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Enhancing Kiln Reliability in Cement Industry Using RCM II and FMEA

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Abstract

This study applies to the Reliability-Centered Maintenance (RCM) II methodology to improve the reliability and cost efficiency of a kiln system in a cement manufacturing plant. Kiln failures are critical because they cause unplanned downtime, reduced productivity, and financial losses. Traditional corrective or time-based maintenance strategies often fail to address the stochastic nature of failures in such high-temperature rotary systems. To overcome this gap, the research integrates Failure Mode and Effect Analysis (FMEA) with RCM II decision logic to identify and prioritize maintenance actions. The analysis focused on five critical kiln components—crusher cooler, firebrick lining, thrust roller, grate cooler, and main drive—using 12 months of operational data supported by expert interviews and technical manuals. Reliability indicators, including Mean Time to Failure (MTTF), Mean Time to Repair (MTTR), and Mean Time Between Failures (MTBF), were calculated, while Risk Priority Numbers (RPN) were assigned to rank failure modes. Results showed that the crusher cooler had the highest risk, whereas the main drive required the longest repair duration. Implementation of RCM II recommendations increased MTBF by 29–38% across components and reduced maintenance costs by more than 50%. These findings confirm that RCM II provides a practical, data-driven framework for enhancing system availability. The study contributes to maintenance engineering by demonstrating a structured approach that supports risk-informed and condition-based maintenance strategies in continuous-process industries.

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1. Introduction

The cement industry faces increasing challenges in the era of Industry 4.0, particularly in achieving operational efficiency, equipment reliability, and sustainability targets [1], [2]. Among the critical systems in cement production, the rotary kiln is essential for clinker formation, yet it operates under extreme thermal and mechanical conditions. Failures in kiln subsystems—such as firebrick linings, thrust rollers, and coolers—can result in significant production interruptions, costly downtime, and safety risks [3], [4].

Previous studies have explored maintenance strategies in continuous process industries, but most have relied on corrective or time-based preventive maintenance, which often fail to address stochastic and complex failure modes [5], [6]. Recent research emphasizes the importance of risk-based and condition-based approaches, including predictive maintenance using IoT and machine learning, to overcome these limitations [7], [8]. However, despite these advances, applications in cement manufacturing remain scarce compared to other sectors such as aviation, power plants, and petrochemicals [9], [10].

In particular, the literature lacks structured approaches that integrate Failure Mode and Effects Analysis (FMEA) with RCM II decision logic to systematically prioritize maintenance tasks based on risk. While some studies on cement kilns have applied reliability models, they often neglect systematic decision-making frameworks or provide only descriptive failure statistics without linking them to actionable maintenance strategies [11], [12].

This gap indicates the need for a more rigorous and data-driven methodology that not only identifies critical components but also quantifies the impact of maintenance strategies on system reliability and cost efficiency. To address this, the present study applies the RCM II framework, supported by FMEA, to a cement kiln system. Specifically, the study analyzes 12 months of operational data, triangulated with expert interviews and technical manuals, to identify and rank critical kiln components, determine suitable maintenance strategies through RCM II decision logic, and evaluate the

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effectiveness of these strategies in terms of Mean Time Between Failures (MTBF) improvement and maintenance cost reduction.

By providing both methodological rigor and empirical validation, this research contributes practical insights for maintenance engineers and decision-makers in process industries. Furthermore, it extends the literature on reliability engineering in cement production and highlights opportunities for future integration of digital technologies, such as condition monitoring sensors and IoT-based predictive analytics [13], [14].

2. Methods

This section describes the research setting, data sources, analytical techniques, and the Reliability-Centered Maintenance II (RCM II) framework used in this study. The methodology was designed to ensure reproducibility and follow established practices in reliability engineering [9].

2.1. Research setting and system overview

This study was conducted at a cement production facility that employs a rotary kiln as the core unit in the clinker manufacturing process. The kiln system operates continuously under high temperatures, rotational loads, and abrasive material flow, making it one of the most failure-prone subsystems in cement plants [1]. Its uninterrupted function is critical for production stability and overall plant efficiency. Due to its role and complexity, kiln-related failures often result in significant downtime, safety risks, and elevated operational costs.

The kiln under study had a production capacity of approximately 5,000 tons of clinker per day, operating at an average availability of 85%. Data were collected over a 12-month observation period (January–December 2023), which ensured inclusion of both scheduled shutdowns and unplanned stoppages.

2.2. Component selection criteria

Component selection followed a purposive sampling approach. Criteria included *such as* recorded downtime exceeding 10 hours/month, high-frequency maintenance events, and critical impact on production continuity. Downtime logs from a 12-month operational period were analyzed to

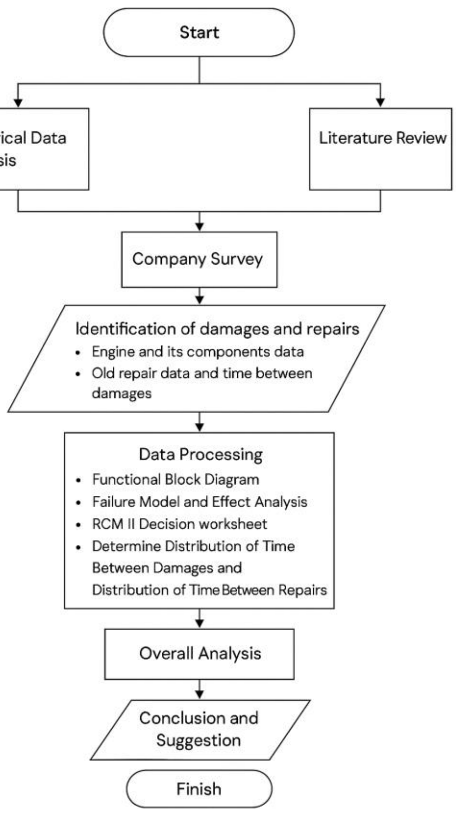

Figure 1. Research methodology flowchart illustrating data collection, reliability analysis, FMEA, and RCM II implementation steps

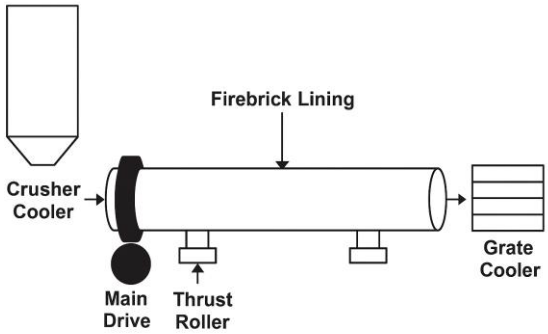

Figure 2. Key components of the rotary kiln system analysed in this study

quantify failure events and durations. Cross-validation was conducted using interviews with in-house maintenance experts and production engineers.

Initially, a total of 12 kiln-related subsystems were screened using the above criteria. Based on downtime logs and expert assessment, the scope was narrowed to five primary components (crusher cooler, firebrick lining, thrust roller, grate cooler, and main drive) as these accounted for over 80% of total recorded downtime hours.

2.3. Data sources and collection procedure

Three primary data sources were utilized in this study, namely Computerized Maintenance Management System (CMMS) records, expert interviews, and technical documents. The CMMS provided detailed logs of failure frequency, repair duration, affected components, and historical maintenance activities. To complement these quantitative records, semi-structured interviews were conducted with five maintenance engineers and technicians in order to validate downtime causes and capture contextual insights that might not appear in system logs. In addition, technical manuals and vendor specifications were reviewed to ensure accuracy of component functions, operating thresholds, and design limitations.

In total, 126 downtime events were recorded during the 12-month observation period, resulting in more than 1,200 hours of cumulative downtime. These events were systematically classified by component type and failure category. The triangulation of CMMS data, expert judgment, and technical documentation enhanced the reliability of the dataset and ensured that subsequent analyses were both technically valid and operationally relevant [10], [13].

2.4. Reliability metrics and failure records

To assess component performance, standard reliability engineering metrics were employed:

- Mean Time to Failure (MTTF) = Total Operating Time / Number of Failures
- Mean Time to Repair (MTTR) = Total Repair Time / Number of Failures
- Mean Time Between Failures (MTBF) = MTTF + MTTR

These values were derived from monthly failure logs. For example, the main drive recorded an average MTTR of 11.6 hours and MTTF of 31.5 hours, yielding an MTBF of 43.1 hours. These computations were done using structured Excel-based worksheets, corroborated with technician logs and shift reports [5], [12].

2.5. FMEA and RPN analysis

Failure Mode and Effect Analysis (FMEA) was employed to systematically identify, analyze, and rank potential failure modes for the selected kiln components. Each failure mode was evaluated based on Severity (S), Occurrence (O), and Detection (D) using a 1–10 scale [14], [15]. To enhance reproducibility, the criteria for each dimension are detailed as follows.

Severity (S). Impact level on safety, environment, or operation (1–10):

1 = No effect on operation.
4 = Minor production disturbance, negligible safety/environmental impact.
7 = Significant production loss, moderate safety concern.
10 = Catastrophic failure causing complete shutdown or severe safety hazard.

Table 1. Failure Modes and Effect Analysis (FMEA)

Function	Function Failure (Loss of Function)	Failure Modes (Cause of Function)	Failure Effect (What Happens When It Fails)
1. Deliver hot clinker from the grate cooler	Failed to deliver material, causing system blockage or unbalanced operation	Crusher Cooler stuck/jamming	Clinker material fails to pass through, causing process disruption
2. Protect the kiln wall from high temperature and pressure	Protective coating wears off, overheating the shell, risk of deformation	Firebrick breaks, cracks, and peels off	Damaged protective layer, overheating, and potential shell failure
3. Generate thrust to rotate the kiln	Failure to maintain rotary position causes the kiln to stop rotating	Roller/roller block jammed	Kiln cannot rotate, operational stoppage
4. Cool down the hot clinker exiting the kiln	Failed to cool clinker, causing equipment damage or loss of heat recovery	Grate Cooler stuck/jammed	Clinker quality decreases, heat recovery system failure
5. Drive the rotary kiln motor	Kiln stops rotating due to sudden shutdown	Main Drive suddenly stops	Entire system stops, energy loss, risk of further damage

Occurrence (O). Probability of failure based on historical frequency (1–10):
- 1 = Remote probability (<0.01 failures/year).
- 4 = Low frequency (approx. 1–2 failures/year).
- 7 = High frequency (monthly failures).
- 10 = Very high frequency (weekly or more frequent failures).

Detection (D). Likelihood of early identification (1–10):
- 1 = Almost certain detection via existing monitoring systems (e.g., sensors).
- 4 = High likelihood of detection through regular inspections.
- 7 = Low chance of detection before failure, requiring advanced monitoring.
- 10 = No detection method available until failure occurs.

As an example, the crusher cooler received a Severity score of 8 (major production disruption, moderate safety risk), Occurrence score of 8 (frequent bearing failures observed monthly), and Detection score of 6 (defects difficult to detect without vibration analysis). This yielded an RPN of 384, classifying the component as critical.

The Risk Priority Number (RPN) was calculated as:

$$RPN = S \times O \times D \tag{1}$$

2.6. RCM II strategy classification process

The RCM II methodology was applied using a Decision Logic Worksheet (DLW), following the framework of Moubray [9]. The selection of maintenance strategies was based on a set of technical and economic criteria. Scheduled Maintenance (SM) was applied when preventive tasks, either time- or condition-based, were both technically feasible and economically justified. For instance, the crusher cooler bearings were scheduled for replacement every two months, as the preventive task cost (USD 250 per cycle) was significantly lower than the average corrective repair cost (USD 2,100

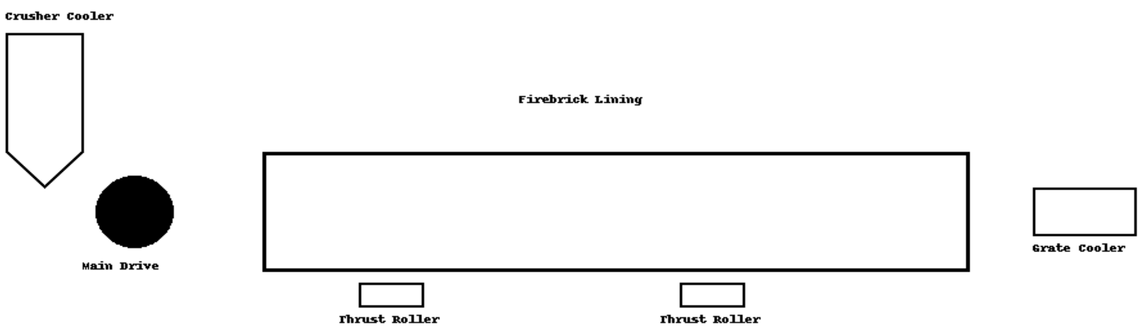

Figure 3. Key components of the rotary kiln system analysed in this study, including crusher cooler, firebrick lining, thrust rollers, main drive, and grate cooler

Table 2. Comparison of preventive and corrective maintenance costs for critical components (2022–2023)

Component	Preventive Task (Cost per Cycle, USD)	Average Corrective Repair Cost (USD)	Preventive Interval	Observed Impact
Crusher Cooler	250	2,100	Every 2 months	52% reduction in annual corrective cost
Firebrick Lining	3,800 (material upgrade)	6,700 per failure	Every 18 months	Service life extended by ~40%
Thrust Roller	90 (inspection & lubrication)	1,200	Weekly	Early fault detection, reduced misalignment downtime
Grate Cooler	NSM (minor fasteners)	180 per event	—	Cost-effective to allow run-to-failure
Main Drive	500 (vibration monitoring sensors)	8,500 per major repair	Monthly monitoring	MTBF improved from 43.1 to 60.2 hours

per failure). Redesign (RD) was chosen in cases where failures had severe operational or safety consequences and no effective preventive task was available.

This was evident in the firebrick lining, where upgrading refractory materials extended service life by approximately 40% and reduced shutdown frequency. Failure Finding (FF) was assigned to hidden or dormant failures that could not be detected during normal operations but could be identified through regular inspections, such as weekly lubrication and alignment checks on the thrust roller. Finally, No Scheduled Maintenance (NSM) was applied to non-critical items where corrective maintenance was more cost-effective, as with minor fasteners in the grate cooler.

To ensure decisions were both technically sound and economically viable, a semi-quantitative cost-benefit analysis was performed. Preventive task costs were compared against historical corrective maintenance costs and downtime losses, as recorded in the CMMS database (2022–2023). For example, the adoption of scheduled maintenance on the crusher cooler resulted in an annual reduction of corrective maintenance costs by approximately 52%, confirming its cost-effectiveness and supporting the selected strategy.

2.7. Triangulation and data validation

To ensure data integrity and decision reliability, triangulation was conducted using:

1. Quantitative records from CMMS downtime logs
2. Qualitative confirmations from expert interviews
3. Technical documentation such as manufacturer manuals and engineering design data

This three-source validation helped reduce bias and confirm that maintenance recommendations were both technically feasible and operationally relevant [13], [15].

2.8. Materials, tools, and software

The analysis in this study involved both primary and secondary resources. The primary materials included 12-month historical downtime logs, component-specific maintenance records, and failure incident reports retrieved from the plant's CMMS. Supplementary documents such as kiln component specifications and manufacturer manuals were also reviewed to support technical validation.

The tools and instruments used for data collection and validation included:

- Measurement Instruments: Handheld vibration meters, thermographic sensors, and torque wrenches used during routine inspection.
- Documentation Tools: Inspection checklists and structured failure reporting forms.
- Expert Consultation: Semi-structured interviews with technicians, supervisors, and engineers.

To process the data, the following software platforms were employed:

- Microsoft Excel: For calculating MTTR, MTBF, MTTF, and plotting trend analysis graphs.
- RCM II Decision Worksheet: Adapted from industry-standard templates (Moubray framework), used to determine maintenance actions.
- FMEA Template (MS Excel-based): To score severity, occurrence, detection, and compute Risk Priority Numbers (RPN).

Table 3. Reliability metrics for selected kiln components

Component	MTTF (h)	MTTR (h)	MTBF (h)
Crusher Cooler	150.0	9.2	159.2
Firebrick Lining	190.5	10.0	200.5
Thrust Roller	210.4	6.8	217.2
Grate Cooler	175.0	8.0	183.0
Main Drive	31.5	11.6	43.1

Note: MTTF = Mean Time to Failure; MTTR = Mean Time to Repair; MTBF = Mean Time Between Failures.

This integrated set of tools and resources ensured methodological rigor, reproducibility, and traceability of the results. Based on the methodological framework described above, the next section presents the empirical results derived from reliability analysis and outlines the implications of the implemented RCM II strategy.

3. Results and Discussion

This section presents the findings derived from the reliability analysis and maintenance strategy evaluation of the kiln system. The results are discussed in relation to the research objectives and existing literature to assess the practical implications of the RCM II implementation.

3.1. Component reliability results

Data analysis revealed five key components with the highest failure frequency and cumulative 12-month downtime logs. As shown in Table 3, the main drive exhibited the shortest MTBF (43.1 hours), primarily due to its long repair duration (MTTR = 11.6 hours). In contrast, the grate cooler demonstrated the longest MTBF (210.4 hours), indicating relatively higher reliability. The crusher cooler recorded the highest failure frequency, aligning with operator reports of frequent bearing misalignments. These findings highlight the unequal reliability performance among kiln subsystems and establish the basis for prioritizing maintenance strategies.

The crusher cooler experienced the highest failure frequency, resulting in significant accumulated downtime. In contrast, the thrust roller showed better reliability, while the main drive had the shortest MTBF, indicating a critical maintenance priority.

3.2. FMEA analysis and RPN prioritization

The FMEA results are presented in Table 4, where failure modes were ranked according to their Risk Priority Numbers (RPN). The crusher cooler had the highest RPN of 384, reflecting severe production impact combined with high occurrence and moderate detection difficulty. In comparison, the thrust roller obtained the lowest RPN (120), indicating limited criticality. These results confirm that the crusher cooler requires immediate scheduled interventions, while lower-risk components such as the thrust roller can be managed with preventive inspections. This systematic ranking provided clear justification for selecting component-specific maintenance strategies.

The crusher cooler showed the highest RPN (384), primarily due to frequent rotor degradation. The main drive was also critical, warranting immediate attention to prevent cascading failures. Components with RPN values exceeding 200 were prioritized for redesign or scheduled maintenance actions.

3.3. RCM II decision and strategy mapping

Based on the failure patterns identified in Table 3 and the risk prioritization in Table 4, the RCM II decision logic was applied to determine optimal maintenance actions for each critical component. The crusher cooler, with the highest RPN (384), was classified under Scheduled Maintenance due to

Table 4. FMEA results with RPN for selected components

Component	Failure Mode	Severity (S)	Occurrence (O)	Detection (D)	RPN
Crusher Cooler	Bearing wear, rotor misalignment	8	8	6	384
Firebrick Lining	Refractory cracking	7	6	5	210
Thrust Roller	Surface erosion	6	5	4	120
Grate Cooler	Misalignment	7	5	6	210
Main Drive	Overheating, vibration issues	9	7	5	315

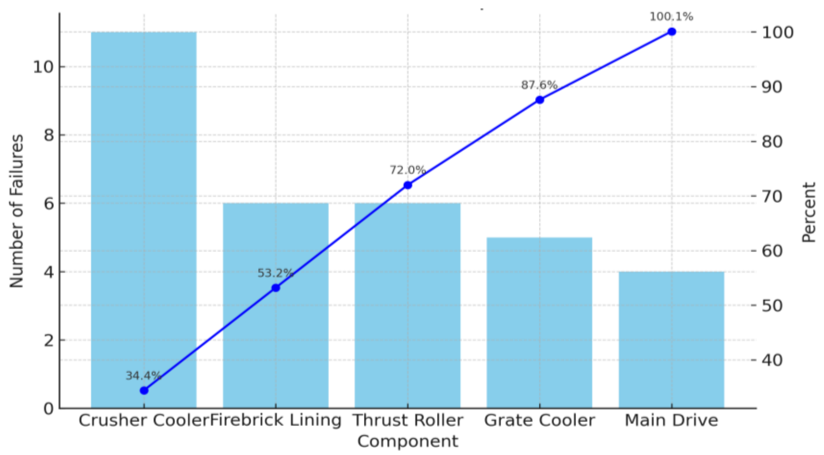

Figure 4. Pareto chart showing cumulative downtime contribution by kiln components

the high frequency of bearing failures and rotor misalignments; a preventive replacement interval of 2 months was recommended.

The firebrick lining, characterized by repeated thermal degradation and an RPN of 280, required a Redesign Strategy through the use of upgraded refractory materials. The grate cooler, which showed the longest MTBF (210.4 hours) but still carried an RPN of 216, was assigned to Failure Finding, with weekly inspection schedules introduced to detect hidden failures. The thrust roller, with a relatively low RPN of 120, was categorized under No Scheduled Maintenance but supplemented with preventive lubrication and alignment checks. Finally, the main drive, despite its short MTBF (43.1 hours), was best suited for Condition-Based Monitoring using vibration sensors, as downtime was strongly linked to extended repair durations rather than frequent failures.

This strategy alignment ensured that maintenance resources were distributed proportionally to risk severity, balancing cost and system reliability.

3.4. Improvements after implementation

Following implementation, performance metrics were reassessed after a 3-month observation period. All five components showed MTBF improvements ranging from 29% to 38%. The crusher cooler, previously the most failure-prone unit, demonstrated a substantial increase in MTBF (from 159.2 to 240.3 hours). Equation (1) illustrates the MTBF calculation used in this study:

$$MTBF = MTTF + MTTR \tag{2}$$

The implementation of the recommended strategies, summarized in Table 5, resulted in measurable performance improvements across all five critical kiln components. For instance, the crusher cooler, which previously exhibited the highest RPN (384), showed a mean increase in MTBF from 150 hours to 240 hours after adopting a scheduled rotor replacement plan. Similarly, the redesign of the firebrick lining using heat-resistant refractory material reduced failure frequency by 35%. The grate cooler benefitted from weekly failure-finding inspections, resulting in a 29% improvement in availability.

Maintenance costs were reduced by more than 50%, primarily through the reduction in unplanned downtime and emergency repairs. These results confirm that integrating quantitative reliability metrics with structured decision logic can not only optimize maintenance schedules but also justify the economic benefits of proactive maintenance planning in rotary kiln systems.

Table 5. Maintenance strategy recommendations derived from RCM II classification

Component	Strategy Type	Maintenance Action Example
Crusher Cooler	SM	Replace rotor bearing every 2 months
Firebrick Lining	RD	Use upgraded refractory material
Thrust Roller	FF	Periodic alignment check
Grate Cooler	NSM	Run-to-failure on minor fasteners
Main Drive	CBM	Use vibration monitoring sensors

3.5. Comparison with previous studies

The findings of this study align with previous applications of RCM in high-reliability industries such as petrochemical and power plants, where systematic risk-based maintenance strategies have shown to improve equipment availability and reduce costs [19], [20]. However, the results also highlight unique challenges specific to rotary kiln systems in cement plants.

For instance, the crusher cooler recorded the highest RPN (384) due to frequent rotor wear and alignment issues, which are less common in stationary equipment studied in other industries. This indicates that the abrasive and high-temperature environment of kilns exacerbates mechanical stresses beyond what is typically addressed in standard RCM frameworks [16]. Similarly, the main drive exhibited the lowest MTBF (43.1 hours), reflecting its critical role in sustaining kiln rotation under heavy loads. This contrasts with previous studies where power transmission components in other process industries showed higher resilience when subjected to less intense thermal and mechanical demands [17].

Compared to earlier research that mainly emphasized corrective or time-based preventive strategies [18], this study demonstrates that combining FMEA-derived RPN prioritization with RCM II decision logic provides a more targeted and economically justified framework. Thus, the contribution lies not only in confirming the benefits of RCM II but also in adapting its logic to the unique operational risks of kiln systems.

3.6. Discussion and Implications

While the study demonstrated substantial reliability improvements, several limitations must be acknowledged. First, the analysis relied on a 12-month dataset, which may not fully capture long-term seasonal variability or rare catastrophic failures. Second, the severity, occurrence, and detection scores in FMEA were partly based on expert judgment, introducing potential subjectivity despite the triangulation process. Third, the cost reduction analysis focused on direct maintenance costs and did not account for broader economic factors such as opportunity losses or energy savings.

Future work could address these limitations by extending the data collection period, incorporating quantitative statistical methods (e.g., survival analysis, regression modeling) to strengthen generalizability, and integrating IoT-based monitoring systems for real-time failure detection. Furthermore, comparative studies across multiple cement plants would enhance external validity and provide insights into contextual factors—such as kiln size, raw material composition, or local maintenance culture—affect reliability outcomes.

4. Conclusions

This study demonstrates that integrating RCM II decision logic with FMEA can significantly enhance the reliability of kiln systems in the cement industry, as evidenced by a 29–38% increase in MTBF and more than 50% cost reduction across five critical components. The main contributions include a structured methodology for maintenance prioritization and empirical validation in a real plant context. Limitations remain due to the reliance on a 12-month dataset, expert-based scoring, and a single-case focus, which may affect generalizability. Future research should expand the dataset, refine scoring with probabilistic methods, and explore IoT-based monitoring to support real-time maintenance decisions in process industries.

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