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OPTIMIZATION OF OPERATIONAL RISK MANAGEMENT IN THE ECUADORIAN MINING INDUSTRY: APPLICATION OF THE FMEA METHODOLOGY AND WEIBULL DISTRIBUTION FOR THE REDUCTION OF FAILURES IN CRITICAL EQUIPMENT

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Abstract: **The design and implementation of a preventive maintenance plan in the Ecuadorian mining industry requires systematic methodologies to reduce failures in crushing and grinding machines, improving operational availability and productivity. The main problem identified is the reliance on corrective maintenance with no historical records of failures, which causes unexpected shutdowns. This study applies the FMEA (Failure Mode and Effects Analysis) methodology to evaluate the criticality of equipment using the Risk Priority Number (NPR), complemented with the Weibull distribution to model useful life times. [1]**
Key equipment such as the ball mill and jaw crusher at a mining beneficiation plant were analyzed. The results indicate that 25% of the subcomponents have NPR > 300 (unacceptable risk), mainly concentrated in structural elements subjected to severe operating conditions. The implementation of the proposed preventive plan is estimated to reduce unplanned shutdowns by 40–50%, increasing availability from 73% to 90%. Weibull integration provides a robust statistical framework for the transition from reactive maintenance to predictive schemes, optimizing intervention intervals and extending the life of critical assets

Keywords: **FMEA, Weibull, mining, operational risk, preventive maintenance, equipment reliability**

I. INTRODUCTION

The Ecuadorian mining industry plays a strategic role in the national economy, especially in the extraction and processing of metallic minerals such as gold, where crushing and grinding processes are critical for operational continuity. In this context, the high demand on machines and equipment, coupled with severe working conditions (dust, vibrations, variable loads), significantly increases the probability of failures, generating unforeseen downtime that reduces productivity and raises operational costs[2]

Many mining companies still maintain a heavy reliance on corrective maintenance, performing interventions only when the breakdown occurs, resulting in prolonged downtime, loss of production and accelerated wear and tear of key assets. The absence of structured systems for the recording and historical analysis of failures limits the ability to predict and plan maintenance. Faced with this scenario, preventive maintenance management has established itself as an essential strategy to guarantee availability, reliability and useful life of equipment. Various studies indicate that the application of preventive maintenance plans significantly reduces failure rates, reduces repair costs and improves operational safety in production lines intensive in mechanical equipment[3][4]

In the context of mining and grinding processes, preventive maintenance acquires special relevance due to the central role of the ball mill and the jaw crusher, whose unavailability directly impacts productivity and the fulfillment of production goals. The implementation of structured plans, with schedules for inspection, lubrication, adjustments and replacement of critical components, is a good practice to avoid recurrent failures and extend the useful life of this equipment. In addition, the technical literature emphasizes the need to complement preventive maintenance with analysis tools that allow resources to be prioritized according to the importance and risk associated with each asset[1]

Among these tools, the Failure Mode and Effect Analysis (FMEA) is used to identify failure modes, evaluate their severity, frequency of occurrence and detection capacity, allowing maintenance actions to be focused on the most vulnerable components. The use of criticality matrices and strategy assignment models based on availability and risk makes it possible to prioritize teams and define preventive interventions proportional to risk. In this way, maintenance management is no longer a reactive activity but a planned process aligned with productivity and operational continuity objectives.[5][6][7]

In the context of Ecuadorian mining, where operations are exposed to various operational uncertainties, it is essential to have robust methodologies to anticipate and mitigate risks. The Weibull distribution, known for its ability to model the lifetime of components and equipment under various operating conditions, plays a key role in estimating the probability of failure of critical systems. Its application in risk management allows for precise adjustment of the expected useful life of equipment, improved maintenance times and reduced the likelihood of catastrophic failures.[8]

The main purpose of this study is to design and implement a preventive maintenance plan for crushing and grinding machines in the Ecuadorian mining industry, combining FMEA and Weibull analysis, with the aim of reducing failure rates, improving operational availability and increasing production efficiency. Through the diagnosis of the current state of critical machines, the systematic evaluation of failure modes and the statistical modeling of life times, a replicable methodology is proposed that transforms reactive schemes into preventive-predictive approaches[9]

II. METHODS AND MATERIALS

Research Design

A descriptive field study was carried out, applied directly in a processing plant of the Ecuadorian mining industry. The approach was mixed, combining quantitative analyses of historical operational data with qualitative assessments based on multidisciplinary expert judgment. The analysis period covered twelve-month failure records prior to the study, supplemented by on-site technical inspections[7][2]

Population and study sample

74 occurrences of failures recorded in equipment in the crushing and grinding area were analyzed, distributed in eight main machines: ball mill, jaw crusher, conical crusher, conveyor belts, sorting screen, agitation tank, oxygenation blower and feeding cart. 20 failure modes were identified in critical components of the ball mill and jaw crusher.[10]

Instruments and tools

The following data collection and analysis instruments were used:

- Inventory Sheets: Detailed record of machines, equipment, and tools with alphanumeric codes for traceability
- Machinery Data Sheets: Operational Specifications, Nominal Capacities and Design Conditions
- Historical maintenance reports: Fault data, downtime, causes and previous corrective actions
- FMEA Matrix: Structured table for systematic analysis of failure modes with evaluation of severity (S), occurrence (O) and detectability (D) on a scale of 1–10
- Pareto Chart: Identification of Dominant Faults Using Frequency Analysis
- Criticality Matrix: Two-dimensional evaluation (frequency vs. consequence) for risk prioritization
- Weibull Analysis Software: Computational Tools for Distribution Adjustment and Parameter Estimation by Maximum Likelihood

FMEA Methodology

A multidisciplinary team was formed with personnel with experience in operation, maintenance, engineering and supervision. The processincludedthefollowingstages:[11]

Functional exploded view: Identification of components and subcomponents of critical equipment, their functions, potential failure modes, effects on the process and root causes.

Index Assignment: Each failure mode was evaluated using a scale of 1–10 to:

Severity (S): Magnitude of the impact on safety, production, and costs

Occurrence (O): Probability that the failure mode will occur under operational conditions

Detectability (D): The ability of current detection systems to identify mode before causing failure.

Calculation of Risk Priority Number: $NPR = S \times O \times D$

Risk classification: NPRs were grouped into three ranges:

- Acceptable: $NPR < 150$
- AcceptableReduction: $150 \leq NPR < 300$
- Inaceptable: $NPR \geq 300$

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Pareto analysis

A Pareto diagram was developed to identify the 20% of equipment responsible for 80% of failure occurrences, allowing efforts to be concentrated on assets with a greater impact on operational readiness.[12]

Weibull Modeling

For the estimation of Weibull distribution parameters, the maximum likelihood method (MLE) was used. The probabilitydensityfunctionisdefined as:[13]

$$f(x;\lambda,k) = \frac{k}{\lambda}\left(\frac{x}{\lambda}\right)^{k-1} \exp\left(-\left(\frac{x}{\lambda}\right)^{k}\right)$$

Where is the scale parameter (characteristic life) and is the shape parameter (which determines the type of failures: k < 1 child wear, k = 1 random, k > 1 aging wear).λk

The log-likelihood function to be maximized is:[14]

$$\ln L(k,\lambda) = \sum_{i=1}^{n}\left[\ln(k) - k\ln(\lambda) + (k-1)\ln(x_i) - \left(\frac{x_i}{\lambda}\right)^{k}\right]$$

The parameters were estimated using numerical optimization algorithms implemented in Python using the scipy.stats.weibull_min.fit() function. Once the parameters were adjusted, reliability, failure rate, and expected half-life curves were calculated for each critical piece of equipment.[15]

Design of the preventive maintenance plan

Based on the prioritization by NPR and Weibull analysis, a maintenance plan was designed aimed at subcomponents of lower reliability, specifying:[16]

- Specific maintenance tasks (inspection, lubrication, adjustment, replacement)
- Frequencies (daily, monthly, every 4, 8, 12 months)
- Estimatedintervention times
- Assigned managers (supervisor, mechanics, electricians, assistants)

Detailed annual schedules were developed for the ball mill and jaw crusher, with the aim of decreasing the probability of failure, increasing availability and reducing unplanned downtime as can be seen in Figure 1.

<table>
<tr><th colspan="12">FAILURE MODAL ANALYSIS AND EFFECTS OF FAILURE FMEA</th></tr>
<tr><td colspan="3" rowspan="3">COMPANY NAME</td><td colspan="2">Maintenance area</td><td>Code:</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
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Figure 1. FMEA Format Source: Own elaboration.

NPRs were grouped into acceptable risk, acceptable reduction and unacceptable risk ranges, which allowed the identification of elements with less reliability, such as the sheet steel cylinder, ball mill caps and crusher (NPR 480–500–360) and the side plates, positioning spring and eccentric shaft bearing in the jaw crusher (NPR 300–360).[17]

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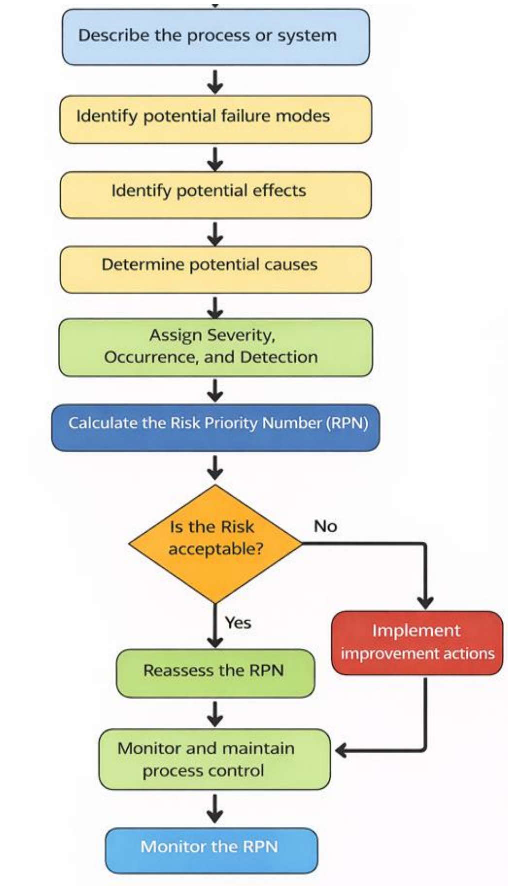

Figure 2. Systematic FMEA Analysis ProcessSource: Own elaboration.

Failure percentages were calculated according to risk level for each subcomponent, quantifying the proportion of elements in acceptable condition, acceptable reduction and unacceptable, which allowed the reliability of each equipment to be evaluated in an aggregate manner (for example, 20% of mill subcomponents in unacceptable condition and 30% in the crusher).

Inventory sheets, machinery technical sheets, maintenance reports, criticality matrix and FMEA tables were used as instruments to record and process failure and maintenance data.[18]

Based on the prioritization by NPR and the risk percentages, a preventive maintenance plan was designed aimed at the subcomponents of lower reliability, defining specific tasks, frequencies (daily, monthly, every 4, 8 and 12 months), intervention times and responsible personnel (supervisor, mechanics, electricians and assistants).[19]

Based on this reliability-focused maintenance approach, annual schedules were drawn up for the ball mill and jaw crusher, with the aim of decreasing the probability of failure, increasing availability, and reducing unplanned downtime affecting production, Figure 2 explains the systematic process for the execution of the maintenance plan[20]

III. RESULTS

Pareto analysisofoccurrences

A total of 74 failure occurrences were recorded distributed among eight main equipment. The ball mill topped the list with 20 occurrences (27%), followed by the jaw crusher with 18 occurrences (24%), both accumulating 51% of all recorded failures. This analysis clearly identified priority assets for intervention.

The critical components of both equipment were analyzed, calculating NPR for 20 failure modes. 25% of the subcomponents presented NPR > 300 (unacceptable risk), Table 2 summarizes the failures of the machines as can be seen in Figure 4.

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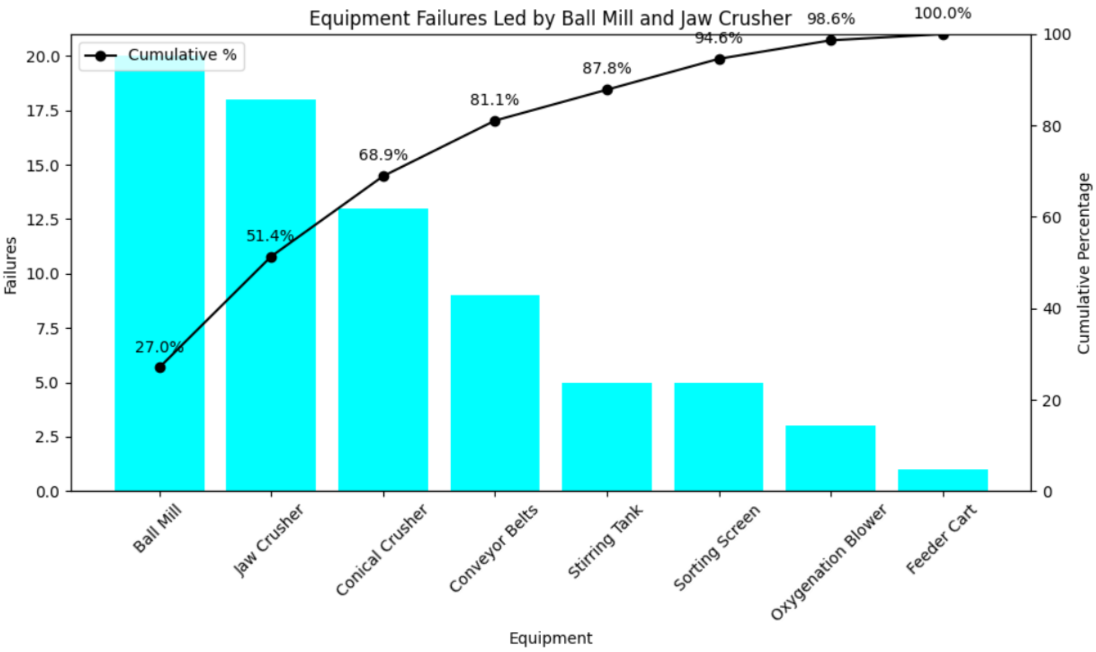

Figure 3. Pareto occurrence of failures Source: Own elaboration.

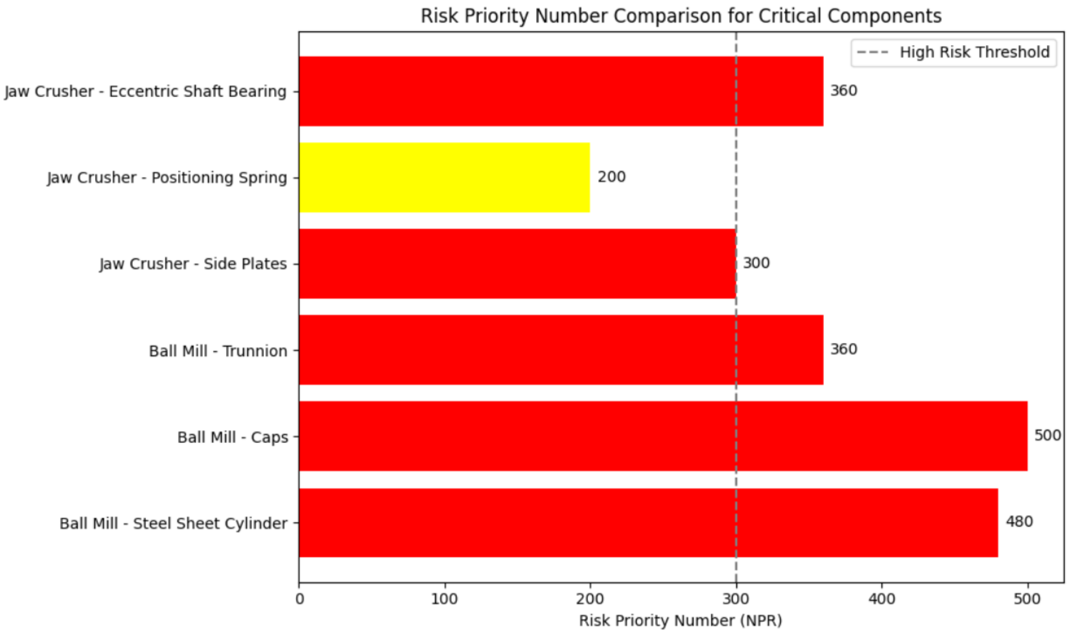

Figure 4. Classification of Mining Machinery Failures Source: Own elaboration.

Implementation of the preventive plan, based on FMEA NPRs, would reduce unplanned shutdowns by 40–50%, increasing the availability of critical equipment from the current 73% to 90%. By integrating Weibull distribution into the analysis, it will be possible to more accurately estimate the service life of equipment and predict failures before they occur, optimizing intervention times and further improving operational reliability. Weibull distribution, when applied to model the failure times of critical equipment, provides a predictive approach that, combined with the preventive maintenance plan, maximizes efficiency, reduces operating costs and extends the useful life of assets, ensuring continuous and reliable performance of critical systems in the mining industry. Figure 3 shows the flowchart for the execution of the maintenance plan.

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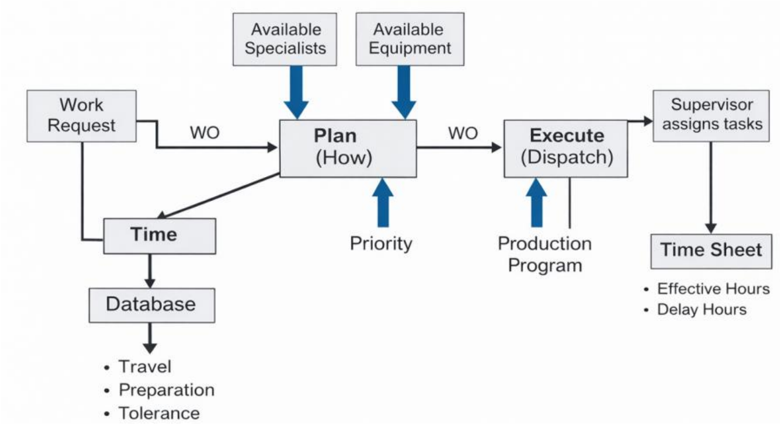

Figure 5. Maintenance Plan Source: Own elaboration.

In Python, we use the scipy.stats.weibull_min.fit() function to make this adjustment, which uses the maximum likelihood method internally.

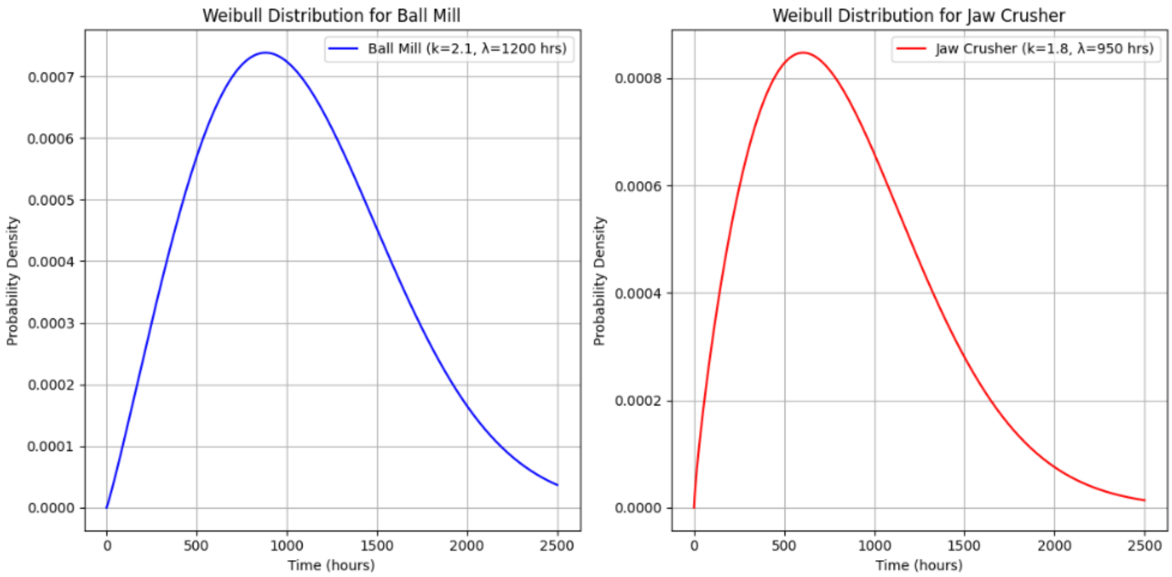

Figure 6. Weibull Curve Source: Own elaboration.

IV. DISCUSSION

The results of the FMEA confirm that the predominant corrective maintenance strategy generates concentration of unacceptable risks in key subcomponents, coinciding with documented findings that highlight the negative impact of the absence of preventive plans on equipment availability and reliability. The identification of failure modes with elevated NPRs in components such as ball mill caps and cylinder, as well as in side plates and bearing of the eccentric shaft of the crusher, shows that the failures originate mainly in elements subjected to high mechanical stresses under severe conditions, requiring more robust and systematic maintenance strategies.

The estimate of improvement in availability of 73% to 90% from the implementation of the preventive plan highlights the potential of this methodology to transform reactive into proactive schemes, aligning with previous experiences that report reductions of 30–50% in failure rates when well-structured preventive plans are applied. This improvement suggests a positive impact on the plant's overall productivity, by decreasing unplanned downtime and stabilizing the flow of mineral processing in crushing and grinding stages.

The integration of the Weibull distribution complements the FMEA approach by providing a robust statistical tool for modeling the temporal behavior of failures. The use of maximum likelihood estimation allows us to obtain useful life curves that serve as a reference to schedule interventions before equipment enters the accelerated failure zone. The estimated parameters (k > 1 for both equipment) indicate that the failure rate increases over time, validating the preventive maintenance strategy over reactive approaches.

The combination of FMEA, criticality analysis, Pareto and Weibull modeling constitutes a comprehensive operational risk management framework replicable in other contexts of the Ecuadorian mining industry, particularly in operations with severe conditions and high dependence on mechanical equipment. However, the effectiveness of the proposed plan will depend on the availability of robust historical data, organizational commitment to continuous updating of maintenance records, and training of personnel in interpreting analysis tools.

From an operational perspective, the implementation of this comprehensive approach allows to move from a maintenance model focused on reactivity (post-failure repair) to a preventive-predictive model, where interventions are scheduled based on scientific risk analysis and statistical predictions of useful life. This is particularly relevant in mining contexts where operational continuity is critical for profitability and safety.

V. CONCLUSIONS

The joint application of FMEA and criticality analysis made it possible to identify that approximately 25% of subcomponents of crushing and grinding equipment present levels of unacceptable risk (NPR > 300), mainly concentrated in structural elements of the ball mill and jaw crusher subjected to severe operating conditions.

The design of the preventive maintenance plan, based on NPR prioritization and Pareto analysis, structured tasks, frequencies and managers oriented to subcomponents of lower reliability, projecting an estimated reduction of 40–50% of unplanned downtime and an increase in availability from 73% to 90%.

The Weibull distribution provided a quantitative basis for modeling failure times of critical equipment, facilitating the transition from corrective schemes to preventive-predictive approaches and allowing scientific definition of optimal intervention intervals.

The proposed comprehensive approach, combining detailed asset inventory, FMEA, criticality matrix, Pareto diagram and Weibull modeling, constitutes a replicable methodology to optimize operational risk management in the Ecuadorian mining industry, especially in plants with high dependence on crushing and grinding equipment.

To ensure the sustainability of the preventive plan, the following is required: strengthening of historical failure and maintenance systems, continuous training of personnel in reliability tools, and progressive integration of digital predictive monitoring systems (sensors, condition analysis).

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