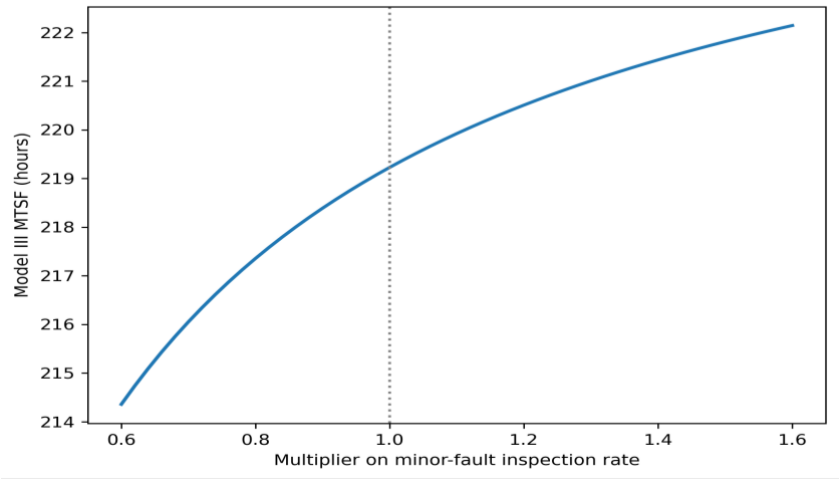

Figure 1. Model III MTSF under variation of the assumed minor-fault inspection response rate.

4.3 Switching coverage and dormant failure

The baseline assumes successful switching coverage $c = 0.96$, meaning the PLC-directed transfer succeeds in 96% of switching *demands in the hypothetical model*. It is not inferred from the 24 illustrative test records. Figure 2 recomputes the Model IV absorbing first-passage matrix while varying c; all other parameters are held fixed. The resulting change reflects a direct increase or decrease in the hazard of failed switching, whereas unrelated mechanical and electrical failure pathways remain.

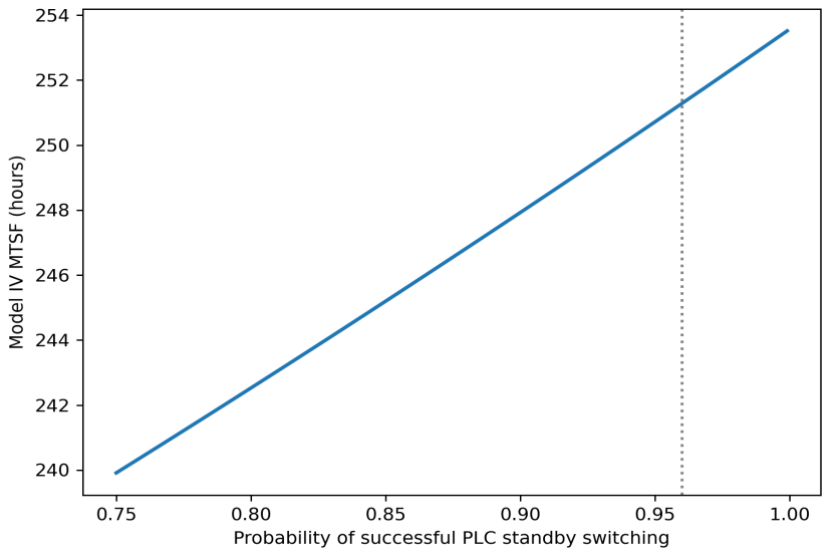

Figure 2. Model IV first-passage MTSF as a function of successful cold-standby switching probability.

Figure 3 varies the active standby-pump failure rate around the assumed baseline of $0.00110\ h^{-1}$. Figure 3 displays MTSF on an explicitly magnified vertical scale because the change is modest (about 0.43 hours over the plotted range); it does not imply a large reliability effect. The same generator gives a small decrease in steady-state availability. MTSF concerns first full interruption from a renewed condition, whereas availability includes restoration cycles. Dormant-failure sensitivity is not interpreted as a validated effect: the simplified ten-state formulation omits some competing non-pump faults while standby readiness is lost, which can produce counterintuitive trends when the dormant hazard alone is varied. An expanded state model is required before using λ_D for a practical optimization decision.

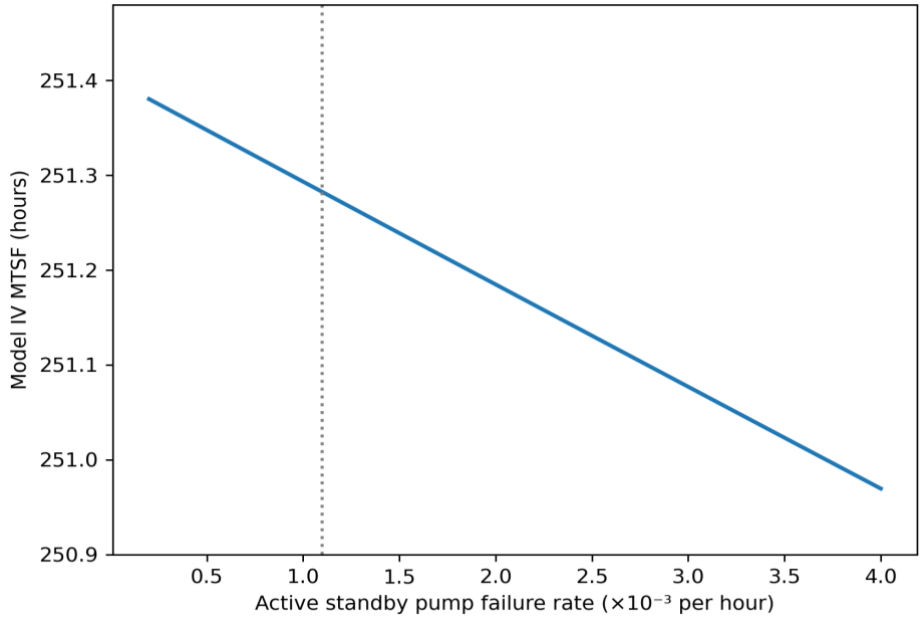

Figure 3. Magnified full-system MTSF sensitivity to failures of the active standby pump.

Table 4. Scenario interpretation and industrial verification requirements.

Modelled factor	What the mathematics changes	Evidence needed before deployment
Faster inspection response	Competition between inspection and fault escalation	Timestamped fault onset, acknowledgement and decision times

Higher switching coverage	Probability that transition succeeds	Repeated controlled switch tests with confirmed success/failure
Lower dormant standby failure	Probability that backup is ready on demand	Periodic proving-test and latent-fault discovery records
Faster primary pump repair	Duration of standby-only operating condition	Technician service records and spare-part delays
Additional policy expenditure	Expected profit but not physical reliability at fixed rates	Itemized capex, annual service costs and energy demand

4.4 Profit threshold for the standby architecture

At the stated thesis baseline, the profit difference is $\Delta P = P_{IV} - P_{III} = ₹287.21$ per modelled hour. Let B be additional *unbudgeted* expenditure assigned exclusively to the standby policy. As an accounting identity with all transition intensities and production rewards held fixed,

$$\Delta P(B) = 287.21 - B, \qquad B_{BE} = ₹287.21\ h^{-1}. \qquad (12)$$

This represents approximately ₹6,893 per uninterrupted 24-hour modelling day. Figure 4 illustrates the change in the comparative profit margin. It must not be interpreted as an optimized replacement schedule or a plant-approved capital budget; real installation costs would need amortization, financing and energy consumption. Moreover, if increased testing expense actually improves standby readiness, the fixed-transition approximation ceases to be appropriate.

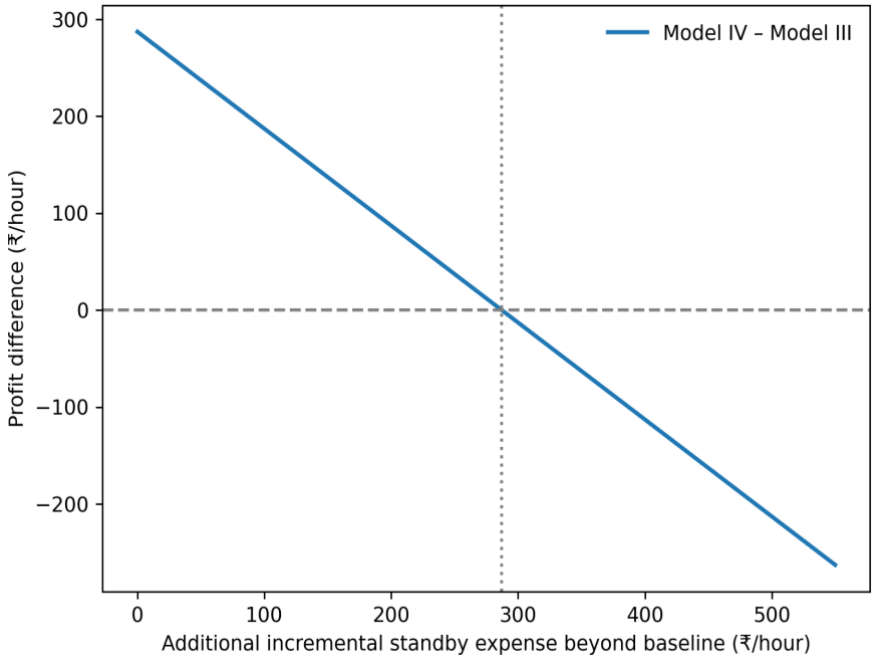

Figure 4. Incremental standby-policy expenditure at which the baseline observed profit advantage over Model III reaches zero.

V. Discussion

The two hypothetical systems reflect different risk-control mechanisms. PLC inspection aims to recognize a developing fault before it becomes a complete interruption, whereas standby redundancy aims to preserve lubrication supply after a primary pump failure. Both approaches are plausible engineering hypotheses, but the former depends on trustworthy detection and verification, and the latter depends on backup readiness, switching control and repair completion. The present calculation makes these dependencies visible rather than assuming that every alarm is diagnostic or that every switching demand succeeds.

The comparative baseline is sensitive to three interpretive constraints. First, the observed fault register provides no validated diagnostic confusion matrix. The fraction of fault-linked alerts cannot support sensitivity, specificity or predictive-value claims. Second, the standby design is a subsystem intervention; the grinding line remains vulnerable to unprotected major faults. Third, the Model III and Model IV architectures differ in their service states and assumed restoration channels, so observed superiority of Model IV is a *scenario result*, not the isolated effect of redundancy. In a future controlled comparison, Model III would be held fixed while only the pump-subsystem transition structure and costs were changed.

The oil-buffer assumption warrants particular attention. Treating the three-minute switching attempt as reduced-production rather than immediate complete failure requires adequate retained lubrication pressure and an acceptable bearing temperature response. No buffer-volume or pressure-transient data were supplied, so the assumed production reward during switching is hypothetical. A conservative sensitivity experiment should classify switching as a complete outage whenever oil pressure falls below its safe limit.

Reliability also requires evaluation of hidden standby failure. A spare pump with nominally low active failure probability may nevertheless be unavailable when requested because dormant faults were not detected by proving tests. This risk is represented separately through λ_D instead of artificially reducing the full line's generic mechanical failure rate. Classical standby theory similarly stresses demand-time readiness and maintenance interactions (Osaki & Nakagawa, 1971; Nakagawa & Osaki, 1975).

The results suggest a sensible field-validation sequence: establish event timestamps and sensor truth labels; verify alarm-to-work-order linkage; characterize maintenance completion distributions; conduct supervised standby proving tests; validate switch transients and buffer capacity; and then collect a properly costed before–after dataset. The tests should not be treated as complete until unsuccessful and inconclusive outcomes are recorded, since excluding them would bias coverage estimates upward.

VI. Conclusion

A stochastic screening analysis compared a PLC-inspection strategy with a proposed cold-standby lubrication-pump strategy for a cement grinding line. The revised thesis scenarios gave MTSF values of 219.23 and 251.24 hours, availability values of 98.27% and 98.63%, and expected profit values of ₹90,265.27 and ₹90,552.48 per modelled hour, respectively. Switching coverage, dormant standby faults and additional operating expenditure govern whether the hypothetical redundancy benefit is sustained. The apparent ₹287.21/h profit margin is eliminated by an equal amount of unbudgeted standby expenditure when other inputs are held fixed. The work provides a mathematical screening tool and a clear list of needed validation measurements; it does not establish actual industrial performance or prove that adding a standby pump would improve the plant.

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