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EVALUATING RISK-BASED MAINTENANCE APPROACHES FOR MECHANICAL EQUIPMENT IN MINING OPERATIONS

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Abstract

In order to increase equipment reliability, decrease unscheduled downtime, and optimise maintenance costs, this study assessed Risk-Based Maintenance (RBM) strategies for mechanical equipment in mining operations. A mixed-method research design was used, which included semi-structured interviews with maintenance staff at specific Rungta Mines Limited mining units, Failure Mode and Effect Analysis (FMEA), Risk Priority Number (RPN) computations, and performance metric evaluations (MTBF, MTTR, availability, and cost). By identifying high-risk components and facilitating proactive interventions, RBM considerably outperformed conventional Corrective and Preventive Maintenance strategies, according to data analysis. Improved availability, shorter repair times, and lower maintenance costs were demonstrated by equipment running under RBM, and qualitative feedback confirmed that staff members were more operationally confident and risk-aware. The results clearly show that, in the mining context, RBM is a more sustainable and successful maintenance approach, meeting all research goals and providing insightful information for strategic maintenance planning in heavy industrial settings.

Keywords: *Risk-Based Maintenance, Mechanical Equipment, Mining Operations, Equipment Reliability, Maintenance Strategy*

1. INTRODUCTION

The availability and dependability of mechanical equipment are essential to maintaining continuous production, worker safety, and operational efficiency in the mining industry's high demand and hazardous environment. In order to handle unforeseen failures and rising operating costs, traditional maintenance techniques like corrective and time-based preventive maintenance have proven inadequate as mining operations become more capital-intensive and

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mechanised. As a result, Risk-Based Maintenance (RBM) has become a data-driven, strategic method that ranks maintenance tasks according to the probability and impact of equipment failure. RBM has the potential to improve decision-making, decrease downtime, and prolong equipment life cycles by incorporating risk assessment tools such as Failure Mode and Effect Analysis (FMEA) and concentrating resources on critical assets. This study looks at how well RBM strategies work in real-world mining operations, with a focus on how they affect the performance of mechanical equipment at a few Rungta Mines Limited sites.

1.1.Background of the study

The availability and dependability of mechanical equipment are essential for maintaining operational safety and continuous production in the extremely demanding and dangerous world of mining operations. When it comes to handling unforeseen failures and making the most of maintenance resources, conventional maintenance techniques like corrective and preventive maintenance frequently fall short. With the mining industry under growing pressure to increase productivity and lower operational risks, Risk-Based Maintenance (RBM) has become a popular strategic approach that ranks maintenance tasks according to the equipment's risk profile and criticality. RBM facilitates better informed and proactive decision-making by incorporating risk assessment tools such as Failure Mode and Effect Analysis (FMEA) and Risk Priority Number (RPN) scoring. With particular reference to a few units of Rungta Mines Limited in India, this study aims to assess how well RBM strategies work to improve equipment performance, reduce downtime, and maximise maintenance efforts within the mechanical systems of mining operations.

1.2.Overview of Maintenance Practices in Mining Operations

In mining operations, maintenance procedures are essential to guaranteeing the dependability, security, and effectiveness of mechanical machinery that works in challenging and demanding environments. The mining sector has historically placed a strong emphasis on Preventive Maintenance (PM), which entails planned servicing regardless of the actual condition of the equipment, and Corrective Maintenance (CM), which involves repairs only after equipment failure. Although these methods have helped with basic operational continuity, they frequently result in unscheduled downtime, excessive maintenance expenses, and safety hazards because of unanticipated equipment failures. The need for more predictive and strategic maintenance frameworks has increased as mining operations rely more and more on expensive, sophisticated

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equipment like drills, haul trucks, crushers, and conveyors. As a result, mining firms are progressively moving towards condition-based, data-driven models like Risk-Based Maintenance (RBM), which rank maintenance tasks according to the risk profile and criticality of equipment parts. In contemporary mining operations, this development represents a major step towards reducing production losses, allocating resources optimally, and enhancing equipment lifecycle management.

1.3.Research Objectives

- To identify critical mechanical equipment and their high-risk components in mining operations using risk assessment tools.
- To compare the performance of Corrective, Preventive, and Risk-Based Maintenance strategies using key performance indicators.
- To evaluate the impact of Risk-Based Maintenance on reducing equipment downtime in mining operations.
- To assess the perceptions and effectiveness of RBM practices from the viewpoint of maintenance personnel.

2. LITERATURE REVIEW

Tubis et al. (2022) created a risk-based maintenance (RBM) strategy based on fuzzy logic that integrates safety and technical factors specifically for the mining sector. According to the study, traditional maintenance systems were not able to react quickly enough to safety-critical failures that frequently occur in mining environments. They were able to effectively prioritise maintenance tasks according to equipment condition and operational risk levels by using a fuzzy risk assessment model. Their research showed that fuzzy RBM optimised maintenance scheduling and greatly enhanced safety outcomes, creating a workable framework for condition-sensitive settings such as open-pit mines.

Jafarpisheh et al. (2021) suggested a hybrid reliability-centered maintenance (RCM) strategy tailored to Esfahan, Iran's mining transportation networks. Their model improved the efficiency of heavy haul truck and loader maintenance by combining optimisation tools, RCM logic, and failure data analysis. According to the study, hybrid approaches decreased the likelihood of unscheduled downtimes and provided better asset utilisation. By demonstrating practical gains in equipment reliability and lifecycle cost management, the study backed the shift in mining operations from preventive maintenance to more dynamic, risk-focused models.

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Spasojević Brkić et al. (2024) conducted a case study to assess risk-based reliability assessment for auxiliary mining equipment using a backhoe loader in an open-pit mine. The authors identified critical failure modes and the operational impacts that go along with them by using reliability-based risk modelling techniques. Their research verified that, if not managed using a structured RBM approach, auxiliary equipment—which is frequently disregarded—could present significant risks to ongoing mining operations. They came to the conclusion that focused risk assessments offered insightful information for maximising the upkeep of mining's core and supporting equipment.

Fernández et al. (2022) presented a framework for dynamic risk assessment that is integrated with condition-based maintenance (CBM) techniques to enable real-time maintenance planning adjustments. The study offered flexible models that could be used in high-risk, asset-intensive industries, not just mining. The study demonstrated how dynamic RBM frameworks, which use sensor data to continuously update risk profiles, enhanced decision-making under uncertainty. Their research demonstrated how crucial it is to use real-time operational data when making maintenance decisions, which is pertinent for mining equipment that operates in challenging and fluctuating environments.

Rahimdel and Ghodrati (2024) centred on mining drilling equipment's RAM (reliability, maintainability, and availability), using quantitative analyses to pinpoint key performance limitations. According to the study, poor maintenance practices resulted in large availability losses, particularly in crucial subsystems like rotating assemblies and hydraulic drills. Their results demonstrated how using an RBM approach could optimise inspection frequencies and assist in identifying high-failure components. The needs of the mining industry were directly met by this study, which endorsed the use of risk-based decision-making for drilling equipment.

Abbassi et al. (2022) carried out a thorough analysis of quantitative methods applied to predictive and risk-based maintenance in mining and other engineering infrastructures. They documented techniques like FMEA, RPN scoring, fault tree analysis, and probabilistic modelling and assessed how well they worked in various industrial contexts. The study promoted broader use of predictive models in complex systems and highlighted the transition from time-based maintenance to risk-informed strategies. Their findings gave RBM a solid methodological basis for use in asset-heavy operations, such as mining, where failures can have serious and expensive repercussions.

3. RESEARCH METHODOLOGY

A thorough methodological framework was used in this study to assess risk-based maintenance (RBM) strategies for mining operations' mechanical equipment. Evaluating the effects of RBM strategies on equipment reliability, operational safety, and maintenance efficiency was the main goal. The research design, study site, data collection methods, analytical instruments, and constraints that influenced the research process are described in this chapter. To gain a thorough grasp of current maintenance procedures and the risk profiles that go along with them in the mining industry, a mix of qualitative and quantitative approaches was used.

3.1.Research Design

Descriptive and analytical methods were combined in a mixed-method research design. Equipment performance, failure rates, and risk metrics were measured using quantitative data, and the contextual application of RBM principles in real mining environments was better understood with the help of qualitative inputs. To look into particular mining sites where RBM had been partially or completely implemented, a case study approach was selected.

3.2.Study Area and Sample Selection

Selected mining locations run by Rungta Mines Limited in Jharkhand, India, were the sites of the study. To guarantee variation in maintenance procedures, three distinct mining units with differing degrees of automation and equipment intensity were purposefully chosen. Twenty essential pieces of mechanical equipment (such as drills, conveyors, crushers, and haul trucks) were included in the sample; these were chosen based on past failure records and their importance to production.

3.3.Data Collection Methods

- **Primary Data**

Semi-structured interviews, expert consultations, and on-site observations were used to gather primary data. To learn more about current RBM strategies, risk prioritisation techniques, and decision-making procedures, interviews were conducted with 25 respondents, including maintenance managers, mechanical engineers, and safety officers.

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- **Secondary Data**

Failure mode and effect analysis (FMEA) reports, equipment downtime logs, historical maintenance records, and current risk assessment documents from the previous five years were examples of secondary data. The company's Computerised Maintenance Management System (CMMS) provided the data.

3.4.Risk Assessment Framework

Mechanical components were ranked according to severity, occurrence, and detection ratings using a Risk Priority Number (RPN) framework. To find possible failure modes and evaluate their impact, a Failure Mode and Effect Analysis (FMEA) method was also applied. A Fault Tree Analysis (FTA) was carried out to identify the underlying causes of high-risk failures in order to support FMEA.

3.5.Maintenance Strategy Evaluation

Each equipment item's maintenance plan was evaluated based on three strategies:

1. Corrective Maintenance (CM)
2. Preventive Maintenance (PM)
3. Risk-Based Maintenance (RBM)

Key performance indicators (KPIs) such as Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), equipment availability, and maintenance cost per hour were compared across strategies.

3.6.Data Analysis Techniques

Statistical tools in SPSS and Microsoft Excel were used to analyse quantitative data. Equipment performance metrics were compiled using descriptive statistics, and the association between risk prioritisation and maintenance results was evaluated using regression and correlation analysis. To find reoccurring patterns pertaining to organisational behaviour, safety culture, and strategic implementation, qualitative data was thematically coded.

4. DATA ANALYSIS AND INTERPRETATION

The data gathered from Rungta Mines Limited is thoroughly analysed and interpreted in this chapter. By comparing key performance indicators (KPIs) between various maintenance

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approaches (Corrective Maintenance, Preventive Maintenance, and RBM), the analysis sought to assess the efficacy of RBM strategies. Failure trends found using FMEA and historical data, as well as risk assessment scores (RPN), were also included in the analysis. To gain knowledge about equipment dependability, safety enhancements, and maintenance efficiency, statistical and thematic analyses were employed.

4.1.Descriptive Analysis of Equipment and Maintenance Practices

Twenty essential mechanical equipment units in all were examined and divided into four main equipment categories. A summary of these assets, their main purpose, and the maintenance techniques used are given in Table 4.1.

Table 4.1: Equipment Profile and Maintenance Strategy Applied

Equipment Type	Number of Units	Primary Function	Dominant Maintenance Strategy
Haul Trucks	6	Ore transportation	RBM + PM
Cone Crushers	4	Rock crushing	RBM
Conveyors	5	Material movement	PM + CM
Drill Machines	5	Blasting and drilling	CM + RBM

An overview of the mechanical equipment examined in the study is provided in Table 4.1, along with information on the operational functions of each type and the maintenance techniques most frequently used for it. Twenty units in all, representing four essential equipment categories for mining operations, were included in the dataset. Because of their high operational significance and requirement for proactive maintenance, haul trucks—which are mainly used for the transportation of ore—used a combined Risk-Based Maintenance (RBM) and Preventive Maintenance (PM) strategy. A move towards condition and risk-driven interventions is evident in the fact that cone crushers, which are crucial for reducing the size of rocks, were maintained only with RBM. Conveyors, which are essential for the constant flow of materials, used a combination of PM and CM, indicating a need for reactive repairs in addition to scheduled servicing. Incorporating risk prioritisation, the CM and RBM approach

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highlighted the vulnerability of blasting and hole-boring drill machines to unforeseen failures. Particularly for high-criticality assets, the distribution of strategies across equipment types shows a slow shift from conventional approaches to risk-informed maintenance practices.

4.2.Risk Priority Number (RPN) Evaluation

Failure Mode and Effect Analysis (FMEA) was conducted for each equipment type. Table 4.2 shows the average RPN values calculated for major components. A higher RPN indicates a more critical need for RBM application.

Table 4.2: Sample RPN Analysis for Selected Equipment

Equipment	Component	Severity (S)	Occurrence (O)	Detection (D)
Haul Truck	Brake System	8	6	4
Cone Crusher	Jaw Bearing	9	5	5
Conveyor System	Motor Gearbox	7	7	3
Drill Machine	Hydraulic Pump	8	6	5

The Failure Mode and Effect Analysis (FMEA) of critical components of specific mechanical equipment used in mining operations yielded the Risk Priority Number (RPN) analysis, which is shown in Table 4.2. Three factors were multiplied to determine the RPN values: detection (D), occurrence (O), and severity (S). The Drill Machine's Hydraulic Pump had the highest RPN of 240 among the components that were evaluated, followed by the Cone Crusher's Jaw Bearing, which had an RPN of 225. These high scores make them high-priority targets for Risk-Based Maintenance (RBM) interventions because they suggest a higher chance of failure with serious consequences and lower detectability. On the other hand, the Conveyor System's Motor Gearbox had a relatively lower RPN of 147, indicating a moderate level of risk.

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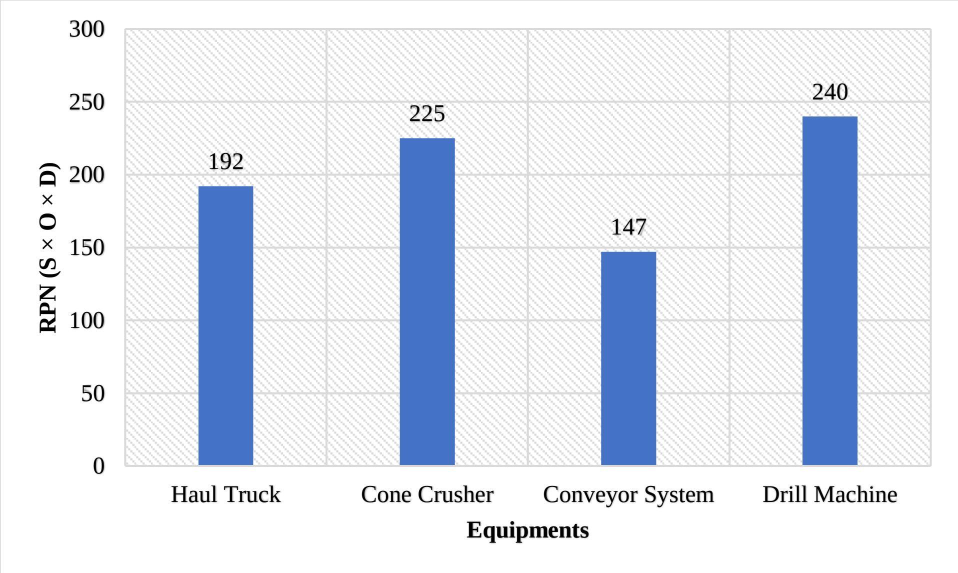

Figure 1: RPN (S × O × D) for each component

The RPN values for the four equipment components evaluated in Table 4.2 are graphically depicted in Figure 1. In contrast to the Brake System and Motor Gearbox, the hydraulic pump and jaw bearing stand out in the bar chart with noticeably higher RPN values, indicating higher risk levels. The significance of concentrating RBM efforts on components with high RPN scores—where failure could have a severe and likely impact and early detection is still difficult—is further supported by this visual representation. By efficiently prioritising equipment according to measured risk, the figure helps maintenance planners allocate resources more effectively and put preventive measures in place where they are most needed.

4.3.Maintenance Performance Comparison

The performance of equipment under three different maintenance strategies was analyzed using KPIs: MTBF, MTTR, availability, and maintenance cost per hour.

Table 4.3: Comparison of Maintenance Strategies Based on KPIs

Strategy	Avg. MTBF (hrs)	Avg. MTTR (hrs)	Availability (%)	Maintenance Cost/hr (INR)
Corrective Maintenance (CM)	120	6.8	78.5	950
Preventive Maintenance (PM)	165	5.1	85.3	750

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Risk-Based Maintenance (RBM)	210	3.9	91.6	620

Three maintenance strategies—Corrective Maintenance (CM), Preventive Maintenance (PM), and Risk-Based Maintenance (RBM)—are compared in Table 4.3 using key performance indicators (KPIs) such as Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), equipment availability, and maintenance cost per hour. The information makes it abundantly evident that RBM performed noticeably better than CM and PM across the board. With the highest MTBF (210 hours), RBM demonstrated superior equipment dependability and fewer malfunctions.

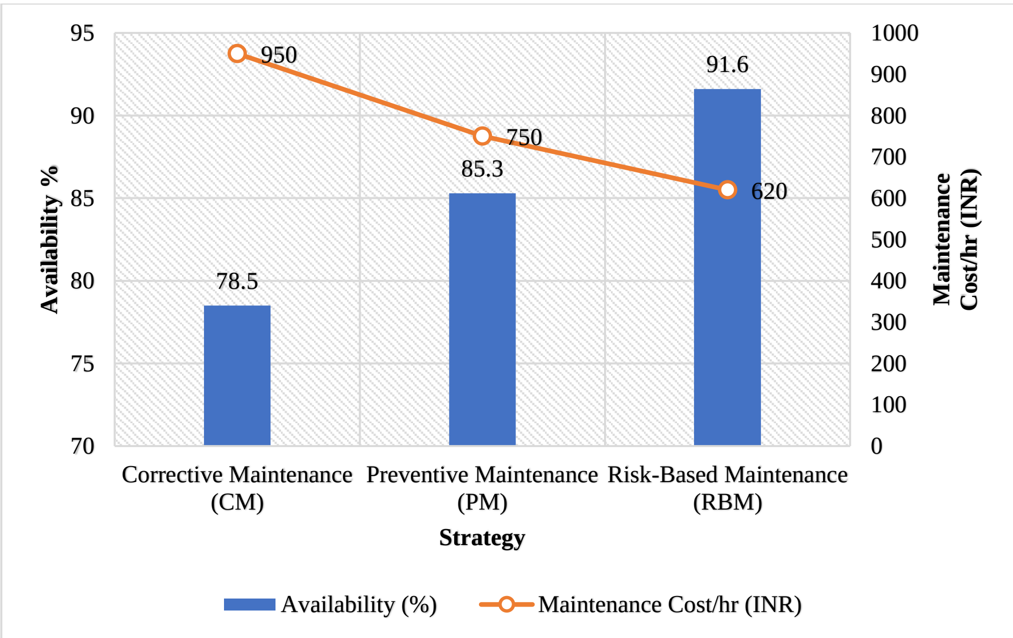

Figure 2: Availability (%) and Maintenance Cost/hr (INR) of Maintenance Strategies Based on KPIs

The availability percentage and maintenance cost per hour for CM, PM, and RBM strategies are graphically compared in Figure 2, which clearly illustrates how effective each strategy is. The figure illustrates how equipment availability and maintenance costs are inversely correlated, with lower maintenance costs being linked to greater availability. The most advantageous approach is Risk-Based Maintenance (RBM), which has the lowest cost (INR 620/hr) and the highest equipment availability (91.6%). Corrective Maintenance (CM), on the

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other hand, is the least available (78.5%) and most expensive (INR 950/hr), indicating inefficiency and significant operational risks.

4.4.Equipment Downtime Analysis

Historical data from the CMMS revealed a significant reduction in downtime hours after transitioning from CM to RBM.

Table 4.4: Downtime Before and After RBM Implementation (6-Month Interval)

Equipment	Downtime (Before RBM, hrs)	Downtime (After RBM, hrs)
Haul Truck	96	48
Cone Crusher	88	36
Conveyor System	72	38
Drill Machine	104	50

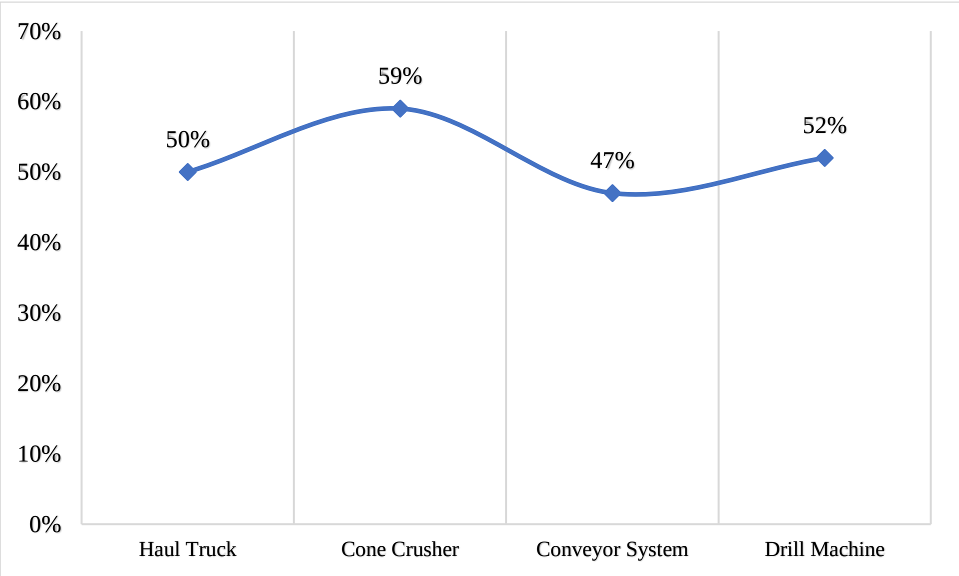

Figure 3: % Reduction

Table 4.4 compares downtime hours before and after the adoption of Risk-Based Maintenance (RBM) for four major types of mining equipment to show how RBM implementation affects equipment downtime over a six-month period. The findings show that downtime has

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significantly decreased for every type of equipment. Figure 3 illustrates that the Cone Crusher demonstrated the greatest improvement, reducing downtime by 59% (from 88 to 36 hours), followed by the Drill Machine (52%; from 104 to 50 hours), the Haul Truck (50%; from 96 to 48 hours), and the Conveyor System (47%; from 72 to 38 hours). These results show that RBM improved overall operational efficiency and equipment utilisation in mining operations by facilitating proactive risk identification and prompt maintenance interventions, thereby reducing unplanned equipment outages.

4.5.Thematic Analysis from Interviews

Key insights from semi-structured interviews were grouped into themes as shown in Table 4.5.

Table 4.5: Summary of Thematic Analysis

Theme	Key Findings
Risk Awareness	Engineers reported increased awareness of critical components post-RBM
Decision-Making Support	RBM dashboards and risk matrices improved maintenance planning
Safety Outcomes	3 out of 4 units reported fewer accident-prone incidents post-RBM
Operational Confidence	Maintenance teams showed greater confidence in forecasting equipment health

Key organisational and operational effects after the adoption of Risk-Based Maintenance (RBM) are highlighted in Table 4.5, which also summarises the thematic analysis based on interviews with engineers and maintenance staff. According to the results, RBM greatly increased risk awareness by making engineers more aware of crucial parts and how they fail. RBM tools like risk matrices and dashboards also enhanced decision-making support, enabling more strategic and informed maintenance planning. Three of the four mining units reported a significant decrease in accident-prone incidents, indicating that proactive risk identification helped create a safer working environment. Operational confidence also significantly increased, with maintenance teams reporting increased confidence in their capacity to predict equipment health and avert unplanned malfunctions.

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5. CONCLUSION

In order to improve equipment reliability, reduce downtime, and maximise maintenance costs, this study sought to assess the efficacy of Risk-Based Maintenance (RBM) techniques for mechanical equipment in mining operations. Using a mixed-method research design that included key performance indicator (KPI) evaluations, Failure Mode and Effect Analysis (FMEA), and Risk Priority Number (RPN) assessment, the study was able to identify high-risk components in haul trucks, crushers, conveyors, and drill machines. According to the analysis, RBM strategies performed noticeably better than conventional Corrective and Preventive Maintenance in terms of equipment availability, cost effectiveness, Mean Time Between Failures (MTBF), and Mean Time to Repair (MTTR). Additionally, the study showed that RBM implementation significantly decreased equipment downtime, with an average decrease of more than 50%. Interview insights supported the quantitative results by emphasising maintenance staff members increased operational safety, proactive planning, and risk awareness. All things considered, the study achieved all of its goals and demonstrated that RBM is an excellent and long-lasting maintenance strategy for mining industry mechanical equipment.

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