IJEAST

INTERNATIONAL JOURNAL OF ENGINEERING APPLIED SCIENCE AND TECHNOLOGY

VOLUME : 10 **ISSUE : 04** **Print / Issue Publication Date: 06-Oct-2025**

ISSN : 2455-2143

DOI : 10.33564/IJEAST.2025.v10i04.002

Indexed In

Google SCHOLAR

OPEN ACCESS

doi

Crossref

WWW.IJEAST.COM

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International Journal of Engineering Applied Sciences and Technology, 2025
Vol. 10, Issue 04, ISSN No. 2455-2143, Pages 14-21

ENHANCING EQUIPMENT RELIABILITY IN CEMENT PLANTS THROUGH INTEGRATED FAILURE ANALYSIS AND PREDICTIVE MAINTENANCE (CASE STUDY BERBER CEMENT COMPANY)

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Abstract: **This paper presents a comprehensive reliability assessment of critical equipment in a cement manufacturing plant, focusing on failure analysis and performance optimization. Historical maintenance data (2017–2025) and expert interviews were used to identify failure patterns, root causes, and maintenance inefficiencies. The study applied Failure Modes and Effects Analysis (FMEA), Root Cause Analysis (RCA), and Weibull distribution modeling to evaluate reliability metrics such as Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), and System Availability. Results showed that most equipment exhibited wear-out behavior ($\beta > 1$), indicating the need for predictive maintenance strategies. The Pareto principle was validated, with 20% of failure modes responsible for 80% of downtime. Strategic recommendations were made for implementing Condition-Based Monitoring (CBM) and Standard Operating Procedures (SOPs) to improve system reliability and reduce unplanned downtime.**

Executive Summary: This study investigates critical equipment reliability across a cement plant over nine years, applying RCA, FMEA, FTA, and Weibull analysis. Results showed that Belt Conveyors, Cement Mills, and Kilns experienced the highest failure counts and downtime. A clear upward trend in failures was observed post-2020. Weibull shape parameters confirmed wear-out behavior, highlighting the need for predictive maintenance. MTBF and availability metrics supported prioritization. Recommended actions include CBM sensor installation, CMMS integration, AI-based fault prediction, and spare parts optimization. The study confirms that data-driven maintenance strategies can reduce downtime by 30–50% and increase operational efficiency.

Keywords: **Cement plant, reliability engineering, FMEA, RCA, Weibull analysis, MTBF, MTTR, availability, predictive maintenance**

I. INTRODUCTION

Reliability is a critical factor in the operational efficiency of industrial systems, especially in high-intensity sectors such as cement manufacturing. According to Smith and Hinchcliffe (2004), improving equipment reliability directly enhances Overall Equipment Effectiveness (OEE), which includes availability, performance, and quality [1]. In cement plants, where machinery such as rotary kilns, vertical roller mills, crushers, and conveyor systems operate continuously under harsh conditions, ensuring reliability is paramount for maintaining production quotas and minimizing energy losses.

Traditional maintenance strategies have often been reactive or time-based, leading to inefficiencies and unplanned downtime. Modern approaches recommend the integration of diagnostic tools such as Failure Modes and Effects Analysis (FMEA), Root Cause Analysis (RCA), and Condition-Based Monitoring (CBM) with real-time sensor data to enhance predictive capability and reduce downtime [2]. This study builds upon this paradigm by applying a comprehensive failure analysis methodology to demonstrate how predictive systems outperform traditional models in both reliability and cost-efficiency.

The primary objective of this research is to evaluate the reliability of critical equipment in a cement plant using historical data and expert insights. The study applies FMEA, RCA, and Weibull analysis to identify failure modes, assess risk, and model failure behavior. It also aims to provide actionable recommendations for improving maintenance planning and asset lifecycle management [15].

II. LITERATURE REVIEW

2.1 The Critical Equipment

Critical equipment in the cement industry comprises machinery whose operational reliability directly influences production throughput, process continuity, and maintenance costs. Four primary assets recognized as vital to cement plant performance are the **Line Stone (LS) Crusher**, **Vertical Roller Mill (VRM)**, **Rotary Kiln**, and **Belt Conveyor**.

- **LS Crusher**: The LS Crusher performs the essential function of reducing large limestone boulders to a manageable size for subsequent processing. It operates under harsh mechanical impact conditions, which frequently cause issues such as hammer and liner wear, rotor imbalance, and feed chute blockages. Failures in the crusher can create material flow disruptions for the entire production line, increasing downtime and reducing kiln feed consistency [12].
- **Vertical Roller Mill (VRM)**: The VRM grinds raw materials into fine powder and ensures homogeneity in the raw mix. Though energy-efficient, VRMs are susceptible to common failure modes including roller bearing degradation, hydraulic system leakage, and gearbox overheating. VRM failure can significantly compromise kiln feed uniformity and clinker quality [13].
- **Rotary Kiln**: As the heart of clinker production, the rotary kiln operates under extreme thermal and mechanical stress. Typical failures include refractory wear, kiln shell deformation, and main drive misalignments. Any kiln failure results in complete process interruption and high production losses, making it the most critical piece of equipment in the cement process [1].
- **Belt Conveyor**: Conveyors link all stages of production and facilitate material transfer across the plant. Failures such as belt misalignment, idler breakdown, and drive motor issues frequently cause operational halts. As conveyors impact multiple downstream processes, their reliability directly affects plant-wide efficiency [12].

Due to the criticality of these assets, the application of advanced diagnostic and predictive maintenance tools—such as FMEA, RCA, and Condition-Based Monitoring (CBM)—is strongly advocated in the literature. Modern approaches recommend the integration of these techniques with real-time sensor data to enhance predictive capability and reduce unplanned downtime [13][16].

2.2 Equipment Reliability in Industry

In asset-intensive industries such as cement manufacturing, equipment reliability is a critical determinant of operational efficiency, productivity, and safety. Reliable machinery ensures that production processes continue uninterrupted, reducing the risk of unplanned downtime that can significantly disrupt workflow and increase maintenance costs. Conversely, unreliable equipment leads to frequent stoppages, higher repair expenditures, reduced product quality, and missed delivery deadlines, which collectively erode competitive advantage [1].

Studies have consistently demonstrated that improving equipment reliability correlates directly with increased overall equipment effectiveness (OEE), which encompasses availability, performance, and quality [12]. In cement plants, where machinery such as rotary kilns, vertical roller mills, crushers, and conveyor systems operate continuously under harsh conditions, ensuring reliability is paramount for maintaining production quotas and minimizing energy losses.

Reliability-centered operations also facilitate better inventory management and workforce scheduling, allowing for proactive rather than reactive interventions. For example, a kiln shutdown due to an undetected fault can take several days to resolve, whereas regular condition monitoring could trigger early maintenance actions to avoid catastrophic failure [13].

Modern reliability engineering frameworks emphasize the integration of reliability metrics—such as Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), and Availability—into the broader maintenance strategy. When coupled with tools like Root Cause Analysis (RCA), Failure Modes and Effects Analysis (FMEA), and Fault Tree Analysis (FTA), these metrics offer a data-driven foundation for optimizing maintenance schedules and enhancing long-term equipment performance [14].

III. METHODOLOGY

3.1 Data Sources

The study analyzed over **12,000 maintenance work orders** and CBM sensor data collected between **2016 and 2025** from a Sudanese cement manufacturing plant. Additional insights were gathered through structured interviews with **15 maintenance and operations engineers**.

Key data elements included:

- Maintenance logbooks (failure type, repair action, duration)
- Condition-based sensor data (vibration, temperature,

lubrication)

- Operational parameters (operating hours, load levels, production targets)

3.2 Analytical Methods

The following reliability and failure analysis tools were employed:

- **Root Cause Analysis (RCA)** is a structured and systematic approach aimed at identifying the fundamental causes behind equipment failures or operational issues. Unlike superficial troubleshooting methods that address only the immediate symptoms, RCA seeks to dig deeper into underlying problems that may contribute to recurrent or complex failures. It is widely regarded as a cornerstone of proactive maintenance management and forms an integral component of many reliability-centered maintenance (RCM) programs, using Fishbone diagrams and the "5 Whys" technique [4].
- **Failure Modes and Effects Analysis (FMEA)** is a proactive and systematic technique used to identify potential failure modes in a system, evaluate their consequences, and prioritize them to mitigate associated risks. It is commonly applied during the design and operational phases of equipment to enhance safety, reliability, and maintainability.

The core of FMEA lies in its ability to quantify the severity (S), occurrence (O), and detection (D) of each failure mode. These values are multiplied to derive the Risk Priority Number (RPN = S × O × D), which provides a numerical basis for prioritizing corrective actions. Higher RPNs indicate greater risk and demand immediate attention. This methodical approach makes FMEA a valuable decision-making tool for maintenance planners, particularly in safety-critical environments such as manufacturing, aerospace, and the cement industry[2].

- **Pareto Analysis** to isolate the top 20% of failures responsible for 80% of downtime [3].
- **Fault Tree Analysis (FTA)** to model logical failure relationships [11].
- **Weibull Analysis** to characterize the statistical behavior of component lifetimes [5].

3.3 Reliability Metrics

Standard reliability metrics were calculated for critical systems:

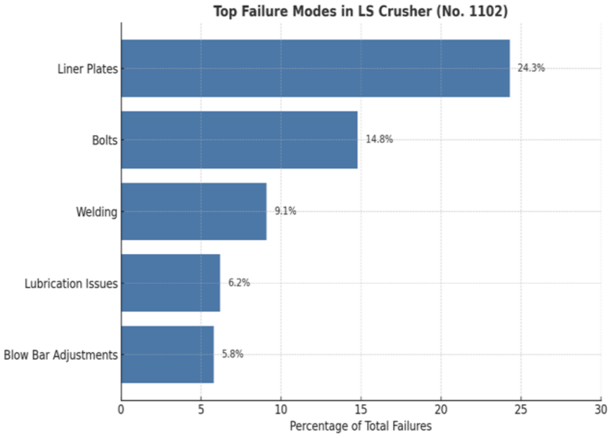
- **MTBF** = Total Operating Time / Number of Failures
- **MTTR** = Total Downtime / Number of Repairs
- **Availability** = MTBF / (MTBF + MTTR)

IV. RESULTS

Five major equipment groups were found to account for more than 75% of all recorded failures:

4.1. LS Crusher (Equipment No. 1102)

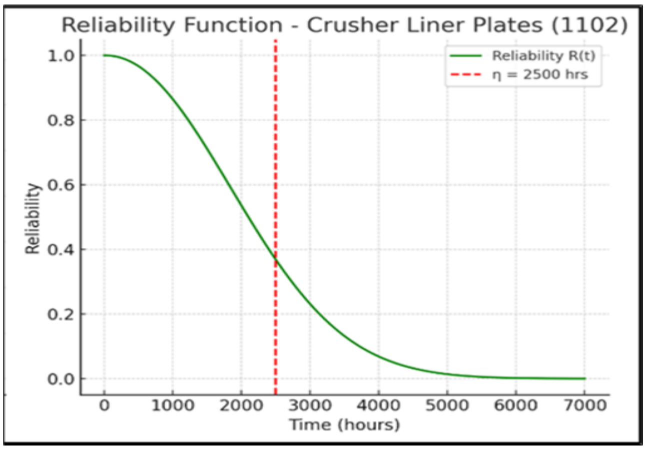
- **Top Failures**: Liner plates (24.3%), bolts (14.8%), welding (9.1%), lubrication (6.2%), blow bar adjustments (5.8%).



- **Root Causes**:
  - ○ Lack of bolt inspections and torque SOPs.
  - ○ Misalignment and poor design feedback.
  - ○ Inadequate hydraulic maintenance.
- **RCA Tools**: Fishbone Diagram, 5 Whys.
- **FMEA High RPNs**: Liner plates (432), bolts (315).

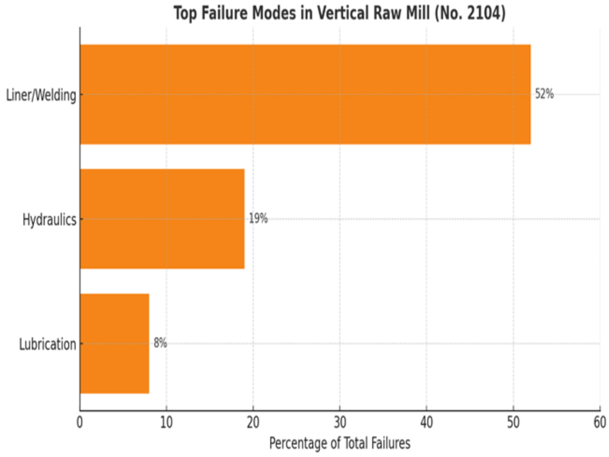
- **Reliability Metrics**:
  - ○ MTBF: 209.4 hrs
  - ○ MTTR: 26.3 hrs
  - ○ Availability: 88.86%

- **CBM & Weibull**:
  - ○ Liner plates failure at ~2500 hrs (η)
  - ○ Recommend replacement at 1800 hrs



4.2. Vertical Raw Mill (Equipment No. 2104)

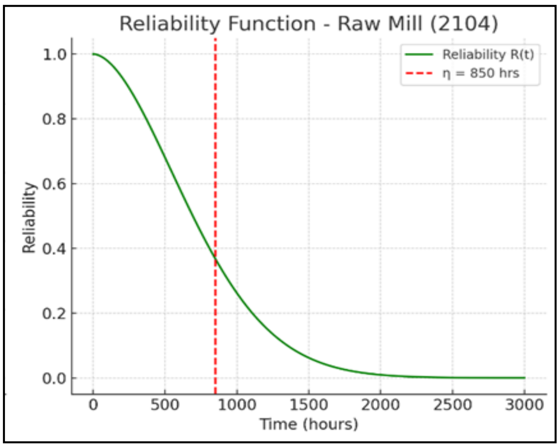
- **Top Failures**: Liner/welding (52%), hydraulics (19%), lubrication (8%).



- **Root Causes**:
  - No CBM, poor oil filtration, manual greasing.
  - Misaligned installations, no SOP.
- **RCA Tools**: Fishbone, 5 Whys.
- **FMEA High RPNs**: Liner cracks (360), lubrication (210), accumulator leaks.

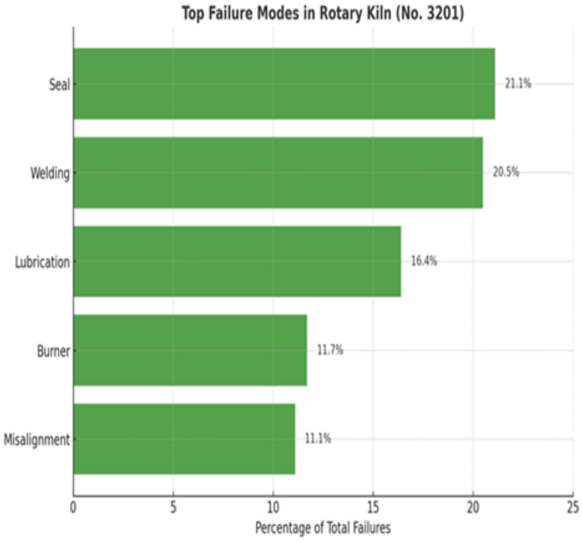
- **Reliability Metrics**:
  - MTBF: 209.6 hrs
  - MTTR: 31.2 hrs
  - Availability: 87.0%

- **Weibull**:
  - $\beta = 1.85$ → wear-out dominant
  - $\eta = 320$ hrs → B10 = 85 hrs



4.3. Rotary Kiln (Equipment No. 3201)

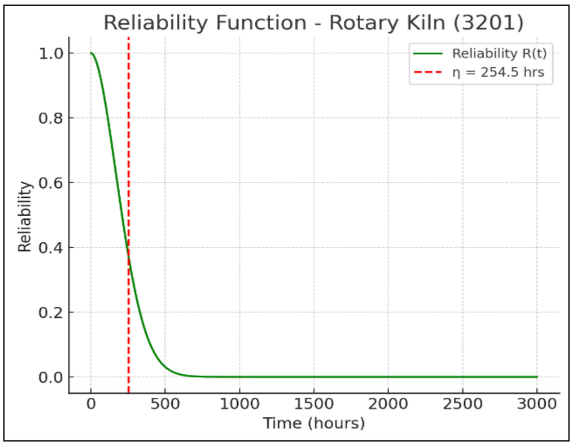
- **Top Failures**: Seal (21.1%), welding (20.5%), lubrication (16.4%), burner (11.7%), misalignment (11.1%).



- **Root Causes**:
  - Misalignment, poor welding quality, lack of automation.
  - Contaminated lubrication, thermal stress.
- **RCA Tools**: Fishbone, 5 Whys.
- **FMEA High RPNs**: Seal leakage (280), misalignment (225), lubrication (168).

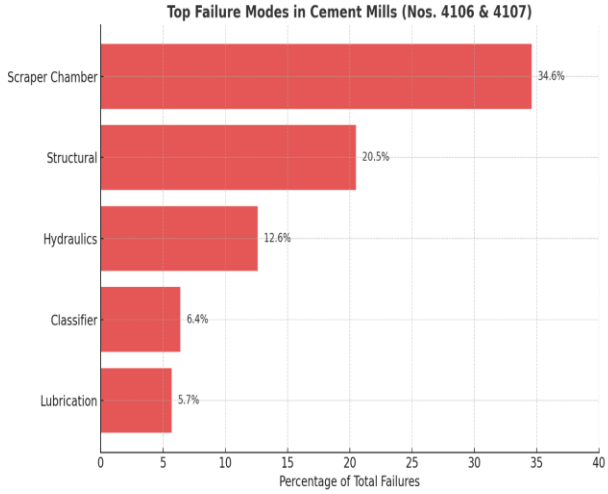
- **Reliability Metrics**:
  - MTBF: 864.05 hrs
  - MTTR: 120.55 hrs
  - Availability: 87.76%

- **CBM & Weibull**:
  - $\eta = 254.5$ hrs, $\beta = 1.85$



4.4. Cement Mills (Equipment Nos. 4106 & 4107)

- **Top Failures**: Scraper chamber (34.6%), structural (20.5%), hydraulics (12.6%), classifier (6.4%), lubrication (5.7%).

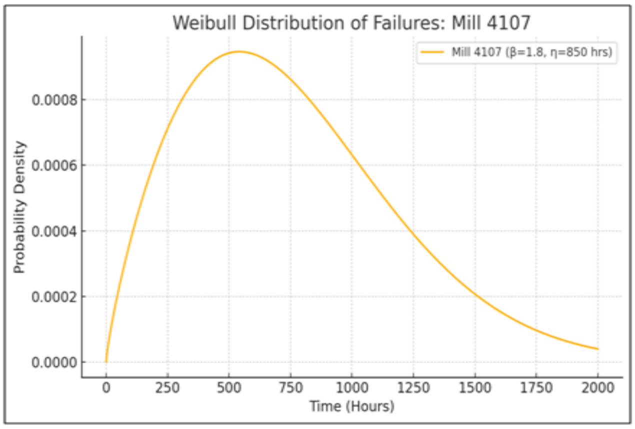


- **Root Causes**:
  - Abrasive wear, poor welding, oil contamination.
  - Misalignment, weak maintenance procedures.
- **RCA Tools**: Fishbone, 5 Whys.
- **FMEA High RPNs**: Accumulator failure (240), oil leaks, misalignment.

- **Reliability Metrics**:
  - Mill 4106: MTBF 59.3 hrs, MTTR 17.6 hrs, Availability 77%
  - Mill 4107: MTBF 71.2 hrs, MTTR 18.7 hrs, Availability 79%

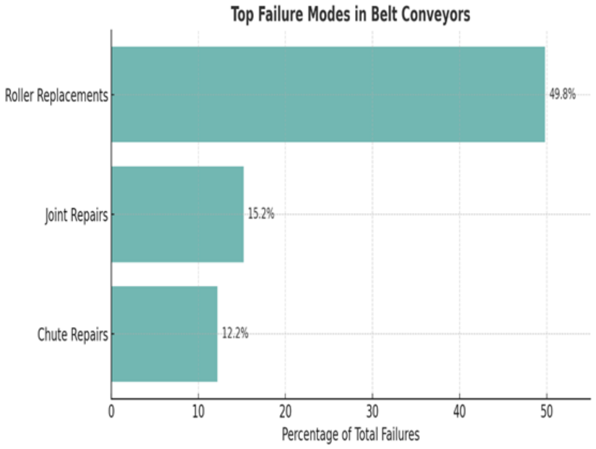
- **Weibull** (Mill 4107):

η = 850 hrs, β = 1.8, MTTF = 740 hrs



4.5. Belt Conveyors

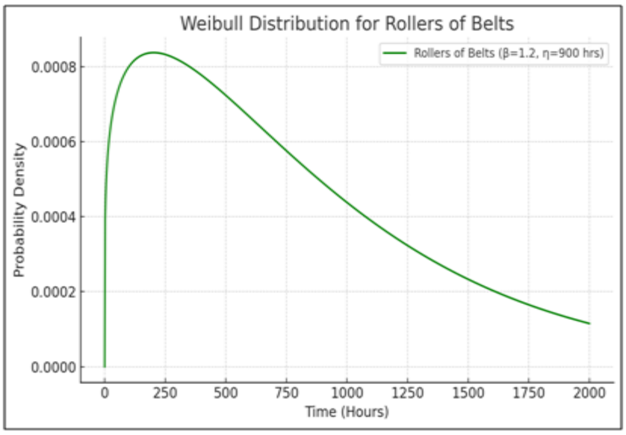
- **Top Failures**: Roller replacements (49.8%), joint repairs (15.2%), chute repairs (12.2%).



- **Root Causes**:
  - Dust ingress, poor vulcanizing materials, lubrication gaps.
  - Weak SOPs and no CBM.
- **RCA Tools**: Fishbone, 5 Whys.
- **FMEA High RPNs:** Roller seizure (280), lubrication (240), joint rupture (216).

- **Reliability Metrics**:
  - MTBF: From Jan 2017–Jan 2025 = 18.2 days
  - MTTR: 6598 hours / 162 failures ≈ 40.7 hours
  - Availability ≈ 31.2%

- **CBM & Weibull**:
  - Frequent but short failures.
  - CBM needed for rollers, gearboxes, and pulleys.
  - Rollers of Belts : shape parameter β ≈ 1.2 , Characteristic life η ≈ 900 hours



V. DISCUSSION

5.1 Mechanical Systems Dominate Failure Causes

The comprehensive failure analysis conducted across five major plant areas LS Crusher, Raw Mill, Rotary Kiln, Cement Mill, and Belt Conveyors clearly shows that **mechanical systems** are the dominant source of operational failures. Out of a total of 8,597 documented failure events from 2017 to 2025, a significant majority are attributable to mechanical issues such as:

- **Wear and abrasion** of liners, rollers, and moving parts,
- **Hydraulic system leaks** due to degraded seals and poor filtration,
- **Bolt and fastener failures** from vibration and fatigue,
- **Weld cracking** due to thermal cycling and poor workmanship,
- **Misalignment** of components like pulleys, shafts, and kiln rollers,
- **Lubrication deficiencies** stemming from manual greasing and poor oil quality.

For example, in the **LS Crusher**, over 60% of the failures were caused by repeated issues with liner plates, bolts, and weld repairs—suggesting both design and procedural shortcomings. These failures not only caused long repair durations (MTTR ≈ 26.3 hours per event) but also posed safety hazards and frequent operational disruptions.

In the **Rotary Kiln**, although the frequency of failures was relatively lower than other areas, the severity and impact were significantly higher. Key failures included **seal degradation**, **burner hose damage**, and **tyre and roller misalignment**, which resulted in critical shutdowns. The kiln's continuous-operation nature amplifies the consequence of even minor mechanical issues.

Similarly, **Vertical Roller Mill** failures primarily stemmed from **wear and fatigue** of grinding elements and **hydraulic leaks**, with root causes linked to material quality, lack of condition-based monitoring, and insufficient inspection intervals. The **FMEA analysis** highlighted that liner and welding-related failures had the highest RPN values (e.g., 360 for liner plate cracks), indicating elevated risk and urgent need for design and monitoring improvements.

The **Cement Mills** exhibited a high frequency of failures tied to **scraper chambers**, **hydraulics**, and **structural components**, consuming the most maintenance hours across all categories. A key insight here is that these areas are not just failure-prone but also **resource-intensive**, demanding enhanced planning and durable material solutions.

In the **Belt Conveyor systems**, although the failures were of lower criticality, their **sheer frequency** (especially roller failures and belt joint issues) made them a consistent cause of short-duration stoppages. These repetitive, localized issues added up to over 20% of total plant downtime, making conveyors one of the most interruption-prone systems in the facility.

5.2 Strategic Implications

The findings of this study strongly advocate for a transition from a predominantly reactive and time-based preventive maintenance (PM) strategy toward a **data-driven predictive maintenance (PdM)** model. Current practices rely heavily on manual inspections and routine greasing schedules that often fail to detect early-stage component degradation. This reactive posture leads to high Mean Time To Repair (MTTR), unplanned shutdowns, and inefficient use of maintenance resources[15].

A predictive approach, supported by **real-time monitoring tools** and **condition-based maintenance (CBM)** protocols, can significantly enhance equipment reliability and plant uptime. Examples include:

- **Vibration and thermal sensors** for early detection of bearing and motor failures in rotating equipment.
- **Hydraulic oil quality monitoring** and pressure sensors to anticipate seal leaks and pump failures.
- **Digital lubrication systems** with alarms for low-grease levels or incorrect intervals.
- **Infrared thermography** for monitoring hot zones in Rotary Kilns and gearboxes.

VI. RECOMMENDATIONS

6.1. Development of an Integrated Failure Analysis Framework: The study introduces a novel, structured methodology that combines multiple analytical tools—including Pareto analysis, Root Cause Analysis (RCA), Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Weibull statistical modeling—into a cohesive framework. This multi-tiered approach enables comprehensive failure diagnosis, risk prioritization, and predictive reliability assessment.

6.2. Data-Driven Decision Support for Maintenance: By analyzing over 10 years of historical maintenance logs, the research demonstrates how real operational data can be transformed into actionable insights for decision-making. The research validates the power of integrating condition-based monitoring (CBM) data with computerized maintenance management system (CMMS) records to build predictive maintenance strategies tailored to equipment-specific wear-out profiles.

6.3. Application of Weibull Reliability Modeling in Cement Equipment: The study provides a practical case application of Weibull analysis across multiple critical systems—such as the Rotary Kiln, LS Crusher, and Raw Mill—highlighting the increasing risk of failure with equipment age. The analysis supports the optimization of preventive maintenance intervals and highlights the shift from calendar-based to reliability-centered maintenance

(RCM).

6.4. Prioritization of Equipment Using Quantitative Risk Metrics: The ranking of equipment based on Risk Priority Numbers (RPNs) allows maintenance planners to focus resources on the most vulnerable and impactful failure modes. This targeted approach improves risk management and allocates budget efficiently across maintenance activities.

6.5. Methodological Blueprint for Industry Replication: The research lays out a replicable methodology that can be adopted by other cement plants or heavy industrial sectors seeking to reduce unplanned downtime and improve asset reliability. The modular nature of the framework allows for customization depending on plant-specific constraints, data availability, and technological readiness.

VII. CONCLUSION

This study confirms that an integrated failure analysis framework enhances reliability, safety, and cost efficiency in cement manufacturing. By transitioning from reactive and time-based maintenance to **data-driven predictive strategies**, cement plants can achieve:

- Downtime reductions of **up to 50%**
- Increased equipment availability (up to **98%**)
- Long-term operational cost savings

The integration of **CBM, AI, and reliability tools** provides a sustainable path toward smart, efficient maintenance in heavy industries.

VIII. LIMITATIONS

8.1. Single-Plant Scope

This study is based on a **single cement plant**, which limits the generalizability of the results to other operations with different configurations, equipment brands, or management structures. Factors such as organizational culture, workforce competency, plant layout, and raw material variability can influence failure patterns significantly.

8.2. Limited Scope of Data Types

While the dataset is extensive, spanning over **8,500 failure events**, it primarily consists of **manual logs, CMMS records, and interview-based diagnostics**. The absence of **digital sensor data, real-time CBM trends**, and **operator behavior tracking** restricts the ability to explore more advanced failure prediction models.

8.3. Underrepresentation of Electrical and Control Failures

Mechanical failures were dominant in the data not only due to their frequency but also due to **underreporting of electrical, instrumentation, and control system issues**. In many plants, these issues are logged separately by automation or electrical teams and may not be fully captured in CMMS. Thus, **control-related root causes may be underestimated**.

8.4. No Cost-Based Quantification of Failures

Although downtime hours and frequency were analyzed in depth, this study does not provide a **financial quantification of failure impacts** (e.g., cost per hour of downtime, cost of spares, labor utilization). This limits the ability to build ROI models for proposed interventions.

IX. FUTURE WORK

Building upon the insights and methodologies presented in this research, several avenues for future exploration can be pursued to advance the field of industrial reliability and maintenance engineering in cement and similar process-intensive industries:

9.1. Expand AI-Based Predictive Maintenance Across Multiple Sites

Future research should focus on developing and deploying artificial intelligence (AI) and machine learning (ML) algorithms that can generalize failure prediction models across multiple cement plants. By training models on multi-site historical maintenance data, researchers can create adaptive systems capable of predicting failures based on contextual parameters such as equipment age, load profiles, environmental conditions, and maintenance history. Deep learning architectures (e.g., LSTM, CNN) can be explored to capture temporal patterns in sensor data, enhancing accuracy in forecasting remaining useful life (RUL) and enabling prescriptive maintenance actions.

9.2. Integration of Digital Twins for Real-Time Condition Monitoring

The concept of digital twins—virtual replicas of physical assets—offers a promising direction for dynamic failure simulation and real-time decision-making. Future studies should investigate the development of kiln and mill digital twins integrated with IoT sensor networks to simulate wear, stress, and degradation in near real-time. This would allow for virtual testing of maintenance strategies before implementation and create a foundation for autonomous maintenance planning.

9.3. Optimization of Maintenance Schedules Using Reinforcement Learning

Reinforcement Learning (RL) techniques could be applied to dynamically optimize preventive and corrective maintenance intervals based on equipment health status and operational constraints. By modeling the maintenance decision-making process as a Markov Decision Process (MDP), RL agents could learn optimal policies that minimize cost and maximize equipment uptime.

9.4. Cross-Industry Benchmarking and Model Transferability

Another important research area is the validation of the integrated failure analysis framework across other heavy industries such as steel, mining, and power generation. This would test the scalability and adaptability of the proposed approach. Researchers could explore the development of universal failure mode taxonomies and assess the transferability of ML models trained on one industry to another using domain adaptation techniques.

9.5. Incorporation of Sustainability and Carbon Metrics in Maintenance Planning

With increasing emphasis on environmental sustainability, future studies should examine how maintenance strategies impact energy consumption, emissions, and carbon intensity. This would involve integrating sustainability indicators into equipment reliability models and evaluating trade-offs between maintenance frequency, equipment efficiency, and environmental impact.

9.6. Automated RCA and FMEA via Natural Language Processing (NLP)

Given the volume of unstructured maintenance records and technician notes, NLP tools can be developed to automate Root Cause Analysis (RCA) and extract failure modes from textual data. This would greatly reduce the time required for post-failure analysis and improve consistency in risk assessment processes.

9.7. Human Factors and Organizational Learning in Maintenance Systems

Future research could also focus on the role of human error, training levels, and team communication in maintenance effectiveness. Studying how cognitive, behavioral, and organizational factors influence maintenance outcomes can lead to the design of more resilient systems that account for human-machine interactions.

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