SUN PUBLISHER
مجلة جامعة صنعاء للعلوم التطبيقية والتكنولوجيا
Sana'a University Journal of Applied Sciences and Technology
https://journals.su.edu.ye/index.php/jast/

Analyzing Maintenance Strategies and Development of a Model for Strategy Formulation – A Case Study of Cement Industry

Hafed Al-Nabhani * and Khalil Al-Hatab

Department of Mechanical Engineering, Faculty of Engineering, Sana'a University, Sana'a, Yemen

*Corresponding author: hafed.alnbhani@gmail.com

Abstract

Effective maintenance strategies are critical for ensuring efficiency, reliability, and sustainability in the cement industry, where equipment downtime significantly affect productivity and costs. This study evaluates existing maintenance practices in Yemeni cement factories and proposes an optimized strategy using the Analytic Hierarchy Process (AHP). A mixed-methods design combined survey data from 118 professionals with case studies from three cement plants. The findings reveal a predominant reliance on Corrective Maintenance (CM) owing to technological and training limitations, while Preventive Maintenance (PM) is inconsistently applied. By contrast, predictive maintenance (PdM) and Proactive Maintenance (PrM), though demonstrably more effective, remain underutilized. The AHP model prioritizes key operational criteria—productivity, cost, reliability, and availability—and identifies PrM as the highest-ranked strategy because of its superior benefits in enhancing reliability and productivity. This research advocates for a phased transition toward PdM/PrM, recommending strategic investments in scalable technologies, such as Internet of Things (IoT)-enabled condition monitoring and Artificial Intelligence (AI)-driven analytics, alongside government-supported training initiatives. By adapting the AHP framework to a conflict-affected setting, this study provides a replicable blueprint for industries in fragile economies. Future research could expand the AHP model to include environmental and social criteria, apply it across other industrial sectors in Yemen, and conduct longitudinal studies to assess the long-term impact of the recommended strategies.

Article Info

Keywords:
Effective Maintenance Strategies , Analytic Hierarchy Process (AHP), Cement Industry, Yemen.

Article History:
Received: 20-August-2025,
Revised: 21-October-2025,
Accepted: 2-November-2025,
Available online: 28 December 2025.

1. INTRODUCTION

In modern industrial landscapes, the evolution from reactive to proactive maintenance has become the cornerstone of operational excellence. Historically, maintenance has been confined to a reactive stance, addressing equipment failures as they occur. However, this approach has proven insufficient for ensuring the long-term reliability and efficiency of complex industrial systems [1]. Today, the focus has shifted to a holistic and proactive paradigm, in which maintenance is a strategic function aimed at sustaining optimal equipment performance and preventing failures before they occur. This is particularly critical in capital-intensive sectors, such as cement manufacturing, where equipment downtime can lead to significant production losses and financial repercussions.

The transition to more advanced maintenance strategies, such as Predictive Maintenance (PdM) and Proactive Maintenance (PrM), has been a subject of extensive research. For instance, PdM leverages condition-monitoring technologies and data analytics to predict potential failures, allowing for timely intervention [2]. PrM goes a step further by focusing on identifying and eliminating the root causes of failure, thereby preventing recurrence [3]. The adoption of these strategies has yielded substantial benefits, including improved equipment reliability, reduced maintenance costs, and enhanced productivity [4]. Complementary methodologies such as Total Productive Maintenance (TPM) and Reliability-Centered

Maintenance (RCM) have also demonstrated success in improving equipment reliability and operational efficiency, particularly in environments where structured maintenance planning is lacking [5–7]. Recent advances in IoT applications and AI-powered predictive analytics have further accelerated the transformation of maintenance practices globally within the cement industry [8, 9].

Despite the clear advantages of proactive and predictive maintenance approaches, their adoption in industrial settings, particularly in developing resource-limited environments, faces persistent barriers. These include limited technical expertise, access to advanced diagnostic technologies, and insufficient financial resources. As noted by Khazraei and Deuse [10], such constraints hinder the broad implementation of advanced maintenance taxonomies, and call for adaptive, strategically informed decision-making frameworks to navigate contextual challenges. Consequently, many industries in these regions continue to rely on traditional Corrective Maintenance (CM) and inconsistently applied Preventive Maintenance (PM), leading to persistent operational inefficiencies and a cycle of recurring failures [5, 7]. For example, empirical evidence from Yemen's industrial sector reveals that poor spare parts planning, a lack of structured training, and inefficient maintenance scheduling contribute significantly to equipment breakdowns and productivity losses [11]. Similarly, cement plants in Libya have reported frequent operational disruptions owing to insufficient awareness and adherence to the best maintenance practices [5, 12].

In light of these challenges, researchers are increasingly turning to Multi-Criteria Decision-Making (MCDM) techniques to guide maintenance strategy selection. Among these, the Analytic Hierarchy Process (AHP), originally developed by Thomas Saaty in 1980, stands out for its ability to handle complex decisions by integrating qualitative and quantitative judgments into a structured framework. [13]. AHP has been successfully applied in various industrial contexts, including cement plants in Nigeria [14] and Kenya [15], to prioritize maintenance strategies based on criteria, such as cost, reliability, and availability.

However, a notable gap exists in applying AHP within the Yemeni cement industry, a sector operating under uniquely difficult conditions marked by economic instability and political conflict that introduce additional layers of complexity and challenges to maintenance efforts [16]. This study aimed to fill this gap by developing a tailored AHP model to identify the optimal maintenance strategy for selected cement plants in Yemen. In doing so, it offers a replicable framework for industries operating in similarly constrained environments, contributing to the broader discourse on sustainable industrial development in fragile economies.

Specifically, this research focuses on three cement plants in Yemen, assessing their current maintenance strategies and formulating an improved approach for more effective maintenance decision-making. The research was guided by the following key sub-objectives:

- To identify and comprehensively analyze the current maintenance strategies employed in selected cement plants.
- To develop a tailored Analytic Hierarchy Process (AHP) model for maintenance strategy formulation specific to the Yemeni context.
- The AHP model was applied to a case study of selected cement plants in Yemen to identify the optimal maintenance strategies.

This study has significant implications for both academic discourse and industrial practices. Within Yemen's cement sector, optimizing maintenance strategies can mitigate losses from equipment downtime and enhance the overall productivity. Practitioners have developed a structured AHP-based framework tailored to challenging industrial settings, effectively bridging the gap between theoretical models and practical implementation. This study demonstrates how adopting effective maintenance approaches can yield tangible benefits, including extended equipment lifespans, reduced costs, and fewer unplanned shutdowns. Beyond the Yemeni context, this study enriches the Multi-Criteria Decision-Making (MCDM) literature by showcasing AHP's adaptability in politically volatile and technologically constrained environments, offering a replicable blueprint for similar industries across developing economies.

2. RESEARCH METHODOLOGY

This study adopted a descriptive methodology within a mixed-methods framework to evaluate and formulate maintenance strategies within the Yemeni cement industry. A case study design, focusing on three strategically selected cement plants (Emran, Bajel, and National Cement Company) was utilized to provide an in-depth contextual understanding of maintenance practices and the unique operational challenges faced by professionals in Yemen.

Data were collected via structured electronic questionnaires administered to a purposive sample of 118 maintenance professionals across three cement plants. This method allowed for the capture of measurable insights into existing practices, perceived strengths, weaknesses, and areas requiring improvement, thereby providing a robust empirical foundation for this study.

To systematically evaluate and prioritize maintenance strategies, Multi-Criteria Decision-Making (MCDM) techniques were incorporated, with a specific focus on the Analytic Hierarchy Process (AHP). AHP was chosen over other MCDM methods because of its proven efficacy in structuring complex, multi-objective problems into a hierarchical framework, its ability to handle both qualitative and quantitative criteria, and its capacity to incorporate subjective expert judgments into a quantitative framework [13, 17]. This makes AHP particularly well-suited for strategy prioritization, where decisions often involve trade-offs between conflicting objectives such as cost, reliability, and availability [14, 15]. The AHP framework in this study considered key operational criteria that are widely recognized in the literature as critical performance indicators for maintenance systems [18].

Data analysis was performed using SPSS version 26, while AHP computations were conducted using Expert Choice software, supported by Excel for initial data structuring. Expert Choice enhanced the precision of pairwise comparisons, consistency checks, and priority weight computations, enabling a seamless transition from raw judgments to actionable decision support outputs.

2.1. Research Design and Data Collection

Questionnaire Design

A structured questionnaire was used as the primary data- collection instrument, supporting the study's mixed-methods framework. This paper is organized into three key sections.

1. Respondent Information: Captured demographic data, job roles, and experience levels of participants, offering a broad view of maintenance operations across different organizational roles.
2. Maintenance Strategies: Assessed perceptions of the strengths and weaknesses of existing maintenance practices, alongside challenges encountered in improving them.
3. Maintenance strategy formulation: Evaluate maintenance decision-making criteria and strategic alternatives by collecting individual importance ratings from participants using Saaty's 1–9 scale [13]. Instead of conducting direct pairwise comparisons, the participants rated each criterion independently, followed by rating the relative importance of each maintenance strategy with respect to each criterion. These individual ratings were then averaged across the sample to construct composite pairwise comparison matrices, which formed the basis of the AHP model [19, 20]. This method enables the synthesis of structured judgments from a diverse respondent pool, ensuring both methodological rigor and practical relevance.

Additionally, the questionnaire included a cover letter explaining the significance and purpose of the study. To ensure clarity, validity, and usability, the instrument was reviewed by two professors specializing in Mechanical Engineering at Sana'a University. It was then pilot tested with a sample of maintenance professionals, leading to minor refinements based on their feedback. The instrument reliability was statistically verified, achieving a Cronbach's alpha score of 0.92, which exceeded the standard threshold of 0.70, indicating high internal consistency.

Sampling Method

A purposive sampling strategy was employed to target individuals with direct experience in maintenance decision -making within Yemen's cement industry. The total population across the three selected plants was approximately 150 maintenance staff members, with approximately 50 employees at each site. The required sample size was determined using Krejcie and Morgan's table [21], which recommends a minimum of 108 participants for a population of 150 at a 95% confidence level and 5% margin of error. To enhance the response quality and ensure broad representation, 150 electronic questionnaires were distributed via secure social networking platforms to maintenance managers, engineers, and technicians. In total, 120 responses were received, resulting in an 80% response rate. After a quality check, 118 questionnaires were deemed valid for analysis; two responses were excluded because of incompleteness or lack of relevant experience.

Case Study Selection

This study examines maintenance practices in Yemen's cement industry through an in-depth analysis of three major cement plants strategically selected to reflect a diverse range of operational environments and ownership structures.

1. Emran Cement Plant (government-owned): A large facility with an annual production capacity of 1.5 million tons. It faces ongoing challenges, including resource limitations and production inefficiencies, offering a representative context for examining maintenance strategies within publicly managed industrial operations.
2. Bajel Cement Plant (government-owned): An older plant with a production capacity of 700,000 tons per year. It struggles with the aging infrastructure and operational constraints, making it a valuable case for evaluating maintenance adaptations in legacy facilities.
3. National Cement Company (private sector): A technologically advanced plant with a design capacity of 2.7 million tons per year. Despite its modern infrastructure, it encounters resource-related challenges, enabling comparative insights into how maintenance strategies differ across public and private sector settings.

This purposeful selection ensures broad representation across organizational types, technical conditions, and operational scales, supporting a comprehensive analysis relevant to Yemen's cement sector.

2.2. AHP Process for Evaluating Maintenance Strategies

The AHP method was applied to prioritize strategic maintenance approaches across the selected cement plants.

The step-by-step procedure for constructing and evaluating the AHP framework is outlined as follows.:

1. **Hierarchical Structuring**: A three-level hierarchy was constructed with the overall goal at the top, four criteria at the second level, and four maintenance strategy alternatives at the bottom level:
   - **Goal Definition:** The primary objective was to identify the most effective maintenance strategy tailored to the operational needs of the Yemeni plants.
   - **Criteria Identification:** Four key evaluation criteria—Productivity, Cost, Reliability, and Availability—were selected based on industry best practices, expert input from plant managers, and a review of the relevant literature. No sub-criteria were included, maintaining a balance between simplicity and practicality.
   - **Alternatives Identification:** Four maintenance strategies were evaluated based in their perceived performance under each criterion: Corrective Maintenance (CM), Preventive Maintenance (PM), Predictive Maintenance (PdM), and Proactive Maintenance (PrM).

   These criteria represent core operational dimensions that influence maintenance effectiveness, whereas the alternatives reflect widely adopted industrial practices. The hierarchical structure supports transparent and systematic prioritization, facilitating informed strategic planning. Figure 1 illustrates the structure of the AHP model, including goals, criteria, and alternatives.

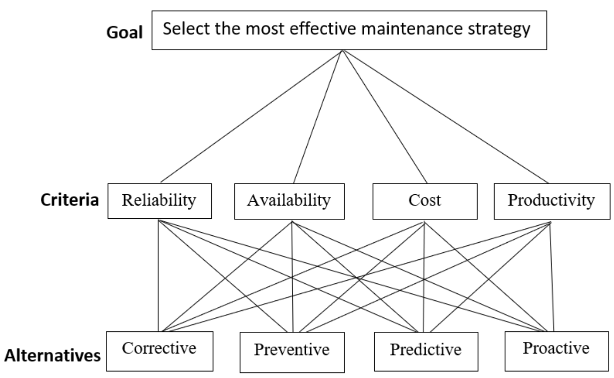

Figure 1. AHP Model for Maintenance Strategy prioritization

2. **Pairwise Comparisons:** Pairwise comparison is a core component of AHP that enables the structured evaluation of decision criteria and alternatives. In this study, the participants provided independent importance ratings for each criterion using Saaty's 1–9 scale, as presented in Table 1. These individual ratings were statistically aggregated to estimate the relative ratios among the criteria, which were then used to construct the pairwise comparison matrices required by the AHP methodology.
   Each maintenance strategy was appraised under each criterion using priority scores derived from the participant evaluations. These scores represent the perceived effectiveness of each alternative with respect to specific criteria, facilitating quantitative comparisons and hierarchical synthesis within the AHP framework.

Table 1. Nine-point scale of relative importance

Intensity of Importance	Definition
1	Equal Importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2, 4, 6, 8	For compromises between the above in comparing elements i and j
Reciprocals of above	- If i is 3 compared to J - Then j is 1/3 compared to i

3. **Weight Calculation:** Priority weights were computed by normalizing the pairwise comparison matrices and averaging the resulting row values. To assess the internal consistency of judgments, the Consistency Index (CI) and Consistency Ratio (CR) were calculated using the following formulae:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (1)$$

$$CR = \frac{CI}{RI} \quad (2)$$

   where $\lambda_{\max}$ is the largest eigenvalue of the comparison matrix, *n* is the number of elements being compared, and RI is the Random Consistency Index corresponding to the matrix size, as defined by Saaty [13] and presented in Table 2. A *CR* value below 0.10 is generally considered acceptable.

Table 2. Random consistence index (RI) for different matrix orders

Matrix size	1	2	3	4	5	6	7	8
Random consistence index (RI)	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41

4. **Aggregation and Ranking**: Final rankings of the maintenance strategies were determined using an additive aggregation method, consistent with Saaty's AHP framework [13]. The overall weighted score for each alternative is calculated as follows:

$$W_{A_i} = \sum_{j=1}^{n} \left(W_j \times W_{A_{i,j}} \right) \quad (3)$$

where n is the number of criteria, W_j is the normalized weight of criterion j, and $W_{A_{i,j}}$ is the normalized priority score of alternative i under criterion j. This method ensures that the final scores reflect a weighted synthesis of all the criteria according to their relative importance. The alternative with the highest composite score is identified as the most suitable maintenance strategy.

3. RESULTS AND DISCUSSIONS

This section presents the results of the data analysis, beginning with a demographic overview of the survey respondents, followed by an examination of the current maintenance practices, their strengths and weaknesses, challenges to their improvement, statistical inferences, and correlation analyses. The section concludes with the findings of the AHP model, which identifies the optimal maintenance strategy for the selected cement plants.

3.1. Participants Demographics

The demographic distribution of the respondents was examined in terms of job roles and experience levels within the maintenance departments of the selected cement plants. This profile analysis provided an essential context for understanding participants' perspectives on maintenance strategies in the Yemeni cement sector.

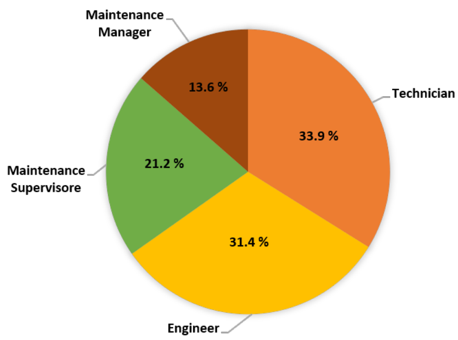

Figure 2. Role in the maintenance Department

Figure 2 illustrates the analysis of participants' specialization (role). The largest group of respondents were technicians (33.9%), followed closely by engineers (31.4%), Maintenance Supervisors (21.2%), and Maintenance Managers (13.6%). This diverse representation of roles ensures that the study captures both operational and managerial insights, and provide a comprehensive evaluation of maintenance strategies from various hierarchical levels. The participation of senior professionals (Maintenance Supervisors and Managers) further reinforces the credibility of the study's findings as they are directly involved in decision-making and strategy implementation.

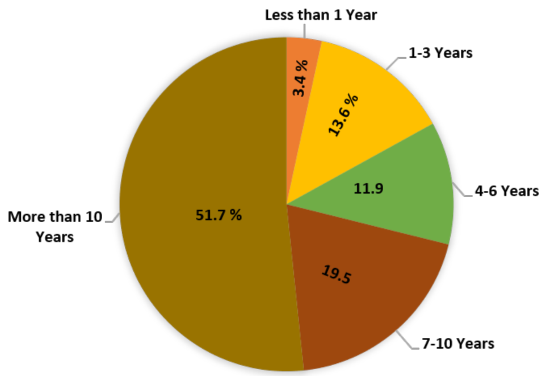

Figure 3. Experience in the maintenance Department

Figure 3 illustrates the analysis of respondents' experience. A significant majority (51.7%) of respondents possessed more than 10 years of maintenance experience, offering in-depth insights into long-term maintenance challenges and best practices. This group was followed by those with 7-10 years of experience (19.5%), representing a strong cohort of mid-career professionals with valuable hands-on expertise. Other experience groups include 4-6 years (11.9%) and 1-3 years (13.6%)of experience. A small percentage (3.4%) had less than one year of experience, providing a fresh perspective on emerging trends and initial challenges. The high level of expertise among respondents indicates that the data collected are reliable and credible, as participants possess direct and extensive experience in maintenance decision-making.

3.2. Current Maintenance Practices and Their Strengths and Weaknesses

Table 3 presents a descriptive analysis of the maintenance strategies currently being implemented in the Yemeni cement industry. The findings revealed a strong reliance on reactive approaches, with CM being the most extensively adopted strategy (mean = 0.678). This aligns with previous research in similar contexts, such as Albarkoly and Park's [5] study of the Libyan cement industry, which also reported heavy dependence on CM. The prevalence of CM is often attributed to its operational simplicity, although it typically leads to increased downtime and higher long-term costs, as highlighted by Graisa and Al-Habaibeh [6]. PM is also widely used (mean = 0.763); however, its effectiveness is often undermined by inconsistent implementation. Albarkoly [7] warned that without a structured approach, PM can become a routine expense rather than a value-adding activity. In contrast, advanced strategies, such as PdM and PrM, are significantly underutilized (means of 0.246 and 0.322, respectively). This underutilization reflects common technological and resource constraints in developing countries, a trend also noted by Graisa [12], who highlighted the barriers faced by developing economies in accessing the technologies required for PdM and PrM. To bridge this gap, Mahmud et al. [14] recommended the use of strategic decision tools such as the Analytic Hierarchy Process (AHP) to guide cement plants in selecting optimal maintenance approaches and reducing their reliance on CM.

Table 3. Current maintenance strategies and their strengths and weaknesses

Information	N	Mean	Std. Deviation
Current Maintenance Strategies			
Corrective Maintenance	118	0.678	0.469
Preventive Maintenance	118	0.763	0.427
Predictive Maintenance	118	0.246	0.432
Proactive Maintenance	118	0.322	0.469
Strengths of Current Maintenance Strategies			
Improved equipment reliability	118	0.636	0.483
Reduced maintenance costs	118	0.525	0.502
Improved equipment availability	118	0.297	0.459
Enhanced productivity	118	0.297	0.459
Other ,Enhanced safety of equipment	118	0.085	0.280
Weaknesses of Current Maintenance Strategies			
Frequent failures and unplanned downtimes	118	0.576	0.496
Lack of proactive approach to address root causes of failures	118	0.568	0.498
High maintenance costs	118	0.195	0.398
Insufficient equipment reliability and availability	118	0.170	0.377
Other, Lack of spare parts	118	0.093	0.292
Valid N (listwise)	118		

Strengths and Weaknesses of Current Maintenance Strategies: Despite their limitations, current maintenance strategies offer some benefits, as shown in Table 3. "Improved Reliability" was the most frequently cited strength (mean = 0.636), a finding that aligns with the studies by Muinde et al. [15] and Galankashi et al. [22], who attribute reliability gains to a balanced application of PM and CM. Basri et al. [23] further emphasized that disciplined PM planning is crucial for enhancing reliability. "Reduced Maintenance Costs" (mean = 0.525) was another notable benefit, as effective PM can decrease the frequency of costly corrective interventions. However, improvements in equipment availability and productivity were minimal (mean = 0.297) and safety enhancements were rarely noted (mean = 0.085). This lack of focus on safety is a significant concern, as Nedzanani et al. [24] argued that a strong safety culture must be integral to any maintenance strategy, particularly in high-risk industries.

On the downside, Table 3 shows that the most critical weaknesses identified were frequent failures and unplanned downtimes" (mean = 0.576). This is a common issue in industries that rely heavily on CM, as documented by Mungani and Visser , and Silva et al. [25]. Anaba et al. [26] linked CM to schedule disruptions and inflated costs. The "lack of a proactive approach" (mean = 0.568) further compounded this inefficiency. Tinga et al. [27] stressed that a dynamic PrM mindset is essential for eliminating recurring equipment failure. Other weaknesses, such as the hidden costs of CM (e.g., collateral damage and overtime), were less frequently cited (mean = 0.195) but have been extensively documented by Abdelhadi et al. [28]. Finally, poor spare parts management, reflected in a low score for this item (mean = 0.093), was identified as another factor that can exacerbate downtime and inefficiency, a point also reported by Shafeek [29].

These findings underscore the urgent need for a strategic shift from reactive maintenance to proactive maintenance. This transition requires the adoption of structured decision-making tools and modern technologies to improve the reliability, cost efficiency, and overall productivity.

3.3. Challenges for Improving Maintenance Strategies

Table 4 summarizes the key challenges faced by the Yemeni cement plants in their efforts to improve maintenance strategies.

Table 4. Challenges for improving maintenance strategies

Challenges	N	Mean	Std. Deviation
Lack of training courses for different maintenance strategies	118	0.585	0.495
Limited data availability and historical record	118	0.322	0.469
Lack of a structured evaluation methodology	118	0.305	0.462
Limited Technological Resources	118	0.314	0.466
Resistance to changing current practices	118	0.254	0.437
Lack of coordination between crews	118	0.059	0.237
Valid N (listwise)	118		

The most significant obstacle was the "lack of training (mean = 0.585). This finding is consistent with research by Khazraei and Deuse [10] and Kaur [2], who argued that successful maintenance transformation is heavily dependent on comprehensive training for personnel. Other significant challenges include "limited data availability and historical records" (mean = 0.322), which,

Table 5. T-Test Results for maintenance strategy effectiveness

Comparison	t-value	P-value	Significance	Cohen's d
Experience (7-10 years vs. > 10 years)	0.137	0.891	Not significant	0.025
Role (Technicians vs. Managers)	-0.496	0.622	Not significant	0.091

as Koochaki et al. [30] note, hinders the implementation of condition-based diagnostics. Ding and Kamaruddin [31] further suggested that digitalizing maintenance records is essential for improving the predictive accuracy. The "absence of a structured evaluation methodology" (mean = 0.305) also undermines performance measurement. Conklin et al. [32] emphasize the importance of strategic metrics for evaluating the return on investment in maintenance initiatives. Similarly, Ahmadi et al. [33] advocated the use of KPI-based assessments to support continuous improvement.

Access to technology (mean = 0.314) remains a persistent issue, with Gedikli and Ervural [17] arguing that limited investment in modern diagnostic tools impedes progress. "Resistance to change" (mean = 0.254), though less pronounced, can still stall innovation. Braglia et al. [34] suggested that piloting small-scale success stories can help shift the organizational culture, while Barringer [35] emphasized the importance of cultivating a reliability-engineering mindset. Finally, "lack of coordination between teams" (mean = 0.0593) was identified as a minor but significant barrier. As Barringer [36] explained, fragmented maintenance efforts can reduce operational synergy and compromise strategic alignment.

To overcome these challenges, cement plants should prioritize training, establish structured evaluation frameworks, develop robust data management systems, and strategically invest in advanced maintenance technologies. A structured framework such as AHP can guide organizations in selecting cost-effective reliability-centered maintenance strategies that are tailored to their specific operational constraints.

3.4. Inferential Statistics

To explore variations in the perceptions of maintenance strategy effectiveness, independent samples t-tests and one-way ANOVA were conducted. Prior to analysis, data normality was verified using the Shapiro–Wilk test and Q–Q plots, and variance homogeneity was verified using Levene's test, confirming that parametric assumptions were met.

As shown in Table 5, there was no statistically significant difference in the perceived effectiveness of maintenance strategies between participants with 7–10 years of experience and those with more than 10 years of experience ($t = 0.137$, $p = 0.891$), nor between technicians and managers ($t = -0.496$, $p = 0.622$). This suggests that the perceptions of maintenance effectiveness are largely consistent across different levels of experience and job roles.

Similarly, the one-way ANOVA results in Table 6 show no significant differences in perceptions across all experience levels ($F(4, 113) = 2.453$, $p = 0.050$) or job roles ($F = 0.745$, $p = 0.522$). The consistent perceptions across different professional backgrounds suggest that challenges in maintenance are universally recognized within the industry. This finding reinforces the need for standardized and systematic approaches to maintenance strategy, as recommended by Ding and Kamaruddin [31] in their comprehensive review of maintenance policy optimization.

3.5. Correlation Analysis

Pearson's correlation analysis was conducted to examine the interrelationships between the four main criteria: reliability, availability, cost, and productivity. As shown in Table 7, all criteria were significantly and positively correlated ($p < 0.001$), highlighting their interconnectedness in maintenance decision -making.

The analysis revealed strong positive correlations among the key maintenance performance indicators: reliability and availability ($r = 0.778$), reliability and productivity ($r = 0.591$), availability and productivity ($r = 0.640$), and cost and productivity ($r = 0.680$). These results highlight the interconnected nature of these metrics and their collective impact on the operational performance. As Khati and Singh [18] emphasized, optimizing one aspect, such as availability, can significantly influence cost and productivity, particularly in systems with interdependent failure modes. This reinforces the need for a holistic approach to maintenance that balances competing priorities and underscores the importance of integrated strategies that harmonize reliability, cost, and productivity.

Building on correlation analysis, reliability, availability, cost, and productivity emerge as mutually reinforcing dimensions of effective maintenance management. The strategic prioritization of smart maintenance tools, such as AI-driven analytics and IoT-enabled condition monitoring, can unlock productivity gains and align cement plant operations with broader organizational objectives. These insights echo Nedzanani et al.'s [24] findings, which advocate for DMG-based decision frameworks that favor predictive and proactive maintenance strategies to achieve sustainable long-term performance improvements.

3.6. AHP Model Results

The Analytic Hierarchy Process (AHP) was employed to determine the optimal maintenance strategy by synthesizing participants' judgments on both evaluation criteria

Table 6. ANOVA Results for maintenance strategy effectiveness

Comparison	F-value	P-value	Significance	Eta-squared
Experience (1-3 Years, 4-6 Years, 7-10 years, and more than 10 years)	2.453	0.050	Marginally significant	0.080
Role (Technicians, Engineers, Supervisors, and Managers)	0.745	0.522	Not significant	0.026

Table 7. Pearson's Correlation Matrix Between Main Criteria

Variables	Reliability	Availability	Cost	Productivity
Reliability	1	0.778**	0.541**	0.591**
Availability	0.778**	1	0.552**	0.640**
Cost	0.541**	0.552**	1	0.680**
Productivity	0.591**	0.640**	0.680**	1
**. Correlation is significant at 0.001 level (2-tailed).				

and strategic alternatives.

Priority of Main Criteria: The initial phase of AHP analysis focused on establishing the relative importance of the evaluation criteria. The survey participants independently rated each criterion on a scale of 1-9. Mean scores were then used to construct a pairwise comparison matrix. As shown in Table 8, productivity emerged as the most influential criterion (weight = 0.268), followed closely by cost (0.250), reliability (0.241) and availability (0.241). These weights indicate a relatively balanced distribution of importance, with slight emphasis on operational output and cost-effectiveness.

Table 8. Priority of Each Criterion

Criteria	Mean Rating	Weight
Productivity	9.19	0.268
Cost	5.75	0.250
Reliability	5.56	0.241
Availability	5.55	0.241

Ranking of Maintenance Strategies: In the second phase, participants evaluated the effectiveness of four maintenance strategies—Corrective, Preventive, Predictive, and Proactive—against each criterion using the same 1-9 scale presented in Table 9. The ratings were normalized and weighted using previously established criteria.

Table 9. Criteria Ratings Across Maintenance Strategies

Alternative	Reliability	Availability	Cost	Productivity
Corrective	5.34	5.19	5.49	5.76
Preventive	6.39	6.06	5.97	6.47
Predictive	5.96	5.78	5.56	6.03
Proactive	6.64	6.55	6.46	6.92

The weighted scores were aggregated to determine the overall priority of each strategy, based on the AHP model. As shown in Table 10, PrM achieves the highest score (0.275), followed by PM (0.258), PdM (0.241), and CM (0.226). These results suggest a clear preference for forward-looking maintenance approaches that emphasize prevention and system optimization.

Table 10. Final AHP Weights for Maintenance Strategies

Alternative	Total Score	Ranking
Proactive	0.275	1st
Preventive	0.258	2nd
Predictive	0.241	3rd
Corrective	0.226	4th

Consistency ratios (CR) were calculated for each matrix to validate the reliability of pairwise comparisons. All CR values were significantly below the 0.10 threshold, indicating a high level of consistency in participants' judgments.

Key findings and Implications: The AHP model identified PrM as the optimal strategy, with the highest overall score of 0.275. This result aligns with contemporary maintenance philosophies that prioritize prevention over reaction [18], and supports the work of Tinga et al., who advocate for dynamic, usage-based maintenance approaches [27]. PrM demonstrated superior performance across all evaluation criteria, including reliability (6.64), availability (6.55), cost-effectiveness (6.46), and productivity (6.92), highlighting its potential to address the multifaceted challenges facing the Yemeni cement industry.

The ranking hierarchy (PrM > PM > PdM > CM) provides a clear framework for strategic implementation. The PrM's top ranking reflects its ability to simultaneously enhance reliability, reduce costs, and boost productivity, making it especially valuable in resource-constrained environments. Figure 4 illustrates this prioritization, with Proactive Maintenance emerging as the preferred option. This finding echoes the work of Muinde et al., who emphasized the importance of proactive strategies in cement industrial settings [15]. While their study focused on stable environments, this research confirms PrM's viability in fragile, resource-limited environments such as Yemen, extending its relevance to more challenging industrial contexts. The low ranking of CM (0.226) reinforces the need for a strategic shift away from reactive maintenance practices, as advocated by Nedzanani et al. in their study of maintenance strategy selection [24].

Despite its theoretical advantages, the implementation of PrM in Yemen's cement sector presents significant challenges. These include limited access to advanced technologies (e.g., IoT-enabled monitoring and AI-driven analytics), insufficient staff training, and weak

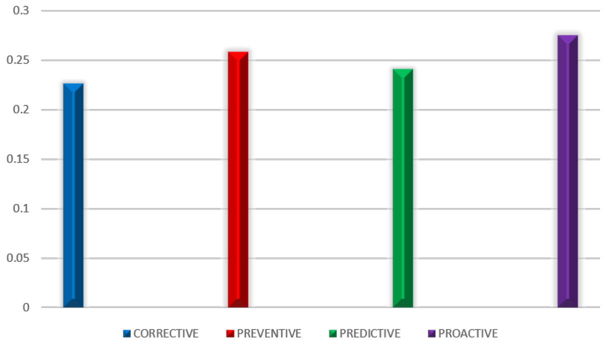

Figure 4. Prioritization of Maintenance Strategies (AHP Results

data management systems, which are typical of conflict-affected, resource-constrained environments. As noted by WorkTrek, proactive maintenance can significantly improve performance and reduce costs; however, success depends on organizational readiness and cultural adaptation [37]. Similarly, the Asian Development Bank emphasizes that proactive investment in infrastructure maintenance yields long-term savings, even in underfunded systems [38]. Case studies from Mexico further demonstrate that data-driven planning can enable proactive strategies to succeed, even in resource-limited environments [39].

This gap between strategic potential and practical limitations underscores the need for a phased, context-sensitive transition that bridges ambition with feasibility. A successful strategy should involve incremental technological investments, targeted training programs, and the cultivation of a proactive organizational culture. Establishing robust data infrastructure and securing managerial and governmental support is critical to overcoming institutional barriers.

Ultimately, this interpretation translates strategic prioritization into feasible implementation steps. It offers a realistic roadmap for sustainable maintenance transformation aligned with Yemen's operational constraints and development context. Moreover, the study contributes to the broader discourse on maintenance optimization in developing economies, demonstrating the adaptability of Multi-Criteria Decision-Making (MCDM) techniques such as AHP in volatile industrial environments.

4. CONCLUSIONS AND RECOMMENDATIONS

This study rigorously investigated maintenance strategies within the Yemeni cement industry using a mixed-methods approach combining surveys and an Analytic Hierarchy Process (AHP) model. Key findings highlight the prevalent reliance on PM, often applied inconsistently, and CM, despite its inefficiencies and long-term costs. More advanced strategies, such as PdM and PrM, remain underutilized for improving operational efficiency.

The AHP model systematically prioritizes operational criteria—productivity, cost, reliability, and availability—with proactive maintenance emerging as the most effective strategy for the Yemeni context. This confirms global trends favoring proactive approaches for long-term operational resilience.

Recognizing Yemen's unique economic and political challenges, the successful adoption of proactive maintenance requires a pragmatic, phased approach grounded in technological limitations, skill deficits, and data availability. Building on these findings, the following recommendations outline a strategic implementation pathway:

1. Incremental Technology Adoption: Prioritize investment in scalable IoT-enabled condition monitoring and AI-driven analytics tailored to current infrastructural capabilities.
2. Focused Human Capital Development: Institute comprehensive, context-specific training programs emphasizing practical diagnostics, data use, and root cause analysis, leveraging partnerships with local academic institutions.
3. Robust Data Infrastructure: Develop centralized, user-friendly data management systems that accommodate existing capabilities and enable the gradual integration of predictive analytics.
4. Organizational Culture and Change Management: Cultivate management commitment and cross-departmental collaboration to foster proactive maintenance mindsets and address resistance through clear communication of benefits and pilot successes.

These recommendations move beyond generic prescriptions to actionable steps tailored to Yemen's cement industry realities, offering a blueprint for other fragile or resource-limited industrial contexts that seek strategic maintenance improvements.

Future research can build on this study in several ways. The AHP model can be expanded to include broader criteria, such as environmental and social factors, to align with sustainability goals. Applying the model to other industrial sectors in Yemen would help to test its generalizability. Additionally, longitudinal studies can assess the long-term impact of recommended strategies on maintenance performance.

5. DISCLOSURE STATEMENT

The author(s) have reported no potential conflict of interest.

REFERENCES

[1] P. N. Muchiri, L. Pintelon, H. Martin, and A.-M. De Meyer, "Empirical analysis of maintenance performance measurement in belgian industries," *Int. J. Prod. Res.*, vol. 48, no. 20, pp. 5905–5924, Oct. 2010. DOI: 10.1080/00207540903160766.

[2] K. Kaur, "A general survey on predictive maintenance (pm)," *SSRN Electron. J.*, 2023. DOI: 10.2139/ssrn.4580881.

[3] S. Werbinska-Wojciechowska and R. Rogowski, "Proactive maintenance of pump systems operating in the mining industry—a systematic review," *Sensors*, vol. 25, no. 8, p. 2365, Apr. 2025. DOI: 10.3390/s25082365.

[4] D. S. Mungani and J. K. Visser, "Maintenance approaches for different production methods," *The South Afr. J. Ind. Eng.*, vol. 24, no. 3, pp. 1–13, Nov. 2013. DOI: 10.7166/24-3-700.

[5] K. M. Albarkoly and K. Park, "Implementing a strategy of reliability centered maintenance (rcm) in the libyan cement industry," *World Acad. Sci. Eng. Technol. Int. J. Social, Behav. Educ. Econ. Bus. Ind. Eng.*, vol. 9, no. 6, pp. 1903–1912, Jun. 2015.

[6] M. Graisa and A. Al-Habaibeh, "An investigation into current production challenges facing the libyan cement industry and the need for innovative total productive maintenance (tpm) strategy," *J. Manuf. Technol. Manag.*, vol. 22, no. 4, pp. 541–558, May 2011. DOI: 10.1108/17410381111126445.

[7] K. Albarkoly, "Exploring the maintenance practices and strategies in the libyan cement industry," Accessed: Dec. 08, 2024, Ph.D. dissertation, Aston University, Birmingham, U.K., 2017. [Online]. Available: http://publications.aston.ac.uk/id/eprint/33341/.

[8] M. T. Hossen Irfan, M. Rafiquzzaman, and Y. A. Manik, "Productivity improvement through lean tools in cement industry – a case study," *Heliyon*, vol. 11, no. 3, e42057, Feb. 2025. DOI: 10.1016/j.heliyon.2025.e42057.

[9] Imubit. "4 ai process optimization strategies for cement plants." Accessed: Oct. 07, 2025. [Online]. Available: https://imubit.com/article/cement-process-optimization-strategies/.

[10] K. Khazraei and J. Deuse, "A strategic standpoint on maintenance taxonomy," *J. Facil. Manag.*, vol. 9, no. 2, pp. 96–113, May 2011. DOI: 10.1108/14725961111128452.

[11] A. M. Badiea, B. A. Wael, and A. A. Adel, "Implementing total productive maintenance in yemeni company for industry and commerce (ycic): Case study," *Eur. J. Appl. Sci.*, vol. 11, no. 2, pp. 212–239, Mar. 2023. DOI: 10.14738/aivp.112.12966.

[12] M. M. Graisa, "An investigation into the need and implementation of total productive maintenance (tpm) in libyan cement industry," Ph.D. dissertation, Nottingham Trent University, 2011. [Online]. Available: https://core.ac.uk/reader/30624110.

[13] T. L. Saaty, "Decision making with the analytic hierarchy process," *Int. J. Serv. Sci.*, vol. 1, no. 1, pp. 83–98, 2008. DOI: 10.1504/IJSSCI.2008.017590.

[14] I. Mahmud, I. Ismail, A. Abdulkarim, G. S. Shehu, G. A. Olarinoye, and U. Musa, "Selection of an appropriate maintenance strategy using analytical hierarchy process of cement plant," *Life Cycle Reliab. Saf. Eng.*, vol. 13, no. 2, pp. 103–109, Jun. 2024. DOI: 10.1007/s41872-024-00249-7.

[15] P. M. Muinde, P. N. Muchiri, and B. W. Ikua, "Maintenance strategy selection using analytic hierarchy process: A case study," *J. Sustain. Res. Eng.*, vol. 1, no. 4, pp. 21–29, 2020. [Online]. Available: https://jsre.jkuat.ac.ke/index.php/jsre/article/view/25.

[16] Federation of Yemen Chambers of Commerce and Industry, "Indicators of the performance of the industrial sector in yemen in light of conflict and war," 2020. [Online]. Available: https://fycci-ye.org/upload/1661240528.pdf.

[17] T. Gedikli and B. Cayir Ervural, "Selection of optimum maintenance strategy using multi-criteria decision-making approaches," in *Industrial Engineering in the Digital Disruption Era*, ser. Lecture Notes in Management and Industrial Engineering, F. Calisir and O. Korhan, Eds., Cham: Springer International Publishing, 2020, pp. 156–170. DOI: 10.1007/978-3-030-42416-9_15.

[18] A. Khati and S. B. Singh, "Availability and cost models for sequentially inspected systems with dependent catastrophic and soft failures," *Qual. Eng.*, vol. 36, no. 1, pp. 191–206, Jan. 2024. DOI: 10.1080/08982112.2023.2289470.

[19] A. Ishizaka and A. Labib, "Review of the main developments in the analytic hierarchy process," *Expert Syst. with Appl.*, vol. 38, no. 11, pp. 14 336–14 345, Oct. 2011. DOI: 10.1016/j.eswa.2011.04.143.

[20] E. Forman and K. Peniwati, "Aggregating individual judgments and priorities with the analytic hierarchy process," *Eur. J. Oper. Res.*, vol. 108, no. 1, pp. 165–169, Jul. 1998. DOI: 10.1016/S0377-2217(97)00244-0.

[21] R. V. Krejcie and D. W. Morgan, "Determining sample size for research activities," *Educ. Psychol. Meas.*, vol. 30, no. 3, pp. 607–610, Sep. 1970. DOI: 10.1177/001316447003000308.

[22] M. R. Galankashi, F. Khorramrouz, M. Esmaeilnezhad, F. M. Rafiei, and M. Hisjam, "Maintenance strategy selection in a cement company: An integrated ahp-fahp approach," in *Proceedings of the 5th International Conference on Industrial, Mechanical, Electrical, and Chemical Engineering (ICIMECE 2019)*, Surakarta, Indonesia, 2020, p. 030 197. DOI: 10.1063/5.0000519.

[23] E. I. Basri, I. H. Abdul Razak, H. Ab-Samat, and S. Kamaruddin, "Preventive maintenance (pm) planning: A review," *J. Qual. Maintenance Eng.*, vol. 23, no. 2, pp. 114–143, May 2017. DOI: 10.1108/JQME-04-2016-0014.

[24] A. Nedzanani, A. Telukdarie, and B. G. Mwanza, "Selection of maintenance strategies using dmg," in *2022 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, Kuala Lumpur, Malaysia: IEEE, Dec. 2022, pp. 359–363. DOI: 10.1109/IEEM55944.2022.9989993.

[25] F. J. D. S. Silva, H. R. G. Viana, and A. N. A. Queiroz, "Availability forecast of mining equipment," *J. Qual. Maintenance Eng.*, vol. 22, no. 4, pp. 418–432, Oct. 2016. DOI: 10.1108/JQME-12-2015-0067.

[26] D. C. Anaba, A. J. Kess-Momoh, and S. A. Ayodeji, "Innovative maintenance strategies for industrial equipment: A review of current practices and future directions," *Open Access Res. J. Sci. Technol.*, vol. 11, no. 2, pp. 029–037, Jul. 2024. DOI: 10.53022/oarjst.2024.11.2.0081.

[27] T. Tinga, F. Wubben, W. Tiddens, H. Wortmann, and G. Gaalman, "Dynamic maintenance based on functional usage profiles," *J. Qual. Maintenance Eng.*, vol. 27, no. 1, pp. 21–42, Jul. 2020. DOI: 10.1108/JQME-01-2019-0002.

[28] A. Abdelhadi, L. C. Alwan, and X. Yue, "Managing storeroom operations using cluster-based preventative maintenance," *J. Qual. Maintenance Eng.*, vol. 21, no. 2, pp. 154–170, May 2015. DOI: 10.1108/JQME-10-2013-0066.

[29] H. Shafeek, "Maintenance practices in cement industry," *Asian Trans. on Eng.*, vol. 1, no. 6, pp. 10–20, 2012.

[30] J. Koochaki, J. A. C. Bokhorst, H. Wortmann, and W. Klingenberg, "Condition based maintenance in the context of opportunistic maintenance," *Int. J. Prod. Res.*, vol. 50, no. 23, pp. 6918–6929, Dec. 2012. DOI: 10.1080/00207543.2011.636924.

[31] S.-H. Ding and S. Kamaruddin, "Maintenance policy optimization—literature review and directions," *Int. J. Adv. Manuf. Technol.*, vol. 76, no. 5–8, pp. 1263–1283, Feb. 2015. DOI: 10.1007/s00170-014-6341-2.

[32] C. Conklin, C. Stewart, and J. Kurosky, “Incorporating an advanced maintenance strategy improves equipment reliability and reduces cement plant costs,” in *2011 IEEE-IAS/PCA 53rd Cement Industry Technical Conference*, St. Louis, MO, USA: IEEE, 2011, pp. 1–7. DOI: 10.1109/CITCON.2011.5934564.

[33] A. Ahmadi, S. Gupta, R. Karim, and U. Kumar, “Selection of maintenance strategy for aircraft systems using multi-criteria decision-making methodologies,” *Int. J. Reliab. Qual. Saf. Eng.*, vol. 17, no. 03, pp. 223–243, Jun. 2010. DOI: 10.1142/S0218539310003779.

[34] M. Braglia, D. Castellano, and M. Frosolini, “An integer linear programming approach to maintenance strategies selection,” *Int. J. Qual. & Reliab. Manag.*, vol. 30, no. 9, pp. 991–1016, Oct. 2013. DOI: 10.1108/IJQRM-05-2012-0059.

[35] H. Barringer, “An overview of reliability engineering principles,” in *Energy Week ’96: ASME/API Energy Week Conference and Exhibition*, Available at OSTI, Houston, TX, USA, 1996.

[36] P. Barringer, “Introduction and evaluation of reliability,” in *Proceedings of the IMEC2004 International Mechanical Engineering Conference*, Kuwait: Kuwait Society of Engineers, Dec. 2004.

[37] R. Tabibian. “Challenges to implementing proactive maintenance.” WorkTrek Blog. [Online]. Available: https://worktrek.com/blog/proactive-maintenance-challenges/.

[38] A. Bardhan. “Maintaining momentum: Three steps countries can take to make infrastructure more resilient.” Asian Development Blog. [Online]. Available: https://blogs.adb.org/blog/maintaining-momentum-three-steps-countries-can-take-make-infrastructure-more-resilient.

[39] M. Montoya-Alcaraz, A. Mungaray-Moctezuma, and L. García, “Sustainable road maintenance planning in developing countries based on pavement management systems: Case study in baja california, méxico,” *Sustainability*, vol. 12, no. 1, p. 36, Dec. 2019.