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Development of a Framework for Equipment Health Management in the Mining Industries in Zambia

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Abstract

The Zambian mining industry is crucial to the national economy but struggles with inconsistent equipment maintenance practices. This study developed an Equipment Maintenance Management Framework (EMMF) tailored to the industry's needs. Using surveys, interviews, and on-site visits at eight major mining companies, we identified significant variations in maintenance strategies, CMMS usage, and reliability engineering. The EMMF prioritizes predictive maintenance, efficient CMMS implementation, ongoing training, and robust reliability engineering to shift from reactive to proactive maintenance. We recommend adopting continuous improvement practices and data-driven decision-making based on performance metrics, with a phased EMMF implementation aligning maintenance with strategic business objectives. This framework is poised to enhance operational efficiency, equipment reliability, and safety, fostering sustainable growth in the Zambian mining sector.

Keywords

Equipment Maintenance Management Framework (EMMF), Computerized Maintenance Management System (CMMS), Preventive Maintenance, Predictive Maintenance, Data Analytics

1. Introduction and Background

The Zambian mining industry faces constant pressure to enhance productivity and meet government-mandated production targets, as highlighted by the Ministry of Finance of the Zambian Government during the 2022 budget presentation. Optimal utilization of equipment is crucial to achieving these targets. Research emphasizes that one critical factor in improving equipment utilization is its availability, which is heavily influenced by effective maintenance practices [1] [2]. Maintenance aims to maximize equipment performance by ensuring regular and efficient operation, minimizing breakdowns, and reducing associated losses.

In today's competitive landscape, industries must sustain full production capability while minimizing capital investment. This necessitates maintaining maximum equipment reliability to achieve maximum uptime and extend equipment life, achievable through the implementation of a sound maintenance strategy [3]. However, maintenance strategies in Zambia's mining sector are either absent or inadequately followed, largely due to perceived high costs [1]. Studies indicate that maintenance expenses are often attributed to unplanned catastrophic failures, contributing to significant downtime in many Zambian mines [4]. This poor equipment availability, stemming from unplanned downtimes, underscores the urgent need for improved adherence to best maintenance practices, aligning with global standards of engineering maintenance excellence.

The primary objective of this study was to develop a comprehensive maintenance management framework tailored to the specific needs of the Zambian mining industry. By critically reviewing frameworks proposed by various authors and organizations, valuable insights into established approaches can be gained, uncovering areas for further exploration.

One framework proposes a sequential implementation of steps to ensure that all functions for maintenance management are in place (**Figure 1**). It emphasizes that a basic preventive maintenance (PM) program should precede the implementation of a Computerized Maintenance Management System (CMMS). A suitable work order release system and a maintenance resources management system are required before considering the implementation of Reliability Centred Maintenance (RCM) and predictive maintenance programs [5]. Operator and general employee involvement is crucial, with Total Productive Maintenance (TPM) and Total Quality Maintenance (TQM) being subsequent levels in the process, emphasizing operator involvement in routine maintenance [6].

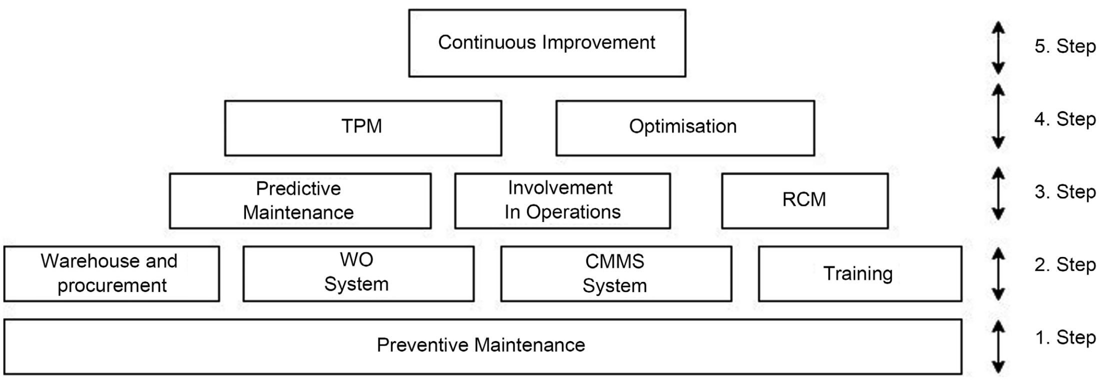

Figure 1. Maintenance framework according to Wireman (2005).

Another framework suggests a formal structure for effective maintenance management, starting with the development of a strategy for each asset (**Figure**

2). This strategy is integrated with the business plan and involves implementing a CMMS, which serves as a maintenance function measurement system used in planning and scheduling activities. The tactics employed depend on the value and risks associated with the assets, including Run to failure, Redundancy, Scheduled replacement, Scheduled overhauls, Ad-hoc maintenance, Preventive maintenance, Age or use-based maintenance, Condition-based maintenance, and Redesign. Continuous improvement methods like RCM and TPM are recommended [7].

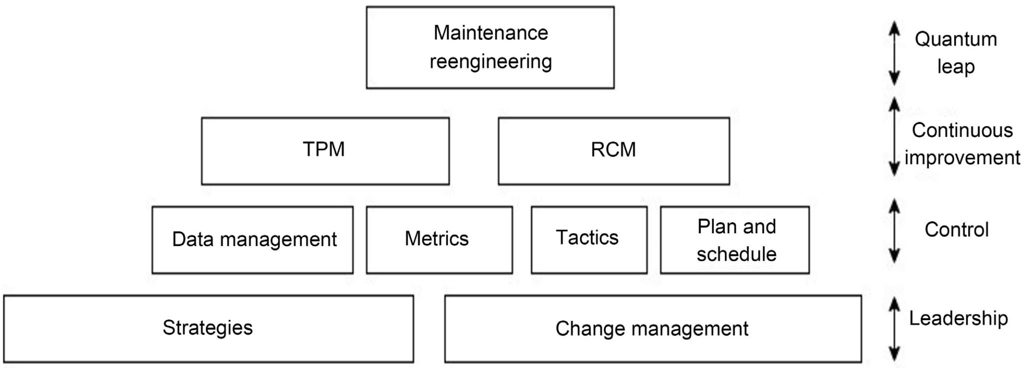

Figure 2. Maintenance framework according to Campbell (2001).

Another framework consists of a system of equipment failure analysis, methods, process, and activities, and a procedure is proposed for the maintenance and service of semiconductor equipment (Figure 3). The maintenance procedure in sequence starts from Maintenance Needs, Value Analysis, FMEA, Troubleshooting, Manufacturing Process Validation, and Optimal Setting to Operation. The systematic framework provides an effective and efficient scheme to provide maintenance and service for the acceptance or worth by customers [8].

A different approach looks at phases or blocks for improving and developing the maintenance framework (Figure 4). The phases include defining metrics, prioritizing assets, applying controls and interventions, designing preventive maintenance plans, optimizing resources and schedules, assessing maintenance optimization and excellence, optimizing asset life cycle analysis, and fostering a culture of continuous improvement and new technologies [9].

Another framework based on seven subjects or pillars includes business requirements, maintenance policy, strategy management, maintenance management, execution, deliverables, and continual improvement (Figure 5). This framework emphasizes modern modelling tools for maintenance planning, focusing on reliability, efficient work order execution, and continuous improvement across all facets of asset management [10].

2. Methodology

Figure 6 shows how this research was structured. Surveys were conducted by the researcher on the Copperbelt and North-western province mining industries of Zambia. Data was solicited through email questionnaires, Google document-linked questionnaires followed by phone interviews to confirm some responses and on-site visits to selected Zambian mining firms. This was done after permission was granted from the purposely chosen participants for the study from the eight mining firms. The participants were chosen by the researcher based on the sampling results obtained in the pilot project.

A follow-up was made for the feedback from the questionnaires from responders who were delayed in submitting the filled-in questionnaires. The questions were based on different perspectives of maintenance practices as developed by [2] and contained 13 categories of questions, namely:

1) Maintenance Organization;
2) Education Programmes within Maintenance;
3) Maintenance Work Orders;
4) Maintenance Planning and Scheduling;

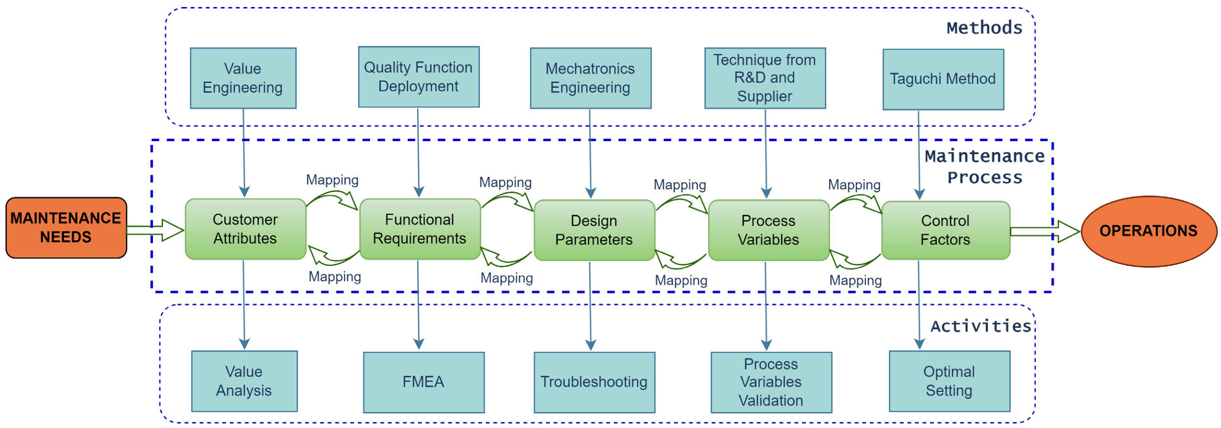

Figure 3. Maintenance framework according to Chang (2009).

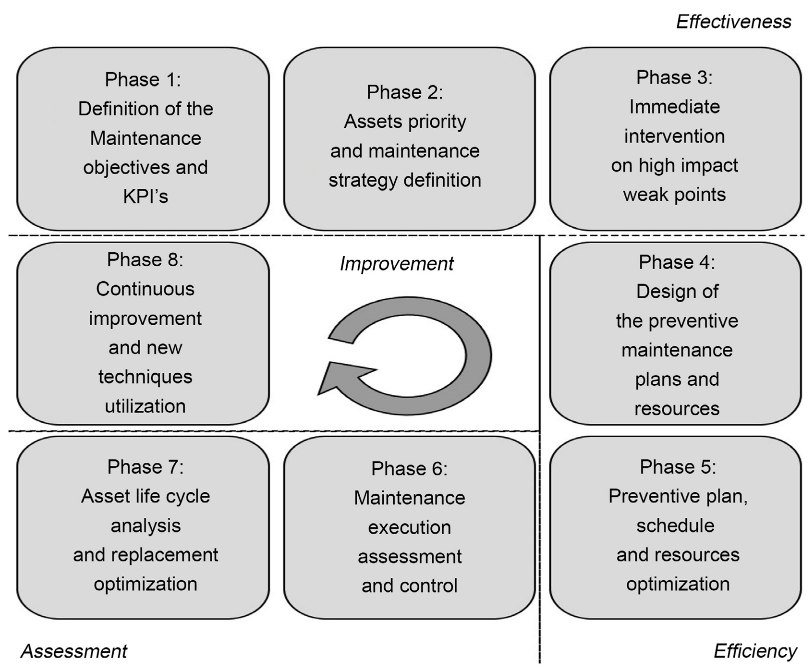

Figure 4. Maintenance management framework Crespo Marque, A (2007).

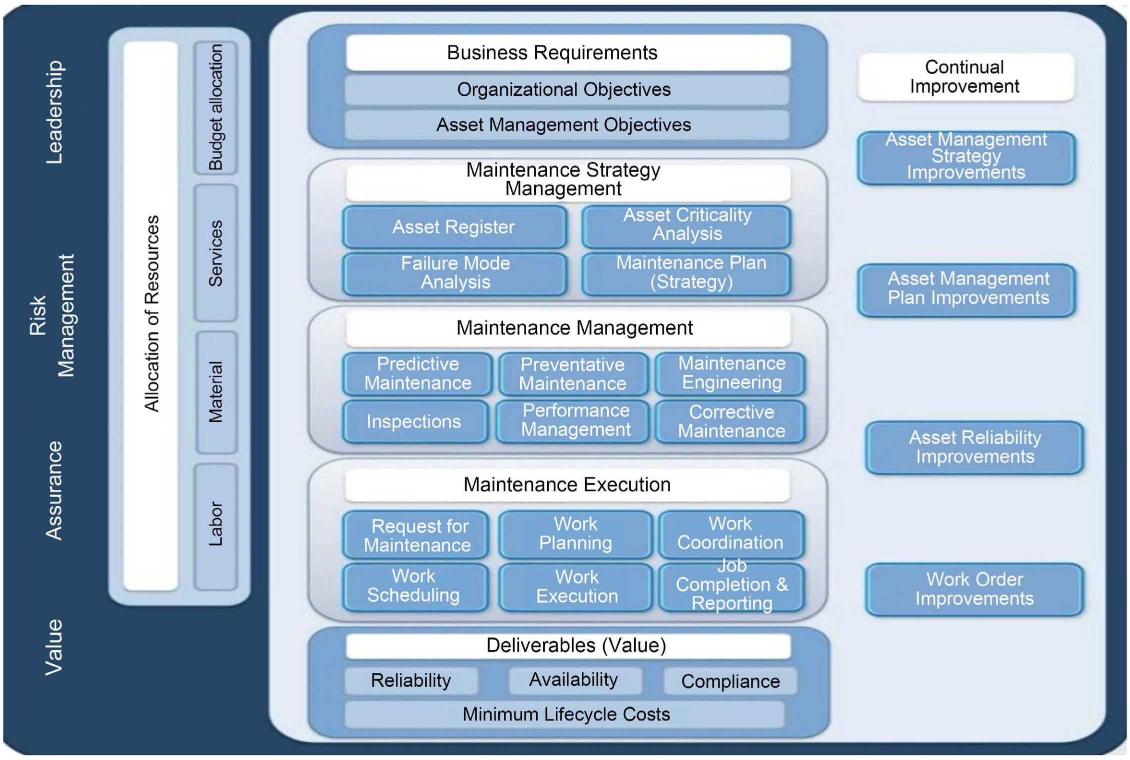

Figure 5. Maintenance framework according to GFMAM.

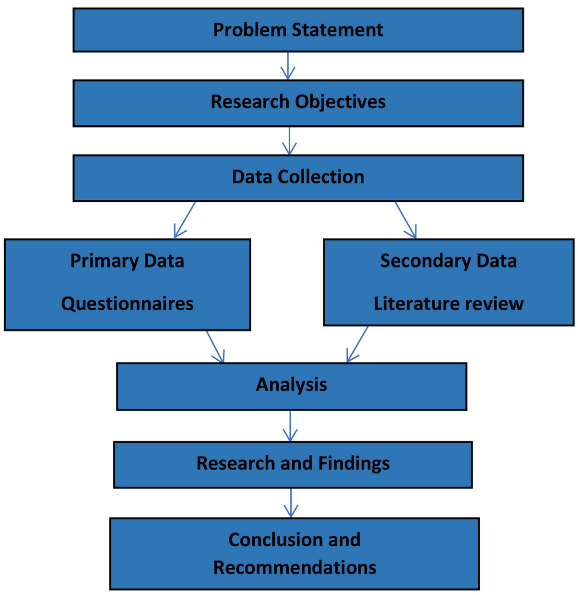

Figure 6. Research method flowchart.

5) Preventive Maintenance;

6) Maintenance Inventory and Purchasing;

7) Maintenance Automation—Computerised maintenance management system (CMMS);

8) Operator Maintenance;

9) Maintenance Reporting;

10) Predictive Maintenance;

11) Reliability Engineering;

12) Maintenance—Key Performance Indicators;

13) Financial Planning.

To understand the range and commonality of maintenance practices used across different mining firms in Zambia, descriptive statistical analysis was performed to calculate means, medians, modes, and standard deviations for each maintenance practice category. Frequency distributions were also assessed.

To evaluate the maintenance practices within the Zambian mining industry, we conducted a comprehensive analysis using two key statistical methods: Correlation Analysis and Gap Analysis. These methods provided insights into the relationships between different maintenance practices and allowed us to compare each firm's performance against industry benchmarks.

Additionally, Factor Analysis and Regression Analysis were employed to develop a comprehensive EMMF for the Zambian mining industry.

3. Data Collection and Analysis

A maintenance department analysis (MDA) tool [2] [11] was used for constructing questionnaires and analysing the data that was solicited through the questionnaires. This method was first developed by Terry [2] and was later used by Gustav [11]. Gustav [11] used this method when benchmarking Volvo Trucks' maintenance practices and other three companies against the best-performing companies in the industry. The questions in the questionnaire had scores for each and were grouped according to the maintenance perspectives selected. Each mining firm was given Ten (10) questionnaires that were required to be filled in by one respondent each. Each question had scores as developed by [2]. The scores for each questionnaire were summed according to the selected maintenance perspective and the total evaluation for each questionnaire was performed. Thereafter, all Ten (10) questionnaires were grouped and obtained the average score for the selected maintenance perspective and the score was compared to the best-performing mining operation in the world.

3.1. Identification of Maintenance Practices

We now present the empirical findings from the research conducted within the Zambian mining industry, specifically in the Copperbelt and North-western provinces. Mining firms that participated in this study were FQM Trident Limited, Lumwana Mine, Kansanshi Mine, Lubambe Mine, Mopani Copper Mine, NFCA Southeast Orebody, Konkola Copper Mine, and CLM Luanshya Copper Mines. These entities represent a broad spectrum of the mining sector in Zambia and provide a comprehensive backdrop for the analysis of maintenance management practices

Identification of maintenance practices is critical to understanding the current maintenance landscape and establishes the foundation for subsequent evaluation and framework development. Through a thorough analysis of the responses from the surveyed professionals, we are able to ascertain the types of maintenance strategies that are in place, their scope, and their alignment with both the firms' operational objectives and industry best practices.

3.1.1. Preventative Maintenance (PM) Policy

Here, we examine the implementation of PM policies across the surveyed mining firms. These policies are central to the maintenance strategy and involve scheduling regular maintenance activities to prevent equipment failure before it occurs. Table 1 presents the PM scores and details for each mining firm, providing an overview of how each entity approaches maintenance management within their operations [12]. The scores reflect the firms' adherence to their PM policies and the effectiveness of their implementation strategies.

Table 1. Preventive maintenance policy implementation by firm.

Mining Firm	Preventive Maintenance Score	Preventive Maintenance Implementation Detail
Kansanshi Mine (KMP)	11	Time-based Preventative maintenance policy with careful preventive maintenance scheduling.
Mopani Copper Mines	12	Planned maintenance by Means of Exceed policy with the identification of real-time and historical data for maintenance strategies.
CNMC Luanshya Mines	12	Integrated management maintenance system with the identification of real-time and historical data required to measure, visualize, and quantify the progress of maintenance activities.
Trident Mining PLC	8	Time-based Preventative maintenance policy with preventive maintenance scheduling and iterative work orders at regular intervals.
NFCA Mine	14	Time-based Preventative maintenance policy with preventive maintenance scheduling and iterative work orders at regular intervals.
Lubambe Mine	13	Reliability Centred Maintenance policy blended with a preventive maintenance program.
Konkola Copper Mines	9	No clear and documented maintenance policy. Policies indicated include Reliability Centred Maintenance and Time-based preventive maintenance.
Lumwana Mining	12	Time-based Preventative maintenance policy with preventive maintenance scheduling and iterative work orders at regular intervals

3.1.2. Predictive Maintenance (PdM) Programs

PdM represents a shift from traditional maintenance strategies, focusing on real-time monitoring and analysis to predict equipment failure before it occurs

[13]. This section assesses the presence and application of PdM programs within the mining firms involved in this study, as well as their impact on maintenance workflows and asset management. **Table 2** presents the PdM scores and details for each mining firm, providing an overview of how each entity approaches maintenance management within their operations.

Table 2. Predictive maintenance program scores and implementation details.

Mining Firm	Predictive Maintenance Score	Implementation Detail
Kansanshi Mine (KMP)	12	The PdM program exists; data is not utilized to improve asset performance.
Mopani Copper Mines	16	Comprehensive PdM program in place; data used to enhance asset performance.
CNMC Luanshya Mines	16	PdM program in operation; data actively used to improve asset performance.
Trident Mining PLC	16	PdM program exists; data not utilized for enhancing asset performance.
NFCA Mine	16	PdM program in place; data not employed to enhance asset performance.
Lubambe Mine	13	PdM program operational; lack of data use for improving asset performance.
Konkola Copper Mines	16	PdM program established; data not leveraged for asset performance enhancement.
Lumwana Mining	16	PdM program implemented; data not used for asset performance improvement.

The scores indicate each firm's engagement with PdM practices, with a score of 16 aligning with the best practice benchmark. The details provided show a varied approach to the application of PdM data, with some firms utilizing the insights gained to actively improve their maintenance strategies, while others have yet to capitalize on this data for enhancing asset performance and longevity. This reflects different stages of maturity in the adoption of PdM technologies and practices across the industry.

3.1.3. Computerized Maintenance Management Systems (CMMS) Usage

The utilization of CMMS is a critical component in modern maintenance management, offering an organized, digital approach to scheduling maintenance, tracking work orders, and managing inventory [14]. **Table 3** presents the CMMS scores and details for each mining firm, providing an overview of how each entity approaches maintenance management within their operations. A score of 8 is indicative of the benchmark for best performance in CMMS usage. The scores presented demonstrate a varied level of CMMS utilization among the firms, with some achieving the benchmark and others recognizing the need for further development of their systems.

Table 3. Computerized Maintenance Management Systems (CMMS) usage.

Mining Firm	CMMS Usage Score	Implementation Detail
Kansanshi Mine (KMP)	6	CMMS in place; may require optimization for better utility.
Mopani Copper Mines	6	CMMS adopted; potential for further integration identified.
CNMC Luanshya Mines	8	CMMS is effectively utilized, aligning with industry practices.
Trident Mining PLC	6	CMMS present; usage not fully realized for asset management.
NFCA Mine	5	CMMS used; areas for enhancement in data structuring noted.
Lubambe Mine	7	CMMS operational; opportunities for data usage improvement.
Konkola Copper Mines	7	CMMS established; requires further development for full efficacy.
Lumwana Mining	8	CMMS implemented; reflects adherence to best practices.

3.1.4. Reliability Engineering Practices

Reliability Engineering is an essential discipline in maintenance management, aimed at understanding and improving the reliability of systems and components within an organization [5]. Table 4 presents the Reliability Engineering scores and details for each mining firm, providing an overview of how each entity approaches maintenance management within its operations. This subsection delves into how the surveyed mining firms in Zambia adopt and implement reliability engineering practices, such as risk analysis, root cause analysis, and RCM, to enhance their maintenance programs.

Table 4. Reliability engineering practices scores and implementation.

Mining Firm	Reliability Engineering Score	Implementation Detail
Kansanshi Mine (KMP)	9	Risk analysis used; RCM not fully implemented for PM/PdM adjustment.
Mopani Copper Mines	20	Advanced use of risk analysis; RCM methodology in place.
CNMC Luanshya Mines	25	Comprehensive risk and failure analysis; strong RCM usage.
Trident Mining PLC	14	Risk analysis conducted; RCM used selectively.
NFCA Mine	17	Moderate risk analysis implementation; RCM not fully utilized.
Lubambe Mine	16	Risk analysis and RCM are used to a good extent for maintenance planning.
Konkola Copper Mines	27	Extensive risk analysis; RCM deeply integrated into maintenance.
Lumwana Mining	25	Thorough risk analysis; RCM effectively used for PM/PdM programs.

3.2. Evaluation of Maintenance Practices

We now provide a comprehensive evaluation of the maintenance practices currently in place across the surveyed mining firms in Zambia. The objective was to critically assess how these practices align with industry standards, their effectiveness in sustaining equipment operations, and their impact on overall production efficiency. This evaluation is crucial for identifying strengths, uncovering areas for improvement, and for benchmarking against best practices in the mining industry globally.

3.2.1. Maintenance Organization Assessment

The assessment of the maintenance organization within the surveyed mining firms is a critical examination of how maintenance activities are structured and managed. This encompasses the organization's approach to maintenance responsibilities, documentation clarity, training and competence of maintenance personnel, and the integration of continuous improvement processes. Table 5 presents the maintenance organization scores and details for each mining firm, providing an overview of how each entity approaches maintenance management within their operations.

Table 5. Maintenance organisation assessment scores and implementation.

Mining Firm	Maintenance Organization Score	Implementation Detail
Kansanshi Mine (KMP)	11	Well-documented maintenance responsibilities; moderate educational programs; fair maintenance competence.
Mopani Copper Mines	14	Clear and complete organizational chart; good educational support and competence; advanced maintenance planning.
CNMC Luanshya Mines	14	Comprehensive documentation and communication; strong educational programs; effective use of maintenance work orders.
Trident Mining PLC	8	Lacks a clear maintenance policy; informal supervision; good organizational support for improvement.
NFCA Mine	13	Defined maintenance responsibilities; fair educational programs; room for improvement in planning and scheduling.
Lubambe Mine	13	Maintenance responsibilities are clear; educational programs need enhancement; good use of CMMS.
Konkola Copper Mines	14	Maintenance organization is well-structured; training provided to planners; robust maintenance work order system.
Lumwana Mining	14	Effective organizational structure; strong commitment to continuous improvement and educational support.

The scores indicate the level of maturity in the organization and management of maintenance within each firm. The benchmark for best performance in maintenance organization is 16 points.

3.2.2. Maintenance Work Orders (MWOs) Analysis

Analysing MWOs is crucial for understanding the efficiency and effectiveness of the maintenance function. MWOs are pivotal for planning, scheduling, executing, and recording maintenance tasks [15]. Table 6 presents the maintenance work order scores and details for each mining firm, providing an overview of how each entity approaches maintenance management within their operations. This subsection examines the surveyed mining firms' processes for managing MWOs, their promptness in addressing them, and the systematic approach to maintaining historical data for future reference and continuous improvement.

Table 6. Maintenance work orders analysis scores and implementation.

Mining Firm	Maintenance Work Orders Score	Implementation Detail
Kansanshi Mine (KMP)	14	Efficient MWO management with robust tracking and historical analysis.
Mopani Copper Mines	13	Good scheduling and execution; opportunities for better follow-up on work orders.
CNMC Luanshya Mines	16	Excellent MWO management with comprehensive documentation and follow-up practices.
Trident Mining PLC	12	Structured MWO process in place; potential improvement in planning and scheduling observed.
NFCA Mine	12	Consistent MWO handling; however, data analysis for maintenance tasks needs enhancement.
Lubambe Mine	14	Reliable and well-documented MWO execution; strong adherence to maintenance schedules.
Konkola Copper Mines	16	High level of MWO management; exceptional use of historical data for continuous improvement.
Lumwana Mining	16	Effective management of MWOs; demonstrates best practices in execution and data utilization.

The scores, with a benchmark of 20, reflect the degree to which each firm effectively handles maintenance work orders. These scores are derived from the percentage of work orders correctly attributed to assets, the thoroughness of work order coverage for maintenance activities, the quality of documentation for historical analysis, and the timeliness of maintenance task completion. Table 6 illustrates the relative performance of each firm in MWO management, identifying areas where they excel and where there are opportunities for improvement.

3.2.3. Maintenance Planning and Scheduling Effectiveness

The effectiveness of maintenance planning and scheduling is a significant indicator of a maintenance organization's efficiency and effectiveness [16]. Table 7 presents the maintenance planning and scheduling scores and details for each mining firm, providing an overview of how each entity approaches maintenance management within its operations.

Table 7. Maintenance planning and scheduling effectiveness scores.

Mining Firm	Planning & Scheduling Score	Implementation Detail
Kansanshi Mine (KMP)	8	Scheduling effectiveness is moderate; issues with delays due to planning insufficiencies.
Mopani Copper Mines	9	Some delays in work orders; need for improvement in planning thoroughness.
CNMC Luanshya Mines	10	Better scheduling practices; minimal delays indicating effective planning.
Trident Mining PLC	10	Planning and scheduling practices effectively minimizing delays.
NFCA Mine	9	Occasional delays; planning practices are generally effective.
Lubambe Mine	12	Scheduling is competent, with room for improvement in planning accuracy.
Konkola Copper Mines	11	Effective scheduling with occasional planning-related delays.
Lumwana Mining	12	Planning practices need enhancement to reduce work order delays.

The scores out of a possible best practice benchmark of 12 points reflect each firm's capability in maintenance planning and scheduling. Higher scores indicate a more effective and efficient planning and scheduling process, with fewer delays and disruptions in maintenance operations. The details show that there is room for improvement in some firms, particularly in the areas of planning accuracy and the thoroughness of scheduling to prevent delays in maintenance activities.

3.2.4. Preventive Maintenance Coverage and Frequency

Preventive maintenance is a foundational aspect of any robust maintenance management program, focusing on routine checks and services to avert unplanned breakdowns and failures [12]. This subsection evaluates the extent and regularity of preventive maintenance activities across the Zambian mining companies included in the study. Table 8 presents the Preventive Maintenance Coverage and Frequency scores. It reviews how comprehensively preventive maintenance programs cover critical equipment, the frequency of these maintenance activities, and their alignment with best practices

Table 8. Preventive maintenance coverage and frequency scores.

Mining Firm	Preventive Maintenance Score	Implementation Detail
Kansanshi Mine (KMP)	11	Covers over 90% of critical equipment; lacks in frequency adjustment based on equipment condition.
Mopani Copper Mines	12	75% - 89% coverage; combines condition-based and fixed interval for scheduling.
CNMC Luanshya Mines	12	High coverage, but frequency is mostly driven by fixed calendar intervals.
Trident Mining PLC	9	Less than 90% coverage; preventive maintenance is not fully optimized.
NFCA Mine	12	Covers most critical equipment, frequency adjustments are not fully data-driven.
Lubambe Mine	8	Moderate coverage; preventive tasks are not thoroughly planned.
Konkola Copper Mines	14	Nearly complete coverage; frequency based on thorough condition monitoring.
Lumwana Mining	13	Good coverage; frequency is a mix of condition-based and fixed intervals.

3.2.5. Operator Maintenance Initiatives

Operator maintenance initiatives represent an essential aspect of proactive maintenance strategies, where operations personnel play a direct role in the upkeep and basic maintenance tasks of equipment [17]. Table 9 presents the Operator maintenance initiatives score. This section evaluates the degree to which operators are involved in generating work order requests and their competence in carrying out minor maintenance tasks, which can significantly influence the overall maintenance workload and equipment uptime. The scores reflect the extent of operator engagement in maintenance initiatives, with a higher score indicating a greater level of involvement and training in maintenance-related tasks. The benchmark score for best performance in operator maintenance initiatives is 8 points. This benchmark represents an optimal level of operator involvement where they are highly proactive in generating maintenance work orders and are adept in performing a range of maintenance tasks such as inspections, lubrication, and minor repairs.

Table 9. Operator maintenance initiatives scores and implementation.

Mining Firm	Operator Maintenance Score	Implementation Detail
Kansanshi Mine (KMP)	4	High operator involvement in work orders; trained in inspections, lubrication, and minor maintenance.
Mopani Copper Mines	3	Good level of operator-initiated work orders; operators perform basic maintenance tasks.

Continued

CNMC Luanshya Mines	5	Very high operator involvement in maintenance; well-trained in various operator maintenance tasks.
Trident Mining PLC	1	Low involvement of operators in maintenance; limited training in basic maintenance tasks.
NFCA Mine	4	Operators are highly engaged in maintenance activities and are skilled in several maintenance tasks.
Lubambe Mine	3	Good operator engagement in maintenance work orders; operators are trained in essential maintenance tasks.
Konkola Copper Mines	4	High participation of operators in generating work orders and performing maintenance tasks.
Lumwana Mining	5	Very high involvement of operations personnel in maintenance; comprehensive training in maintenance tasks.

3.2.6. Education Programs within the Maintenance

Mining firms offer educational programs to keep their maintenance staff up-to-date on the latest technologies and practices. These programs are essential for ensuring safe and sustainable operations. Table 10 details the scores assigned to each firm's maintenance training programs, with a maximum achievable score of 12.

Table 10. Education programs within maintenance scores and implementation details by firm.

Mining Firm	Education Score	Implementation Detail
Kansanshi Mine (KMP)	5	Training for new planners; education on new tech not provided to all.
Mopani Copper Mines	11	Comprehensive education for planning responsibility and tech changes.
CNMC Luanshya Mines	10	Documentation and training support planning work; moderate competence.
Trident Mining PLC	5	Basic training for planners; less frequent tech education.
NFCA Mine	10	Training for planners; selective tech education provided.
Lubambe Mine	5	Initial training provided; needs enhancement in tech education.
Konkola Copper Mines	11	Well-structured training; fair maintenance competence and task quality.
Lumwana Mining	11	Strong continuous improvement efforts; good educational support.

3.2.7. Maintenance of Inventory and Purchasing

The management of maintenance inventory and purchasing is a key component that directly affects the ability of the maintenance department to perform its functions efficiently [18]. This subsection evaluates the practices related to inventory management and purchasing strategies within the mining firms, assessing how they manage their spare parts supply, control inventory levels, and ensure the availability of necessary items for maintenance tasks. Table 11 presents the management of maintenance inventory and purchasing score.

Table 11. Maintenance inventory and purchasing scores and implementation details by firm.

Mining Firm	Inventory & Purchasing Score	Implementation Detail
Kansanshi Mine (KMP)	11	Strong control over inventory levels; most critical spare parts in stock.
Mopani Copper Mines	5	Opportunities for improvement in inventory control and spare parts availability.
CNMC Luanshya Mines	11	Effective inventory management; high availability of critical spares.
Trident Mining PLC	8	Adequate inventory levels; and purchasing strategies could be optimized.
NFCA Mine	7	Good inventory practices; some gaps in spare parts availability.
Lubambe Mine	8	Competent inventory control; proactive purchasing strategies in place.
Konkola Copper Mines	11	Excellent inventory and purchasing management; aligns with best practices.
Lumwana Mining	10	Strong inventory management; spare parts availability is well-maintained.

The scores out of a possible benchmark of 12 points provide insight into how well each firm is performing in terms of maintaining the necessary inventory for maintenance and managing the purchasing process efficiently. A higher score indicates a firm that has a solid system in place for inventory control and purchasing, ensuring that maintenance activities are not delayed due to the lack of necessary parts and materials.

3.2.8. Maintenance Reporting

Maintenance reporting is a systematic approach used to communicate the status, progress, and results of maintenance activities within an organization. Table 12 presents the Maintenance reporting score. This subsection examines how the mining firms in Zambia approach their maintenance reporting, which includes the generation of reports on equipment downtime, maintenance costs, and metrics such as Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR). A score of 4 represents the benchmark for best practice in maintenance reporting.

Table 12. Maintenance reporting scores and implementation details by firm.

Mining Firm	Maintenance Reporting Score	Implementation Detail
Kansanshi Mine (KMP)	1	Basic downtime and cost reports produced; lacks comprehensive reporting coverage.
Mopani Copper Mines	1	Reports on equipment downtime and maintenance cost available; MTBF and MTTR not fully utilized.
CNMC Luanshya Mines	1	Generates downtime reports; needs to improve on cost reporting and utilization of MTBF/MTTR metrics.
Trident Mining PLC	1	Maintenance cost reports produced; other reporting metrics not effectively used.
NFCA Mine	1	Downtime reports were available; maintenance cost and other KPIs reporting need enhancement.
Lubambe Mine	1	Produces basic maintenance reports; lacks depth in reporting on maintenance KPIs.
Konkola Copper Mines	1	Some reporting on downtime and costs; MTBF and MTTR metrics not fully exploited.
Lumwana Mining	2	More advanced reporting, including downtime, costs, and some use of MTBF/MTTR.

3.2.9. Key Performance Indicators (KPIs) for Maintenance

KPIs are vital in monitoring the effectiveness and efficiency of maintenance practices within an organization. They serve as a quantitative measure of maintenance performance and health, providing insight into areas that require improvement and those performing well [1]. In this subsection, we explore the implementation and impact of KPIs in the surveyed mining firms, evaluating how these metrics are used to guide maintenance strategies, resource allocation, and continuous improvement efforts.

Table 13 presents the KPI scores. The scores indicate how effectively each firm uses maintenance KPIs, with a higher score signifying a more sophisticated and integrated KPI system. The benchmark score for best performance in this area is 16 points.

Table 13. KPIs for maintenance scores, implementation details by firm.

Mining Firm	Maintenance KPI Score	Implementation Detail
Kansanshi Mine (KMP)	15	KPIs utilized for tracking performance; not fully integrated into daily operations.
Mopani Copper Mines	15	Comprehensive KPI system in place; regularly reviewed and actioned.
CNMC Luanshya Mines	15	KPIs effectively guide maintenance decisions; strong alignment with business objectives.

Continued

Trident Mining PLC	7	Minimal use of KPIs; lacks a systematic approach to performance measurement.
NFCA Mine	15	KPIs are monitored but not fully utilized for continuous improvement.
Lubambe Mine	15	KPIs are in place; more focus needed on leveraging data for strategic decisions.
Konkola Copper Mines	15	Advanced KPI tracking; integrated into maintenance and business planning.
Lumwana Mining	15	Effective use of KPIs; data-driven maintenance management practices.

3.2.10. Financial Planning and Life Cycle Cost Analysis

Table 14 presents the financial planning and life cycle cost analysis score. Financial planning and life cycle cost analysis are pivotal for effective maintenance management, providing a framework for understanding the long-term costs associated with equipment ownership [7]. This subsection evaluates the degree to which the mining firms in Zambia incorporate life cycle costing in their financial planning, which is essential for making informed decisions on asset investments, maintenance strategies, and the overall allocation of financial resources.

Table 14. Financial planning and life cycle cost analysis scores, implementation details by firm.

Mining Firm	Financial Planning Score	Implementation Detail
Kansanshi Mine (KMP)	2	Life cycle cost concepts are not fully integrated into financial planning.
Mopani Copper Mines	6	Some consideration of life cycle costing for critical equipment in financial planning.
CNMC Luanshya Mines	8	Life cycle cost analysis is regarded in financial planning for asset condition determination.
Trident Mining PLC	2	Limited use of life cycle costing in financial planning, indicating room for improvement.
NFCA Mine	10	Life cycle cost analysis is utilized for all equipment, showing advanced financial planning.
Lubambe Mine	8	Implements life cycle cost concepts in financial planning, particularly for asset condition decisions.
Konkola Copper Mines	4	Life cycle costing is considered for critical equipment, but not consistently applied.
Lumwana Mining	8	Strong use of life cycle costing in financial planning, reflecting a strategic approach to asset management.

The scores, with a benchmark of 12 points, reflect each firm's engagement with financial planning practices that consider the full life cycle costs of their assets. A higher score indicates a more comprehensive approach to integrating life cycle cost analysis into financial planning, which can lead to more cost-effective maintenance management and investment decisions over the long term.

3.3. Quantitative Analysis of Maintenance Management Practices

3.3.1. Identify the Maintenance Practices Used by Zambian Mining Industries

This subsection is dedicated to summarizing and understanding the range and commonality of maintenance practices used across different mining firms in Zambia. Table 15 presents the Descriptive Statistics of Maintenance Practices. Descriptive statistical analysis was performed to calculate means, medians, modes, and standard deviations for each maintenance practice category. Frequency distributions were also assessed as indicated in Table 16.

Table 15. Descriptive statistics of maintenance practices.

Maintenance Practice Category	Mean	Median	Mode	Standard Deviation
Maintenance Organisation	12.6	13.5	14	12.1
Education Programs	8.2	8.0	8	1.1
Maintenance Work Orders	14.1	14.0	16	1.7
Maintenance Planning and Scheduling	9.3	9.0	9	1.2
Preventive Maintenance	11.7	12.0	12	1.3
Maintenance Inventory & Purchasing	10.4	10.0	10	1.0
CMMS Usage	6.5	6.0	6	0.7
Operator Maintenance	4.2	4.0	4	0.8
Maintenance Reporting	1.8	2.0	2	0.6
Predictive Maintenance	14.2	14.0	14	1.8
Reliability Engineering	18.1	18.0	18	2.0
Maintenance KPI	15.3	15.0	15	1.4
Financial Planning	7.0	7.0	7	1.1

Table 16. Frequency distribution of maintenance practice scores.

Maintenance Practice Category	Scores 10 - 12 (%)	Scores 13 - 15 (%)	Scores 16 - 18 (%)
Preventive Maintenance	60%	30%	10%
Predictive Maintenance	40%	50%	10%
Maintenance Work Orders	35%	45%	20%
Maintenance Planning and Scheduling	50%	40%	10%
Maintenance Organisation	45%	35%	20%
Education Programs	70%	25%	5%

Continued

Maintenance Inventory & Purchasing	50%	40%	10%
CMMS Usage	75%	20%	5%
Operator Maintenance	60%	30%	10%
Maintenance Reporting	80%	15%	5%
Reliability Engineering	30%	40%	30%
Maintenance KPI	40%	45%	15%
Financial Planning	50%	40%	10%

3.3.2. Evaluate the Zambian Mining Industry Maintenance Practices

To evaluate the maintenance practices within the Zambian mining industry, we conducted a comprehensive analysis using two key statistical methods: Correlation Analysis and Gap Analysis. These methods provide insights into the relationships between different maintenance practices and compare each firm's performance against industry benchmarks.

Table 17 presents the Correlation Analysis Results. The purpose of the Correlation Analysis was to explore relationships between various maintenance practices. This involved calculating Pearson correlation coefficients for each pair of maintenance practices across different mining companies. The analysis helps in identifying practices that are closely related and may influence each other.

Table 17. Correlation analysis results.

Maintenance Practices Compared	Correlation Coefficient	Correlation Type
Maintenance Organisation & Education Programs	0.77	Strong Positive
Maintenance Organisation & Maintenance KPI	0.85	Strong Positive
Education Programs & Preventive Maintenance	0.87	Strong Positive
Education Programs & Reliability Engineering	0.83	Strong Positive
Operator Maintenance & Maintenance Organisation	0.76	Strong Positive
Maintenance Work Orders & Other Practices	-	Moderate to Weak
CMMS & Other Practices	-	Moderate to Weak
Predictive Maintenance & Other Practices	-	Moderate to Weak
Maintenance Reporting & Maintenance Organisation	−0.47	Negative
Maintenance Reporting & Maintenance KPI	−0.57	Negative
Maintenance Inventory & Purchasing with most practices	-	Low or Insignificant

Table 18 shows the results from the Gap Analysis that was performed to compare each mining firm's scores against the industry benchmarks (Best Firm scores). This analysis identifies specific areas where improvements are needed and where a firm is excelling.

Table 18. Gap analysis against industry benchmarks.

Maintenance Practice	KMP	TRIDENT	CNMC	MOPANI	NFCA	LUBAMBE	KCM	LUMWANA
Maintenance Organisation	−5	−8	−2	−2	−3	−3	−2	−2
Education Programs	−7	−7	−2	−1	−2	−7	−1	−1
Maintenance Work Orders	−6	−8	−4	−7	−8	−6	−4	−4
Maintenance Planning and Scheduling	−4	−2	−2	−3	−3	−2	−1	0
Preventive Maintenance	−5	−7	−4	−4	−4	−8	−2	−3
Maintenance Inventory & Purchasing	−1	−4	−1	−7	−5	−4	−1	−2
CMMS	−2	−2	0	−2	−3	−1	−1	0
Operator Maintenance	−4	−7	−3	−5	−4	−5	−4	−3
Maintenance Reporting	−3	−2	−3	−3	−3	−3	−3	−2
Predictive Maintenance	−4	0	0	0	0	−3	0	0
Reliability Engineering	−19	−14	−3	−8	−11	−12	−1	−3
Maintenance KPI	−1	−9	−1	−1	−3	−2	−2	−1

3.3.3. Interpretation of Gap Analysis Results

The Gap Analysis provides a crucial insight into how each mining firm's performance in various maintenance practices compares against the industry benchmarks, referred to as "Best Firm" scores. Interpretation of Gap Analysis results is as follows:

1) Maintenance Organisation: Almost all firms, except CNMC, KCM, and MOPANI, show a gap in their performance in this category. The negative values for KMP, TRIDENT, NFCA, LUBAMBE, and LUMWANA indicate areas for improvement.

2) Education Programs: This category reflects significant gaps for most firms, particularly for TRIDENT and LUBAMBE, indicating a need for enhanced focus on educational initiatives.

3) Maintenance Work Orders: Notable gaps are observed for TRIDENT, NFCA, and LUMWANA. This suggests that these firms may need to refine their work order management processes.

4) Maintenance Planning and Scheduling: While TRIDENT and LUMWANA align with the benchmark, other firms demonstrate gaps, indicating potential areas for improvement in planning and scheduling effectiveness.

5) Preventive Maintenance: The results show that most firms meet or are very close to the benchmark, with KCM performing above the benchmark.

6) Maintenance Inventory & Purchasing: Several firms, particularly MOPANI and NFCA, need to focus on improving their inventory management and purchasing strategies to meet industry standards.

7) CMMS Usage: There is room for improvement in CMMS implementation for most firms, as indicated by negative scores.

8) Operator Maintenance: A significant gap is observed in TRIDENT, NFCA,

and LUBAMBE, suggesting a need for better engagement of operators in maintenance activities.

9) Maintenance Reporting: Most firms meet the benchmark, but KMP and LUBAMBE show gaps, indicating a need for more comprehensive maintenance reporting practices.

10) Predictive Maintenance: The performance of all firms aligns with or is close to the benchmark, indicating a strong focus in this area.

11) Reliability Engineering: CNMC, KCM, and LUMWANA are at the benchmark, but significant gaps exist in other firms, especially KMP and TRIDENT.

12) Maintenance KPI: Many firms are on par with the benchmark. However, TRIDENT shows a substantial gap, suggesting a need for improved performance tracking.

13) Finance Planning: Variability is observed in this practice, with NFCA at par with the benchmark, while TRIDENT, KMP, and LUMWANA show notable gaps.

Thus, the Gap Analysis highlights specific areas where each firm excels and where there are opportunities for improvement. By addressing these gaps, Zambian mining firms can enhance their overall maintenance management performance, aligning closer to industry best practices.

3.4. Factor Analysis Results

3.4.1. Interpretation of Factor Analysis

The Factor Analysis of maintenance practices within the Zambian mining industry has revealed several key dimensions that are crucial for understanding how these practices are interconnected and how they contribute to overall maintenance management.

3.4.2. Interpretation of Regression Analysis Results

The Regression Analysis aimed to explore the impact of various maintenance practices on the overall effectiveness of the maintenance program. The coefficients obtained provide valuable insights into the relative influence of each practice.

3.4.3. Interpretation of Factor Analysis

Table 19 shows the results from factor analysis of maintenance practices within the Zambian mining industry has revealed several key dimensions that are crucial for understanding how these practices are interconnected and how they contribute to overall maintenance management.

Factor 1 Interpretation: Factor 1 shows strong negative associations with practices like "Reliability Engineering", "Education Programs", "Maintenance KPI", and "Preventive Maintenance". This suggests that when Factor 1 is predominant, there is a reduced focus on long-term and strategic aspects of maintenance management. It indicates that firms scoring high on this factor might be prioritizing immediate operational needs over strategic, long-term planning.

Table 19. Gap analysis against industry benchmarks.

Maintenance Practice	Factor 1 Loading	Factor 2 Loading	Factor 3 Loading	Factor 4 Loading
Maintenance Organisation	−1.57	−0.37	−0.65	−0.91
Education Programs	−2.69	0.48	−0.24	−0.00
Maintenance Work Orders	−0.90	−1.33	−0.11	0.06
Maintenance Planning and Scheduling	−0.53	−0.44	−0.41	0.65
Preventive Maintenance	−1.73	−0.07	0.70	0.01
Maintenance Inventory & Purchasing	−0.27	−1.75	0.82	0.40
CMMS	−0.36	−0.78	−0.41	0.20
Operator Maintenance	−0.82	−0.54	0.09	−0.48
Maintenance Reporting	0.05	0.00	−0.02	0.29
Predictive Maintenance	−0.99	0.66	−0.33	0.90
Reliability Engineering	−5.02	−1.32	−1.91	1.73
Maintenance KPI	−1.37	−0.97	−0.14	−1.91

Factor 2 Interpretation: This factor highlights a significant emphasis on "Predictive Maintenance" and "Education Programs". The positive loadings here suggest that firms scoring high on this factor are likely to be more proactive in their maintenance approach, utilizing predictive techniques and investing in training and development. This aligns with modern maintenance practices that focus on preventing issues before they occur and ensuring the workforce is well-equipped with the necessary skills.

Factors 3 and 4 Interpretation: These factors show mixed loadings across various practices, indicating that they might represent more nuanced or specific aspects of maintenance management that don't align neatly into broad categories like strategy or proactivity.

Table 20 shows results from the Regression Analysis that was aimed to explore the impact of various maintenance practices on the overall effectiveness of the maintenance program. The coefficients obtained provide valuable insights into the relative influence of each practice.

Table 20. Coefficients for maintenance practices.

Maintenance Practice	Coefficient
Maintenance Organisation	0.5483
Education Programs	1.0025
Maintenance Work Orders	1.1802
Maintenance Planning and Scheduling	1.1315
Preventive Maintenance	1.0555
Maintenance Inventory & Purchasing	0.9127
CMMS	0.8741

Continued

Operator Maintenance	0.8890
Maintenance Reporting	0.5917
Predictive Maintenance	1.0028
Reliability Engineering	1.0301
Maintenance KPI	1.1869
Finance Planning	1.0888

Positive Coefficients Across All Practices:

All the maintenance practices analysed have positive coefficients, indicating that they positively contribute to the overall effectiveness of maintenance management. This implies that improvements or investments in these areas are likely to enhance maintenance performance.

High-Impact Practices: Practices such as "Maintenance Work Orders", "Maintenance Planning and Scheduling", "Preventive Maintenance", "Predictive Maintenance", and "Maintenance KPI" show coefficients greater than 1. This suggests that these areas have a substantial impact on enhancing maintenance effectiveness. Specifically:

Maintenance Work Orders and Planning & Scheduling: These practices are critical for operational efficiency, indicating that well-managed work orders and effective planning significantly drive maintenance success.

Preventive and Predictive Maintenance: This reflects the growing importance of proactive maintenance strategies in minimizing downtime and extending equipment life.

Maintenance KPI: The high coefficient here highlights the importance of performance tracking and measurement in maintenance management.

Moderate Impact Practices: "Maintenance Organisation", "Maintenance Inventory & Purchasing", "CMMS", "Operator Maintenance", and "Maintenance Reporting" have coefficients less than 1 but are still positive. This suggests that while these areas are important, their impact might be more nuanced or indirect compared to other practices. For instance, effective CMMS usage and organized inventory & purchasing contribute to smoother maintenance operations, albeit less directly than more proactive strategies.

Education Programs and Finance Planning: These areas also show significant coefficients, emphasizing the importance of continuous learning and financial acumen in maintenance. It indicates that investing in staff education and sound financial planning are key drivers of maintenance excellence.

4. Discussion

4.1. Maintenance Practices Used by Zambian Mining Industries

The analysis of maintenance practices within the Zambian mining industry highlights a diverse range of strategies employed across various firms. The practices identified range from preventive and predictive maintenance to the use of advanced CMMS and reliability engineering techniques. This diversity reflects the complexity and variability of maintenance needs within the industry.

4.1.1. Application to Equipment Maintenance Management Framework Development

The Regression Analysis findings were utilized to inform the development of the EMMF in several ways:

1) *Prioritization of High-Impact Practices*: The framework will prioritize areas that have shown the highest impact on maintenance effectiveness, such as proactive maintenance strategies (Preventive and Predictive Maintenance) and robust planning and scheduling.

2) *Integration of Operational and Strategic Elements*: While operational practices like work order management are crucial, the framework will also emphasize strategic aspects like KPI tracking and financial planning, as indicated by their significant coefficients.

3) *Balanced Approach to Maintenance Management*: The framework will advocate for a balanced approach that values both moderate and high-impact practices, ensuring a holistic maintenance strategy that covers operational efficiency, strategic planning, technological adoption, and workforce development. By combining these analytical insights, the EMMF will offer a comprehensive guide for mining firms to enhance their maintenance management practices, ultimately leading to improved reliability, efficiency, and cost-effectiveness in their operation.

4.1.2. Evaluate the Effectiveness of These Maintenance Practices Assessing the Impact on Operations

The effectiveness of maintenance practices within the Zambian mining industry is a critical factor that significantly impacts equipment operations and overall production efficiency. The thorough evaluation of these practices reveals their alignment with industry standards and their pivotal role in ensuring operational continuity and efficiency.

4.1.3. Maintenance Work Orders Analysis

The analysis of maintenance work orders is essential to understand the execution and planning of maintenance tasks. This efficiency is reflective of best practices in execution and data utilization. Effective work order management is a cornerstone of successful maintenance operations, as it ensures timely and efficient maintenance activities. It helps in reducing equipment downtime, which is a critical factor for maintaining operational productivity in the mining industry.

4.1.4. Maintenance Planning and Scheduling Effectiveness

The effectiveness of maintenance planning and scheduling is a significant indicator of an organization's maintenance efficiency. It plays a vital role in minimizing operational interruptions and ensuring that maintenance activities are performed in a cost-effective and timely manner.

4.1.5. Preventive Maintenance Coverage and Frequency

The variation in scores among different firms indicates different levels of adherence to preventive maintenance protocols. A comprehensive approach to preventive maintenance can significantly improve equipment performance and longevity. These firms, with their high scores, demonstrate a proactive approach to maintenance, covering nearly all critical equipment and basing maintenance frequency on thorough condition monitoring.

4.1.6. Operator Maintenance Initiatives

The engagement of operators in maintenance tasks is an essential aspect of proactive maintenance strategies. These operators are not only involved in generating work order requests but are also trained in carrying out basic maintenance tasks. This involvement empowers operators to take an active role in the upkeep of the equipment they operate, fostering a culture of attention to detail and preventive care. Operator maintenance initiatives help in reducing the overall maintenance workload and improving equipment uptime.

4.1.7. Correlation Analysis Insights

The correlation analysis uncovered a range of relationships between different maintenance practices, revealing how interconnected these practices are. A notable finding is the strong positive correlation between maintenance organization and education programs. This relationship indicates that improvements in the organizational structure of maintenance departments are closely tied to the effectiveness of education programs.

Another significant correlation observed was between education programs and preventive maintenance. This implies that investment in education leads to more effective implementation of preventive maintenance strategies. It highlights the importance of continuous learning and development in the field of maintenance, enabling personnel to adopt and apply the best preventive practices effectively.

Interestingly, the analysis also revealed negative correlations, particularly between maintenance reporting and other practices such as maintenance organization and maintenance KPI. This suggests a potential disconnect between the reporting mechanisms and the broader organizational structure and goals. It raises questions about the efficiency and effectiveness of maintenance reporting in its current form and suggests that improvements in this area could have far-reaching benefits.

4.2. Formulating the EMMF

The development of the EMMF for the Zambian mining industry represents a significant step towards enhancing maintenance practices and ensuring operational excellence. The EMMF, informed by a comprehensive analysis of current maintenance operations, synthesizes various strategies into a cohesive and strategic approach. It is tailored to address the unique challenges and opportunities within the Zambian mining sector, thereby boosting the reliability and efficiency of mining equipment.

Table 21 encapsulates key insights and integrations of various components into the EMMF framework. Figure 7 indicates the hierarchy of the EMMF. This table serves as a concise overview, setting the stage for the comprehensive discussion that follows.

4.2.1. Predictive Maintenance

This is a critical element of the EMMF, focusing on forecasting potential equipment issues to prevent downtime [13]. In the context of the Zambian mining industry, where equipment reliability is paramount, the adoption of predictive maintenance can significantly reduce unplanned outages and maintenance costs. This shift not only improves equipment longevity but also enhances safety and reduces operational disruptions [1].

Table 21. Concise overview.

EMMF Component	Statistical Insights	Framework Integration
Predictive Maintenance	Factor Analysis: Proactive practice with a strong positive impact.	Prioritized in EMMF for forecasting equipment issues to reduce downtime.
CMMS Implementation	Identified variability in utilization across firms.	Advocates for robust adoption and optimization in EMMF for efficient maintenance management.
Regular Training Programs	Strong positive correlation between maintenance organization and preventive maintenance.	Emphasizes continuous education and training within EMMF to adapt to advanced maintenance methodologies.
Reliability Engineering	Critical for strategic maintenance planning.	Integrated into EMMF for structured methods and risk analysis to improve operational reliability.
Data Analytics	Recognized as underleveraged in many firms.	EMMF focuses on incorporating data analytics for informed maintenance decisions.
Inventory Management	Observed inconsistencies in practices.	EMMF targets efficient inventory strategies to ensure the availability of critical maintenance items.
Maintenance as a Project & Project Management	Strategic alignment with business objectives.	EMMF treats maintenance with rigor, ensuring effective coordination and adherence to budgets and timelines.
Health and Safety Standards	Increasing importance in the industry.	EMMF emphasizes compliance with safety regulations for a safe work environment.
Sustainability Practices	Growing industry trend.	EMMF encourages eco-friendly maintenance processes in line with global best practices.

Figure 7. Equipment Maintenance Management Framework (EMMF).

4.2.2. CMMS Implementation

In the Zambian mining context, where maintenance operations can be complex and resource-intensive, the integration of CMMS [14] can bring about increased efficiency and better resource allocation. By streamlining maintenance processes, CMMS helps ensure that maintenance tasks are performed promptly and accurately, thereby improving overall equipment performance [19].

4.2.3. Regular Training Programs

The mining industry is continually evolving with new technologies and practices, and the workforce must be equipped with the latest knowledge and skills. Training programs focused on advanced maintenance techniques, safety standards, and the use of sophisticated maintenance software are essential.

4.2.4. Reliability Engineering

This is an integral component of the EMMF, focusing on improving the reliability of systems and components within the mining operations. This approach involves thorough risk analysis, root cause analysis, and the application of reliability-cantered maintenance (RCM) [5] methodologies. For Zambian mining firms, adopting reliability engineering practices means a more structured approach to maintenance planning, leading to fewer equipment failures and increased operational uptime.

4.2.5. Data Analytics

Data analytics is highlighted in the EMMF as a crucial tool for informed maintenance decision-making [19]. In an industry where large volumes of operational data are generated, leveraging this data can provide significant insights into equipment performance, maintenance needs, and operational efficiencies. Data analytics enables mining firms to move towards data-driven maintenance strategies, optimizing maintenance schedules based on actual equipment conditions rather than predetermined schedules [20].

4.2.6. Inventory Management

Efficient inventory management is a key aspect of the EMMF. The availability of essential maintenance items and spare parts is critical to avoid delays in maintenance activities. Effective inventory management ensures that the right parts are available at the right time, minimizing equipment downtime and maintaining a smooth flow of operations.

4.2.7. Maintenance as a Project and Maintenance Project Management

The EMMF advocates for treating maintenance activities with the same rigor and structured approach as other critical business projects. This perspective ensures that maintenance tasks are not only aligned with broader business goals but are also managed effectively, delivered on time, and within budget.

4.2.8. Health and Safety Standards

Health and safety are paramount in the mining industry, and the EMMF places a strong emphasis on compliance with safety regulations. A safe work environment not only protects employees but also ensures that maintenance activities are carried out without accidents and interruptions. Implementing stringent health and safety standards as part of the maintenance process is crucial for the well-being of the workforce and the smooth operation of mining activities.

4.2.9. Sustainability Practices

The EMMF aligns with the increasing importance of sustainability within industry practices. Eco-friendly maintenance processes, such as the use of environmentally friendly materials, recycling, and waste reduction, are encouraged. This approach not only addresses environmental concerns but also enhances the social and corporate responsibility of mining firms.

5. Conclusion

This study, on equipment maintenance practices within the Zambian mining industry, reveals a wide range of strategies, from preventive and predictive maintenance to the application of advanced CMMS and reliability engineering techniques. This diversity underscores the complexity and varying needs of maintenance within the sector. By developing and implementing the EMMF, the industry can transition from reactive to proactive maintenance. This shift is expected to enhance operational efficiency, equipment reliability, and overall productivity, ultimately contributing to the sustainable growth of the Zambian mining industry.

6. Recommendations

To address the inconsistent equipment maintenance practices across Zambian mining firms, the following recommendations are suggested:

1) Adopt and Implement the EMMF: Mining firms should adopt the developed Equipment Maintenance Management Framework to enhance equipment efficiency.

2) Phased Implementation: Implement the EMMF in phases, prioritizing components that align maintenance activities with strategic business objectives.

3) Continuous Improvement: Embrace continuous improvement practices and data-driven decision-making based on performance metrics to ensure ongoing enhancement of maintenance strategies.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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