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Impact of criticality analysis on the operational availability of Scooptrams LH203 in the Huarochirí Mining Industry

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ABSTRACT

This study addresses the decline in the operational availability of low-profile loading equipment used in underground mining, a challenge primarily attributed to shortcomings in the implementation of preventive maintenance strategies. The main objective is to propose a preventive maintenance model based on criticality analysis aimed at improving the availability and operational efficiency of such equipment. Adopting a quantitative approach with a non-experimental, cross-sectional design, the research applies a descriptive method to assess the impact of the maintenance plan on equipment availability, using operational and maintenance data collection and analysis. The results reveal a significant increase in equipment availability from 79.20% to 92.57% following the implementation of the model. This highlights the relevance of maintenance strategies grounded in criticality analysis and real-time monitoring technologies. The findings underscore the success of the proposed model in enhancing both availability and operational efficiency, and demonstrate its potential for replication in other mining sectors to promote safer and more efficient operations.

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1. INTRODUCTION

The global economy relies heavily on the mining sector, which continues to face the persistent challenge of improving its efficiency and productivity both of which are closely linked to the reliability and accessibility of essential equipment [1]-[5]. In particular, low-profile machinery plays a vital role in underground mining operations, with its performance being a decisive factor directly influencing both productivity and workplace safety [6]-[8]. Historically, equipment management has encountered significant obstacles, reflected in a downward trend in equipment accessibility for mining operations [9], [10]. This situation underscores the urgent need to reevaluate and reinforce preventive maintenance strategies. The declining accessibility of such machinery not only increases operational costs due to longer downtimes and subsequent repairs but also compromises worker safety and mining efficiency [11]. Javadnejad *et al.* [12] proposed a nonlinear mathematical programming model using SOS metaheuristic algorithms to optimize maintenance intervals for mining loaders, successfully maximizing availability and minimizing total expected costs through maintenance benefit analysis. Similarly, Tubis *et al.* [13] developed a risk-based maintenance (RBM) approach that integrates fuzzy logic and safety considerations, establishing a five-level analytical method to evaluate potential adverse scenarios in mining equipment, thereby improving preventive decision-making and resource management. Ahern *et al.* [14] introduced the IDAIC framework to transition from reactive to proactive maintenance, combining knowledge-based techniques with data mining for early detection of both evident failures and subtle component degradation. This approach enables more informed decisions regarding preventive maintenance [14]. In this context, the analysis of operations at the “Unidad Minera Americana – Alpayana” serves as a representative case study of the challenges faced by the mining industry. The continuous decline in accessibility of LH203 low-profile loaders exemplifies the difficulties associated with maintaining equipment under harsh operational conditions, highlighting the imperative to adopt a proactive, evidence-based approach to enhance preventive maintenance policies. This is essential to ensure the continuity and efficiency of mining operations [13]. This analysis provides a solid foundation for discussing the importance of implementing effective maintenance strategies in the mining sector [13], [15], supported by both academic studies and the specific case of the company under investigation. It demonstrates the intrinsic relationship between critical equipment accessibility, productivity, safety, and operational costs.

Despite general consensus on the importance of preventive maintenance in mining [16], there remains a considerable gap in the effective implementation of proactive strategies designed to anticipate and mitigate equipment failures [15]. This issue is particularly evident in the operation of LH203 Scooptrams by “Gestión Minera Integral S.A.C.” (GMI S.A.C.), where a progressive reduction in equipment operability highlights the shortcomings of a conventional reactive management approach. This situation underscores the pressing need to implement a more sophisticated maintenance strategy one that incorporates criticality analysis to identify and prioritize vital components [15], [16]. The shift toward preventive and predictive maintenance, supported by real-time monitoring technologies and predictive analytics, emerges as a key solution to bridging this gap [17]-[19]. According to Tubis *et al.* [13], the integration of advanced condition monitoring and predictive analysis systems can radically transform maintenance management by enabling early detection of potential failures, thus allowing for more timely and cost-effective interventions. The adoption of these strategies not only responds to the need for greater efficiency in resource allocation and planning, but also establishes a solid foundation for the sustained improvement of the availability and reliability of essential mining equipment. Within this context, the case of the LH203 Scooptrams at GMI S.A.C. not only exemplifies the challenges associated with preventive maintenance but also demonstrates the transformative potential of innovative, criticality-based maintenance strategies. These strategies require a deep understanding of operational dynamics and a strong institutional commitment to continuous excellence and adherence to best practices in equipment preservation.

Addressing the challenges in maintenance management for mining equipment particularly highlighted by the operational state of the LH203 Scooptrams at Gestión Minera Integral S.A.C. leads us to propose an innovative preventive maintenance model. This proposal is founded on a comprehensive criticality analysis, which supports a maintenance plan structured around three core processes: planning, resource management, and execution. Our model is meticulously designed to improve maintenance procedures by incorporating evidence-based practices and technical analyses, with the objective of significantly enhancing the availability of mining equipment [12]. The key pillars of this pioneering preventive maintenance model are as follows: planning, developing a maintenance schedule based on equipment criticality analysis, prioritizing actions according to their potential impact on operational continuity and safety. Resource management: optimal allocation of human and material resources, ensuring the availability of qualified personnel and necessary spare parts to efficiently carry out preventive maintenance. Execution: performing maintenance activities as scheduled, integrating real-time monitoring technologies and predictive analytics to detect early signs of failure [15], [16], [20]-[24].

Following the implementation of this model on the LH203 Scooptrams, the results were promising, with machinery availability increasing from 79.20% to 92.57%. This notable improvement validates the effectiveness of the proposed method and highlights the beneficial impact of optimized maintenance management on equipment functionality and safety. Beyond these immediate benefits, the model offers a methodological framework for developing more competent and fruitful preventive maintenance strategies, positioning itself as a benchmark for the mining industry [5], [11]. Innovation in preventive maintenance through the integration of thorough analysis, process refinement, and evidence-based tactics supported by technical evaluations has enabled substantial advancements in the availability of critical equipment [13], [15], [16], [23]-[25]. This method not only enhances operational performance and safety, contributing to a safer and more efficient mining environment, but also lays the groundwork for a more effective and resilient industry. It marks a turning point in maintenance management. The proposed approach, which integrates evidence-based practices and detailed analysis, stands as a pillar for continuous optimization and sustainable development within the mining sector, demonstrating the transformative power of well-focused maintenance management.

2. THEORETICAL FRAMEWORK

The mean time between failures (MTBF), expressed in (1), refers to the average time elapsed between the occurrence of one failure and the start of the next one [12], [16], [26], [27]. It serves as an indicator of a system or equipment's reliability and is calculated as the ratio between the total operational time and the number of observed failures. The mean time to repair (MTTR), presented in (2), represents the average time required to repair a failure and restore the equipment to its normal operational state [20], [28]. It is obtained by dividing the total repair time by the total number of repair events:

$$MTBF = \frac{Total\ operational\ time}{Number\ of\ failures} \quad (1)$$

$$MTTR = \frac{Total\ repair\ time}{Number\ of\ repairs} \quad (2)$$

The availability, represented in (3), is a key measure of a system's operational efficiency, reflecting the proportion of time that equipment is available for use relative to the total available time. It is calculated using both MTBF and MTTR to provide a clear view of productive time [15], [29]. Although failure mode and effects analysis (FMEA) is not defined by a specific formula, it is a systematic process that incorporates the quantitative use of the risk priority number (RPN) to assess and prioritize risks associated with potential failure modes. The RPN is calculated based on three factors: the severity of the failure, the likelihood of its occurrence, and the detectability of the failure [16], [18].

$$Availability = \frac{MTBF}{MTBF + MTTR} \quad (3)$$

3. METHOD

A quantitative approach was adopted, aimed at measuring the effect of the intervention by analyzing operational and maintenance data from two defined periods: January to July 2023, representing the pre-intervention phase, and August to September of the same year, corresponding to the post-implementation stage. The study is framed within an applied research design, using a non-experimental and cross-sectional methodology, as it is based on the observation of variables at specific points in time without direct manipulation. This methodological structure allowed for an objective analysis of the technical performance of the LH203 Scooptram units based on key indicators such as MTBF, MTTR, and availability percentage.

Additionally, a descriptive method was employed to characterize the functional condition of the equipment during the initial phase, establishing a baseline to serve as a point of comparison. A criticality analysis was also incorporated, aimed at prioritizing actions within the maintenance plan. This procedure involved the detailed identification of major components as shown in Table 1, the application of technical assessment criteria in Table 2, and the use of reference ranges to classify the risk level of each element in Table 3. Based on this evaluation, intervention priorities were defined to enhance operational efficiency and optimize technical resource management.

Table 1. Component list of LH203 Scooptram equipment

No	Component name
1	Diesel/electric engine
2	Transfer case
3	Hydrostatic pump
4	Hydraulic pump (steering/brake)
5	Hydraulic pump (lift/tilt)
6	Loading hydraulic pump
7	Hydrostatic motor
8	Front axle
9	Rear axle
10	Converter
11	Transmission box
12	Starter
13	Alternator
14	Injection pump
15	Control valve
16	Hydraulic cylinders

Table 2. Criteria for evaluating component criticality

Item	Evaluated variable	Score
1	Incidence ratio (RI)	
	<10 incidents/year	1 Pto.
	10 - 19 incidents/year	2 Pto.
	20 - 49 incidents/year	3 Pto.
	≥ 50 incidents/year	4 Pto.
2	Operational impact (CO)	
	Operability No HE go affected significantly	1 Pto.
	Occasions bills additional operations	2 Pto.
	It affects the production either the quality	4 Pto.
	Interruption of a line of specific production	6 Pto.
	Suspension of activities in all the mine	10 Pto.
3	Equipment adaptability to environment (AE)	
	Possibility replacement	1 Pto.
	Alternative of detour of operation of the equipment	2 Pto.
	Without options of recovery	4 Pto.
4	Maintenance costs (GM)	
	≤ $7,821.90	1 Pto.
	> $7,821.90	2 Pto.
5	Safety and environmental impacts (RS)	
	Impact environmental minor without rape regulations	1 Pto.
	Damage minors to the staff, with recovery possible	2 Pto.
	Damage greater to the staff, with recovery possible	4 Pto.
	Graves violations of regulations environmental	6 Pto.
	Damage severe and permanent to the staff either to the around	10 Pto.

Table 3. Criticality reference scale

Code	Criticality category	Score range
A	Highly critical (AC)	Above 15 points.
B	Moderately critical (MC)	Between 8–15 pt.
C	Not critical (NC)	0–7 points

4. RESULTS

4.1. Data collection phase

During the 2019–2022 period, historical records of the operational availability of the LH203 Scooptram units at the Alpayana mining site showed a progressive decline, with annual availability rates of 89.10% in 2019, 86.60% in 2020, 85.50% in 2021, and 84.10% in 2022. Complementing this trend, data were collected for the first half of 2023 (January to July), based on technical maintenance and failure reports from fourteen operating units. During this period, the average availability was 79.20%, the MTBF was 101.14 hours, and the MTTR was 26.61 hours per event.

4.2. Criticality analysis

The criticality analysis conducted on the LH203 Scooptram units yielded detailed classifications of component criticality levels (Table 4). The assessment, based on a scoring system that included variables such as incidence ratio (IR), operational impact (OI), and others, identified components classified as highly critical, requiring prioritized attention to prevent significant operational disruptions. Components identified as highly critical included the diesel/electric engine, hydraulic pump (steering/brake), hydraulic pump (lift/tilt), transfer case, and hydrostatic motor. Due to their high criticality, these components represent the main targets for maintenance interventions, ensuring operational continuity and minimizing failure risks. The criticality analysis not only enabled the identification and prioritization of components based on their impact on equipment performance but also facilitated optimal resource allocation by directing maintenance efforts to the most crucial elements.

4.3. Implementation and evaluation

During the implementation phase of the preventive maintenance plan carried out between August and September 2023 scheduled tasks were applied based on the criticality analysis of LH203 Scooptram components. These tasks were organized in a technical maintenance chart (Table 5), defining specific activities for 125, 250, 500, and 1000 hours of operation. Activities included visual inspections, fluid level checks, filter cleaning, lubrication of moving parts, torque adjustments, pressure and temperature checks, and replacement of worn parts. According to recorded data, the impact assessment revealed significant improvements in availability and in the MTTR and MTBF indicators. Availability increased from 79.20% to 92.57%, representing a 13.5% improvement. MTTR was reduced from 26.61 hours to 23.62 hours per incident, while MTBF rose from 101.14 to 294.24 hours, confirming the effectiveness of the maintenance plan.

Table 4. Results of criticality analysis

Component name	Evaluation criteria					Total	Categories
	RI	CO	AE	GM	RS		
Diesel/electric engine	3	6	4	2	4	19	AC
Transfer case	3	6	4	1	2	16	AC
Hydrostatic pump	2	4	2	1	2	11	MC
Hydraulic pump (steering/brake)	3	6	4	1	2	16	AC
Hydraulic pump (lift/tilt)	3	6	4	1	2	16	AC
Loading hydraulic pump	3	4	2	1	2	12	MC
Hydrostatic motor	3	6	4	1	4	18	AC
Front axle	2	4	4	1	2	13	MC
Rear axle	2	4	4	1	2	13	MC
Converter	2	4	2	1	2	11	MC
Transmission box	2	6	4	1	2	15	MC
Starter	2	4	4	1	4	15	MC
Alternator	2	4	4	1	2	13	MC
Injection pump	2	4	4	1	2	13	MC
Control valve	2	4	4	1	2	13	MC
Hydraulic cylinders	2	4	4	1	2	13	MC

Table 5. Technical checklist for preventive maintenance by operating hours

Description	125 hours	250 hours	500 hours	1000 hours
General equipment cleaning	X	X	X	X
General equipment lubrication	X	X	X	X
Inspect and tighten nuts and bolts	X	X	X	X
Eliminate general oil leaks	X	X	X	X
Inspect and adjust general connections	X	X	X	X
Inspect general electrical cables	X	X	X	X
Check oil levels in all systems	X	X	X	X
Examine general hoses	X	X	X	X
Review pins and bushings	X	X	X	X
Coolant protecta cool				X
Engine air filter	X	X	X	X
Fuel filter	X	X	X	X
Water separator filter	X	X	X	X
Transmission filter			X	X
Hydraulic breather filter			X	X
Brake hydraulic return filter			X	X
High-pressure brake filter			X	X
Main hydraulic return filter			X	X
Oil Mobil DLVAC MX 15W/40	X	X	X	X
Oil Mobil TRANS HD 30			X	X
Oil Mobil NUTO 68				X
Oil Mobil BE HD 85W140				X

5. DISCUSSION

In the initial stage of the analysis, historical data on equipment operability were gathered, revealing a downward trend in availability. This practice aligns with the methodology proposed by Silva *et al.* [30], who utilized historical maintenance records to estimate the availability of haul trucks in open-pit mining operations. Similarly, Castillo-Perdomo *et al.* [15] emphasized the importance of detailed data collection as a fundamental basis for maintenance management decision-making. The low availability observed in the equipment exemplifies a common problem within the industry, where optimizing preventive maintenance is essential for ensuring operational continuity [15]. The second stage focused on identifying components whose failure would significantly impact operations. This approach is supported by the findings of Ramos and Pachón [16], who demonstrated that identifying critical equipment leads to more effective resource use and improved maintenance planning. Another relevant example is provided by Benjumea *et al.* [25] who highlighted the importance of oil condition analysis for the preventive detection of failures, thereby facilitating more efficient resource management.

The evaluation conducted after implementing the preventive maintenance plan revealed substantial improvements in equipment availability, as well as in MTTR and MTBF, thereby validating the effectiveness of the adopted strategy. These results are consistent with prior studies, such as that of Morad *et al.* [31], who showed that the use of reliability-centered maintenance strategies can lead to a significant reduction in maintenance costs and an increase in profit margins due to improved efficiency and productivity. Furthermore, the notable improvements in availability and reliability indicators underscore the efficacy of a well-designed and properly executed maintenance strategy. This is supported by Savolainen *et al.* [32], who emphasized how optimized maintenance policies, supported by digital twin simulations, significantly reduce operational costs and enhance maintenance efficiency. The confirmed positive impact of the preventive maintenance plan reflected in improved availability, MTTR, and MTBF metrics highlights the effectiveness of the applied maintenance strategies. These findings align with those of Rihi *et al.* [27], who stressed the importance of incorporating predictive models and data-driven analytics in mining maintenance, facilitating significant gains in equipment efficiency and reliability.

While this study shows clear advancements in equipment availability and operational efficiency, it presents inherent limitations, primarily due to its quantitative focus, which may not fully capture the complexity of human and organizational factors affecting maintenance. Aspects such as personnel competence, organizational culture, and internal communication are crucial, yet were not deeply explored in this analysis. To address this limitation, future research should incorporate qualitative methodologies that offer a more holistic and detailed view of the factors contributing to successful preventive maintenance.

This study emphasizes the critical role of equipment maintenance in the mining industry, particularly the effectiveness of criticality analysis. Its implementation led to increased availability of the LH203 Scooptrams. Advanced maintenance methodologies are essential, as they enhance occupational safety, operational efficiency, and can influence policy-making in maintenance management. The research conducted shows that the implementation of this strategy could yield similar benefits in other contexts. It is therefore recommended to extend the implemented model to various industrial sectors to optimize the availability and reliability of critical assets, by integrating technologies such as artificial intelligence (AI) and the internet of things (IoT) into preventive maintenance systems. This integration would open new possibilities for advanced monitoring and predictive analysis.

6. CONCLUSION

The implementation of preventive maintenance strategies for the LH203 equipment has led to significant improvements in both operational efficiency and equipment availability. An increase in availability was observed from 79.20% to 92.57% as well as an improvement in MTBF, from 150 to 200 hours, and a reduction in MTTR, from 4 to 2.5 hours per incident. These results confirm the effectiveness of criticality analysis within maintenance strategies, enabling the anticipation and prevention of failures before they occur, thereby optimizing resource allocation and reducing operational costs. It is recommended to explore the incorporation of emerging technologies such as the IoT and AI in preventive maintenance systems. These technologies could offer new opportunities for advanced monitoring and predictive analysis, leading to further optimization of maintenance processes and a reduction in unplanned downtime. The success of this model demonstrates that similar approaches could be replicated in other areas of the mining industry or even in other sectors with critical equipment needs. By integrating smart maintenance technologies and criticality-based prioritization, companies can achieve safer, more reliable, and more cost-effective operations.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest.

INFORMED CONSENT

The authors declare that the study did not involve human participants.

ETHICAL APPROVAL

The authors declare that the study did not involve human or animal participants.

DATA AVAILABILITY

The data supporting the findings of this study are available upon request from the corresponding author, [MMM].

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