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METHOD FOR FAILURE MODES ANALYSIS AND RELIABILITY ENHANCEMENT OF GRINDING IN MINERAL PROCESSING PLANTS

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Abstract. *Grinding is a crucial stage in ore beneficiation, responsible for reducing particle size and increasing contact area for chemical reactions. Therefore, ensuring high reliability in raw material grinding is essential to avoid operational failures and production losses. The quality of grinding directly affects subsequent processes like calcination, leaching, and other chemical treatments, underscoring the criticality of reliable operation. The overall goal of enhancing grinding reliability and efficiency was achieved through identifying and prioritizing production loss-inducing failures. Business intelligence analysis using Microsoft's Power BI software enabled the identification of suitable methodologies for optimizing reliability and prioritizing the treatment of specific failures. This failure mode analysis methodology provided valuable insights for addressing failures based on their production impact, resulting in improved reliability and productivity in the grinding sector.*

Keywords: *Mining, Business Intelligence, Productivity*

1. INTRODUCTION

Grinding is a fundamental step in ore beneficiation and poses complex challenges for the mining industry, always intertwined with the question of how to increase its reliability and, consequently, its efficiency. Grinding failure can lead to significant production losses, such as increased difficulty in the chemical treatment of ore, overload in other productive sectors, and delays in product delivery schedules, making the study of failure mode analysis essential. This analysis model summarizes a methodology that assists in identifying and prioritizing failures in equipment and processes.

It is notable that the mining industry is becoming increasingly automated, and according to Coelho (2018), the set of Business Intelligence (BI) tools is also multiplying and diversifying in today's world. Thus, the use of BI tools has been gaining prominence in data analysis and decision-making in these mining industries. In this context, Power BI, a tool developed by Microsoft, has been widely used for real-time data collection, processing, and analysis. The use of this method enables managers to have a more accurate view of equipment operation, identify failures, and take preventive measures more efficiently.

With the use of Power BI, it is possible to periodically monitor grinding performance, identify anomalies, and make more precise decisions. Additionally, the tool allows for the creation of customized reports with performance indicators and graphs that assist in data interpretation. Power BI can be integrated with automation systems present in the plants, enabling a more integrated and efficient management of the production process. This facilitates the understanding of the area's loss profile and ensures better conditions for operation and maintenance management. According to Batista (2023), "the implementation of this process involves integrating data from various sources and using data analysis technologies to generate valuable insights." This increases the accuracy in identifying the root causes of failures and, consequently, the effectiveness of the measures adopted. Therefore, this methodology studies failures in the grinding sector based on the maintenance downtime database for the first half of 2023.

The use of Power BI in the analysis of grinding failures in ore beneficiation plants represents a market advantage. The tool allows for reductions in production losses and can contribute to extending the equipment's lifespan. Furthermore, the analysis enables the adoption of preventive measures to avoid recurring failures. In this way, it is possible to increase the reliability and efficiency of grinding, ensuring a more sustainable and profitable production for companies in the sector. To establish a connection between grinding and failure mode analysis, it is necessary to delve into theoretical studies that provide the foundations for this relationship. Therefore, Gil (2009) emphasizes that "regardless of the research, the need to consult published material is imperative." It is worth noting that the present study was carried out based on a real application in a mining company, and in addition to efficiency aspects, care for the environment and occupational health and safety were considered and suggested. Optimizing grinding not only provides environmental benefits but also contributes to the preservation of natural resources by reducing waste volume. Additionally, by implementing preventive measures for failure mode analysis, it helps ensure a safe and healthy working environment for workers involved in equipment operation and maintenance.

In pursuit of enhancing the reliability of ore milling in a beneficiation plant, this study aims to identify and prioritize failure modes that may lead to production losses, high maintenance costs, and delays in product delivery schedules. Additionally, a comprehensive analysis of the milling production flow, based on a real-life example from a mining operation, will be provided, along with the identification of the key loss profiles in this critical process stage. This set of objectives directs our research towards gaining an in-depth understanding of the challenges faced in ore milling and seeks solutions to optimize its efficiency and reliability. In this perspective, the present study aims to promote a sustainable approach in the mining industry, with an emphasis on grinding reliability. By optimizing grinding, it is possible to reduce the waste of natural resources, minimize harmful emissions, and mitigate occupational risks. Thus, the research contributes to a more efficient, safe, and environmentally responsible ore beneficiation process, aligned with the principles of sustainable development.

2. MATERIALS AND METHODS

This study was conducted in a large-scale company located in the state of Bahia, specialized in mineral extraction and beneficiation. The company, which is of considerable size, has a team ranging from 301 to 500 employees, and one of its main activities is ore grinding. The grinding process has an average feed capacity of 200 tons per hour when operating perfectly. Therefore, this research analyzes and proposes measures to increase reliability in the grinding sector, aiming to optimize operational efficiency and reduce potential interruptions in the production process.

Hence, the following topics will provide an overview of the grinding operation, boundary conditions for the database, and the definition of the tool for information analysis. The subsequent chapter will delve into discussions and present the obtained results, and finally, the last chapter will present the concluding remarks. The methodological approach of this study was divided into several distinct phases. Initially, a comprehensive analysis of the milling process was conducted, identifying the main components and processes involved in the context of the company in question. Subsequently, the boundary conditions for data collection were established, including real-time monitoring of all production stops, both scheduled and unscheduled. A spreadsheet named 'Production Stoppages' was used for data collection and organization, ensuring proper categorization of production stops by assets and types of failures. Later on, the Power BI analysis tool was employed to process the collected data. Additionally, an analytical approach was adopted to identify the main causes of failures and prioritize corrective actions. These methodological steps form the basis of this research study.

2.1 Grinding Flow

The process adopted as the basis for this study involves wet grinding, which, according to Figueira et al. (2010), is the most common method used for cylindrical ball mills. As stated by Luz and Lins (2018), most ores found in the Earth's crust require beneficiation to improve their properties. According to the same authors, for the selective separation of a specific mineral within an ore, it is necessary to understand the liberation particle size of this mineral in relation to the gangue material. Therefore, the ore must undergo grain fragmentation processes, such as crushing and grinding, until it reaches the liberation particle size specified by mineralogical studies related to the ore. In the case at hand, the material from crushing is added to the primary mill, along with water and recycled material, and ground to produce a slurry. This slurry is then stored in a tank and subsequently subjected to the first hydrocycloning process, which, according to Sampaio et al. (2007a), results in two products: the underflow and the overflow. The author adds that "the first contains the majority of the coarse particles that were fed, and the second encompasses the majority of the classified fine particles." Therefore, the material from the underflow is recycled back to the primary mill to achieve the specified particle size, while the material from the overflow is directed to the subsequent processing.

The grinding sector addressed in this research comprises four processing lines. The primary line follows the aforementioned flow, consisting of the primary mill, storage tank, hydrocyclone, and supporting components such as slurry pumps, water pumps, monitoring sensors, pneumatic valves, pipelines, and all the necessary electrical equipment for operation and machinery monitoring. The secondary line, on the other hand, is fed in its first storage tank with the material from the overflow of the hydrocyclone in the primary line. Subsequently, this material is directed to feed the second hydrocyclone, causing the underflow to go to the secondary mill, while the desired particle size overflow goes to the second storage tank. Thus, the secondary line adopts a certain component symmetry with the primary line, although they are not identical. This includes, for example, the similarity of model between the mills and is contrasted by the addition of a storage tank in the secondary line and the difference in supporting equipment, such as slurry pumps, water pumps, and pneumatic valves.

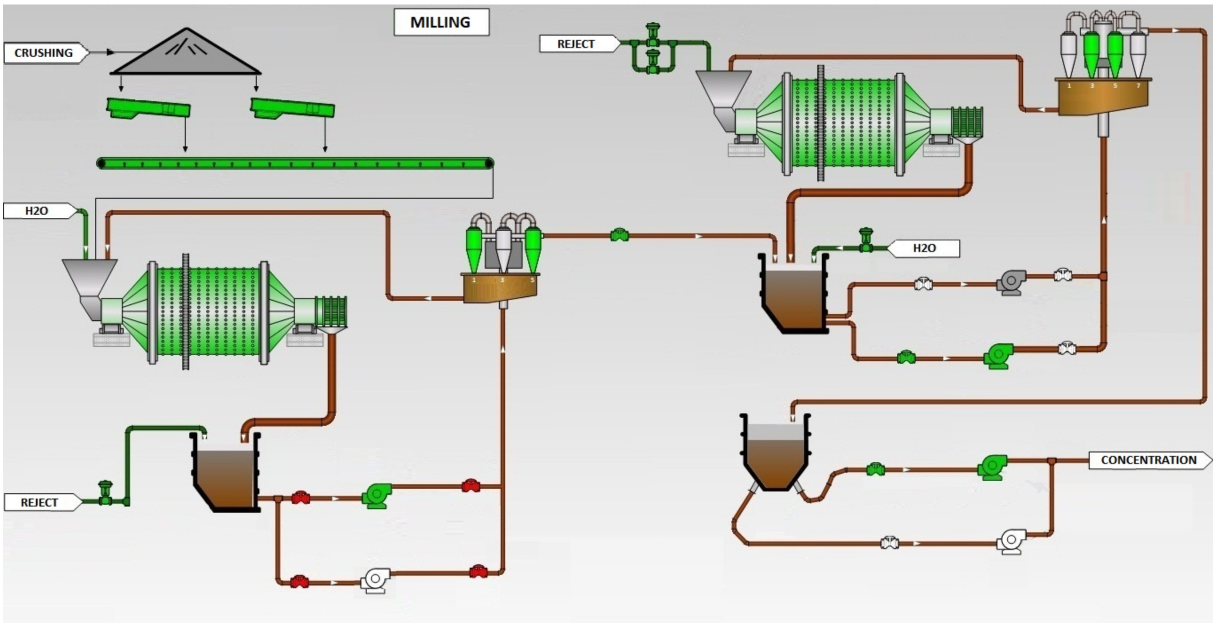

Figure 1. Production flow of the primary and secondary lines.
Source: Own work (2023).

The third processing line in the analyzed grinding sector is concentration. In this stage, the slurry is pumped to the wet low-intensity drum magnetic separators, allowing the separation of the material into two classes: reject and concentrate. According to Sampaio (2007b), "The magnetic particles adhere to the rotating drum, where the magnet is installed, which can be permanent or electromagnet. The magnetic particles are discarded from the circuit as magnetic product." Therefore, the reject is directed to the fourth processing line, while the concentrate is sent, via magnetic separators, to the horizontal vacuum belt filter, which, as described by França and Casqueira (2007), "is a special design conveyor belt that serves as a support for a screen placed on top of the belt, allowing the air to flow through the cake." The same author also mentions that applying a pressure lower than atmospheric pressure to the slurry increases the speed of cake formation, which is the solid phase of the concentrate after this solid-liquid separation.

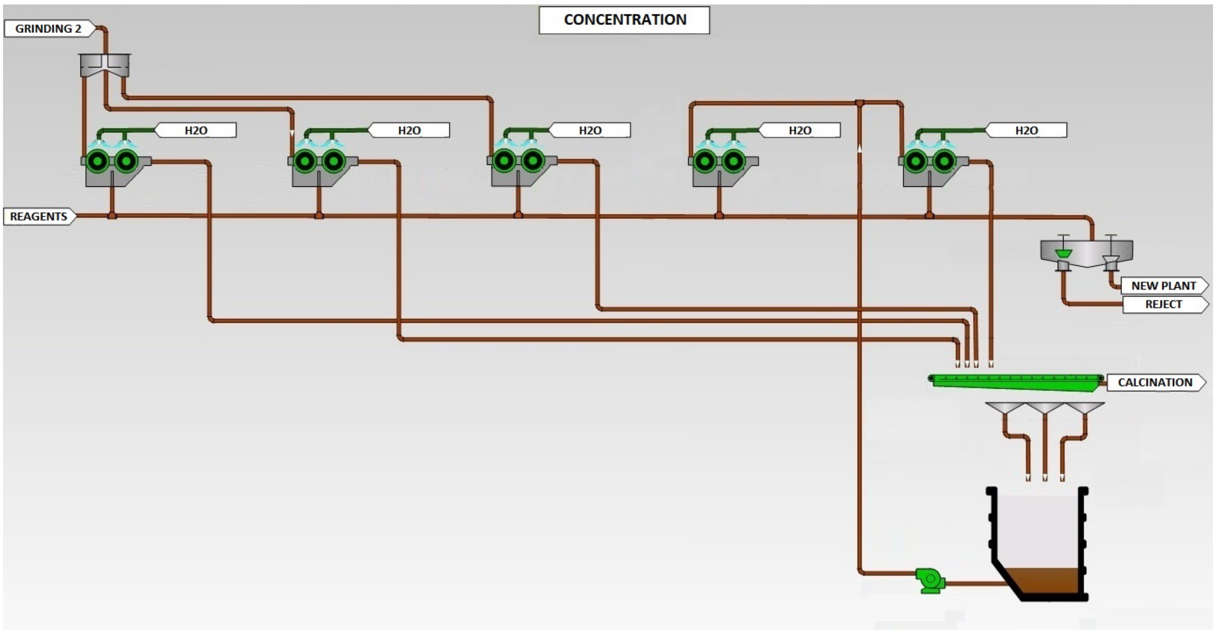

Figure 2. Production flow of the tertiary line.
Source: Own work (2023).

The fourth processing line, which deals with the rejects from the filter and magnetic separators, operates in parallel with the other grinding lines. In this segment, the filtered liquid is pumped to a conventional continuous thickener, which, according to França and Massarani (2002), "consists of a tank equipped with a suspension feed system and a thickened product withdrawal system (scrapers), devices for overflow and underflow discharge." At this stage, the underflow material is recycled back to the concentration line to enhance the beneficiation process, while the overflow is directed to non-magnetic reject ponds or recirculated within the thickener itself.

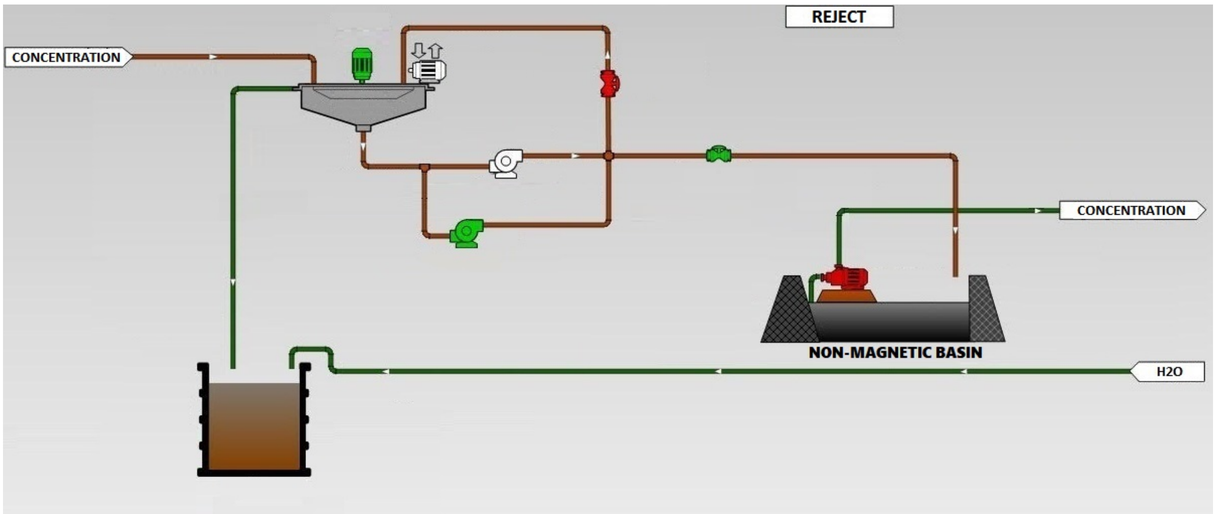

Figure 3. Operational flow of the reject line.
Source: Own work (2023).

It is worth noting that the treatment and proper storage of rejects are of utmost importance in terms of environmental preservation and operational safety. Correct management of rejects minimizes negative impacts on nature, avoiding soil and water contamination. Thus, it is important to establish a contingency plan to deal with emergency situations such as leaks or overflow. This plan should involve training of responsible teams, definition of procedures, and availability of resources. However, this topic will not be included in the scope of discussions in this study, and it is suggested that for future studies, a deeper exploration of the correct treatment and storage of rejects from grinding processes is undertaken.

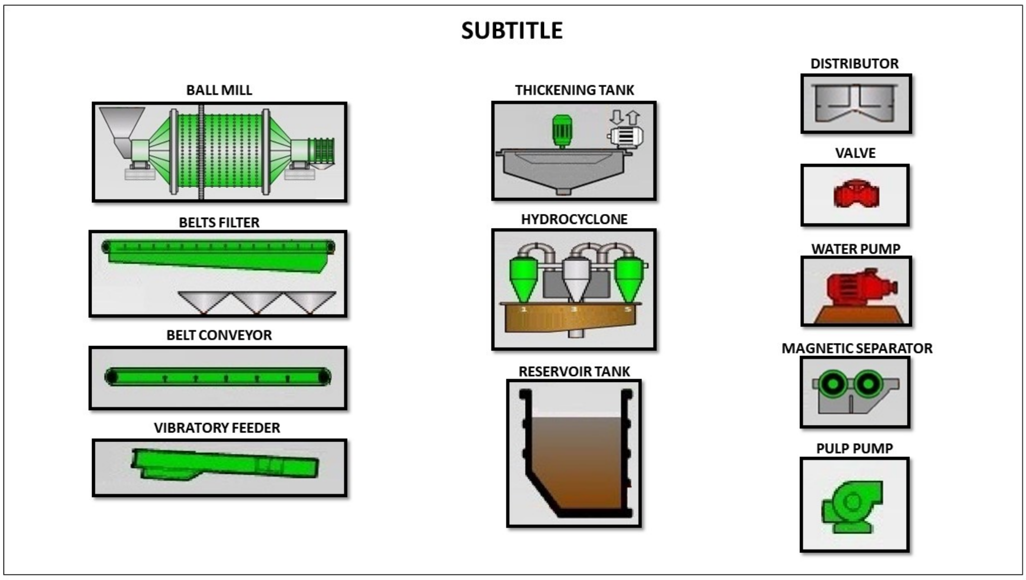

Figure 4. Subtitle
Source: Own work (2023).

Finally, the concentrated material, after going through the filtration process, is destined for the formation of the "bean stack," which serves as a reserve of material that will feed the next ore beneficiation sector in the company, the calcination furnace.

2.2 Database

The mining company analyzed in this research, for the application of failure analysis methodologies, feeds a database with all operational and maintenance events, containing the information displayed in "Figure 5", in order to enable subsequent metrics, based on time, of the stored data for all interruptions in the grinding processing lines. According to Suzano (2020), "the success of various industries depends on the accuracy of the collected information, based on a typology of stops." Thus, it is possible to understand the degree of importance attributed to the process of recording and data collection. As a boundary condition for this study, real-time monitoring is linked to the procedure of recording all production stops, whether planned or unplanned.

The information is attached to the "Production Stops" spreadsheet and encompasses all equipment in the beneficiation plant, including grinding and its processing lines. Therefore, the use of the spreadsheet for storage, collection, and analysis of information is strictly limited to the time-based database, divided into monthly periods. It is worth noting that, for data treatment using Power BI, merged rows and columns should be removed through this software, keeping only the grouping of information by columns, in order to apply business intelligence to the database in question. Thus, the information is gathered and processed, as will be discussed in the following chapters, where both the methods used and the results obtained from the analyses will be highlighted and discussed.

It should be considered that not all activities carried out by the maintenance department result in a production stop in the area. This occurs when the equipment experiencing failure does not act as a highly critical component in the production line, either because it is possible to bypass the equipment using a backup or because the equipment only serves the critical assets, or when it does not directly affect the areas of environment and occupational health. Therefore, to encompass all activities that are not included in the "Production Stops" spreadsheet, the use of a dedicated maintenance management system is necessary. This system will be responsible for recording all maintenance activities, regardless of whether they stop the production sector or not. However, for the purposes of this study, only the stops that affect production, reported by the operation, will be considered, as mentioned above.

DAY	AREA	START	TERMINATION	TOPPED HOUR	MINUTES	SHIFT	DEBIT AREA	EQUIPMENT	CAUSE	COMMENTS	DF/UF
6	Moagem_1	19:00	20:23	01:23	83	A	Elétrica	350-MN-002A	Disjuntor desligado	rea parada por defeito por bloqueio pelo reostato.	DF
6	Moagem_2	19:00	23:59	04:59	299	A	Mecânica	350-MN-002B	Corrente Alta	ea parada devida corrente alto no motor auxiliar do moinho 02	DF
7	Moagem_2	00:00	07:00	07:00	420	A	Elétrica	350-MN-002B	Queimado	Queimar do motor auxiliar MO-102 M1.	DF
7	Moagem_2	07:00	12:18	05:18	318	D	Elétrica	350-MO-102	Queimado	Queimar do motor auxiliar MO-102 M1.	DF
7	Moagem_1	19:24	22:12	02:48	168	A	Mecânica	350-BA-019	Quebrado	área parada devido quebra do acoplamento da 350 BA-19.	DF
7	Moagem_2	19:24	22:12	02:48	168	A	Mecânica	350-BA-019	Quebrado	área parada devido quebra do acoplamento da 350 BA-19.	DF
7	Moagem_2	22:12	23:10	00:58	58	A	Mecânica	350-MN-002B	Quebrado	área permaneceu parada devido acoplamento do 350 MO-102-	DF
8	Moagem_1	13:36	15:29	01:53	113	B	Mecânica	370-FI-001-M1	Reposição	Reposição do parafuso da base de alinhamento do filtro.	DF
8	Moagem_2	13:36	15:29	01:53	113	B	Mecânica	350-MO-101	Reposição	Reposição do parafuso da base de alinhamento do filtro.	DF
9	Moagem_1	05:30	07:00	01:30	90	D	Elétrica	350-MN-002A	Sem energia	parada devido queda de energia.	DF
9	Moagem_2	05:30	07:00	01:30	90	D	Elétrica	350-MN-002B	Sem energia	parada devido queda de energia.	DF
9	Moagem_2	07:00	09:46	02:46	166	B	Mecânica	350-MO-102	Quebrado	Parada devido parafusos do acoplamento do motor auxiliar do	DF
9	Moagem_1	19:03	19:23	00:20	20	D	Produção	350-AL-002B-M	Obstrução	parada devido rocha travada no chute do AL-02 B.	UF
9	Moagem_2	19:03	19:23	00:20	20	D	Produção	350-AL-002B-M	Obstrução	parada devido rocha travada no chute do AL-02 B.	UF
10	Moagem_1	02:28	02:35	00:07	7	D	Mecânica	350-BP-001B-M	Vazamento	parada para inversão da BP-01 B para BP-01 A devido vazament	DF
10	Moagem_2	02:28	02:35	00:07	7	D	Mecânica	350-BP-001B-M	Vazamento	parada para inversão da BP-01 B para BP-01 A devido vazament	DF
10	Moagem_1	12:41	14:47	02:06	126	C	Elétrica	350-BP-010-M	Falha de equip.	Queima dos cabos na caixa de ligação da BP-010.	DF
10	Moagem_2	12:41	14:47	02:06	126	C	Elétrica	350-BP-010-M	Falha de equip.	Queima dos cabos na caixa de ligação da BP-010.	DF
10	Moagem_2	14:47	19:00	04:13	253	C	Mecânica	350-MO-102	Reposição	Reposição de parafusos no acoplamento do motor auxiliar, 350	DF
10	Moagem_2	19:00	23:59	04:59	299	B	Mecânica	350-MO-102	Reposição	Repor parafusos no acoplamento do 350-MO102, motor auxili	DF
10	Moagem_1	21:05	23:00	01:55	115	B	Produção	350-CI-101	Obstrução	Obstrução na ciclonagem 350-CL-101.	UF
11	Moagem_2	00:00	00:47	00:47	47	B	Mecânica	350-MO-102	Reposição	Repor parafusos no acoplamento do 350-MO102, motor auxili	DF
11	Moagem_2	00:48	07:00	06:12	372	B	Produção	350-MO-101	Nível Baixo	Baixo estoque de minério.	UF
11	Moagem_2	07:00	19:00	12:00	720	C	Produção	350-MO-101	Nível Baixo	Baixo estoque de minério.	UF
11	Moagem_2	19:00	23:59	04:59	299	B	Produção	350-MO-101	Falta de Minério	Baixo estoque de minério.	UF
12	Moagem_1	13:11	16:48	03:37	217	A	Mecânica	350-MN-002A	Inspeção	Abertura da janela de visita do 515-BO001.	DF
12	Moagem_2	13:16	17:32	04:16	256	A	Produção	350-MN-002B	Obstrução	parda devido obstrução na caixa de alimentação no moinho 01	UF

Figure 5. Spreadsheet template for real-time production stoppage recording.
Source: Own work (2023).

Finally, it is important to consider stoppages that are not attributed to a specific equipment, but rather to the general area. These entries occur when the failure is collective and should not be attributed to a single asset, for example, when there is a power supply shortage from the electricity distribution company, when scheduled shutdowns occur for the entire area in question, or when there is a lack of ore for processing. Therefore, all stoppages that fall under these conditions should be recorded under the general cost center of the area, in this case, 350-MN-002, which corresponds to the Grinding area. This way, during data analysis, no specific asset will be affected by general entries, and the general area in question will have its own stoppage information, allowing for better control over events and greater accuracy in defining the sector's loss profile.

2.3 Power BI

Power BI is a powerful business intelligence tool developed by Microsoft, widely used for data analysis and decision-making in various companies and industries. This tool plays a fundamental role in the methodology of the article, which aims to analyze failure modes in ore grinding at a mining company. Thus, this study relied on its usage to develop the loss profile of the area, allowing for the identification of equipment with the greatest productivity impact. It is worth noting that Power BI enables real-time data collection, processing, and visualization, providing managers with an accurate view of the analyzed system's performance. Power BI aims to facilitate data interpretation and understanding by identifying relevant trends and patterns for failure analysis. This tool can also be integrated with automation systems in the plant, enabling a more integrated and efficient management of the production process. However, according to Coelho (2018), "Having an organization equipped with a system with extraordinary functions will be of no use if decisions continue to be made based on the empiricism characteristic of its manager."

The analysis of the loss profile carried out in this software contributed to the identification of the main causes of failures and the implementation of prioritization actions, thereby increasing the operational reliability of the grinding process. Based on these aspects, the use of Power BI in the methodology of this article provides a more precise, efficient, and data-driven approach to analyzing failure modes in the sector, contributing to the improvement of operation and maintenance in the ore beneficiation process.

Furthermore, the use of Power BI in the context of failure mode analysis in the mining company's grinding process allows for continuous and real-time data analysis, enabling early detection of problems and the implementation of agile corrective actions. This real-time monitoring capability offers a significant advantage, as any deviations or anomalies can be identified immediately, allowing for a prompt and effective response to minimize negative impacts on productivity and plant performance. Therefore, Power BI proves to be a crucial tool for enhancing management and increasing operational efficiency in the ore beneficiation sector, ensuring decision-making based on solid data and contributing to the achievement of the organization's strategic objectives.

3. RESULTS AND DISCUSSION

It is of utmost importance to filter and identify the main events that caused production unavailability in the grinding lines of a mining company. Figure 6, a result of the business intelligence process using Power BI, stratifies the main failure modes that occurred, the equipment that caused the highest losses, the letters with the highest unavailability, the percentages of mechanical, electrical, and instrumentation activities, as well as the tabulation of all records of production stoppages and their respective impacts on area availability. Therefore, it provides room for defining actions based on the identification of the area's loss profile, indicating the main assets that should be prioritized, aiming for longer production times in the plant and increasing sector reliability, in order to become increasingly stable.

Figure 6. Dashboard: Summary of Failures 2023.
Source: Own work (2023).

Based on the information contained in the previous figure, grounded in the stoppage record database, it is possible to identify that the equipment with the greatest impact on the area's production was the 350-MO-101, which corresponds to the secondary mill in the grinding line. Alone, this equipment caused 234 hours of unavailability in the first semester of 2023. This number is equivalent to 4.5 times the impact of the second equipment, the concentration belt filter (370-FI-001), indicating the need to prioritize this asset during planning and scheduling of preventive activities for the area.

Among the main causes of unavailability in the analyzed scenario are leaks (154 h), breakdowns (96 h), and scheduled shutdowns (461 h). Leaks are undesirable and represent material loss, both in equipment and pipelines, and they also result in the loss of pressurization in material transport lines. On the other hand, breakdowns - whether of machines, assemblies, or subassemblies - are related to increased maintenance costs, both due to the immediate need for replacement and acquisition of parts and components, as well as the loss of profit. As stated by Engeteles (2017), "when a piece of equipment breaks down and stops producing, all the value it could have generated for the company is accounted for as indirect maintenance cost."

Based on the initial insight generated by Power BI, there was a need for a more thorough analysis of the two main failure modes in the grinding sector. Thus, Figure 7 provides an overview of the most critical equipment based on the most recurrent failures.

Figure 7. Equipment by Major Failure Modes.
Source: Own work (2023).

Through the information provided in the relationship between equipment and the two major failure modes, it is possible to identify that, once again, the secondary grinding mill appears as the main contributor to the loss profile of the grinding process during the period in question, representing the highest percentages for stoppages due to leaks and breakdowns.

On the other hand, scheduled shutdowns, also identified as a reducing factor in physical availability in the grinding process in the dashboard, illustrate the opposite scenario. They are desirable and beneficial for the production process as they allow for proactive fault anticipation. However, according to Braidotti (2016), "the elimination of waste from limited maintenance resources is directly dependent on the quality of shutdown planning." If there is inefficiency in planning and prioritizing activities, the main failure modes may not be adequately addressed and prevented. Additionally, according to Metso Outotec (2020), "to carry out a plant shutdown, a large number of processes must be executed to analyze equipment and make necessary corrections. In addition to these processes, the main problem with plant shutdowns is the pause in production." Metso Outotec (2020) further states that it is ideal to have the fewest possible scheduled shutdowns, as every minute of interruption results in financial losses for the company.

In sequence, two timelines were developed to highlight all the scheduled shutdowns that occurred in the two grinding lines during the first semester of 2023. As mentioned earlier, the strategy of conducting preventive shutdowns for failure modes is beneficial, but it must be executed with proper planning, prioritization, and spacing to minimize the impact on productivity. The following figures illustrate the timelines of preventive shutdowns for the two main grinding lines, as well as the variation in reliability and occurrences.

Figure 8. Timeline of scheduled shutdowns for the primary line.
Source: Own work (2023).

Figure 9. Timeline of scheduled shutdowns for the secondary line.
Source: Own work (2023).

Based on Figures 8 and 9, it is possible to identify that variations in the number of occurrences and reliability are directly related. Therefore, the higher the reliability during a period, the lower the number of occurrences. The main challenge, however, is to space out preventive shutdown activities chronologically without causing an increase in corrective occurrences and a subsequent decrease in reliability. To achieve this, the mean time between failures (MTBF) needs to be increased, and this occurs precisely after mapping the loss profile, prioritizing the most critical or recurring failure modes, and addressing the identified events.

According to Abraman (2022), various methodologies are employed by maintenance and reliability engineering in failure mode analysis, which is also the subject of research in the "Documento Nacional 2022" conducted by the institution itself. The following are the results regarding the main tools and methodologies identified by the research:

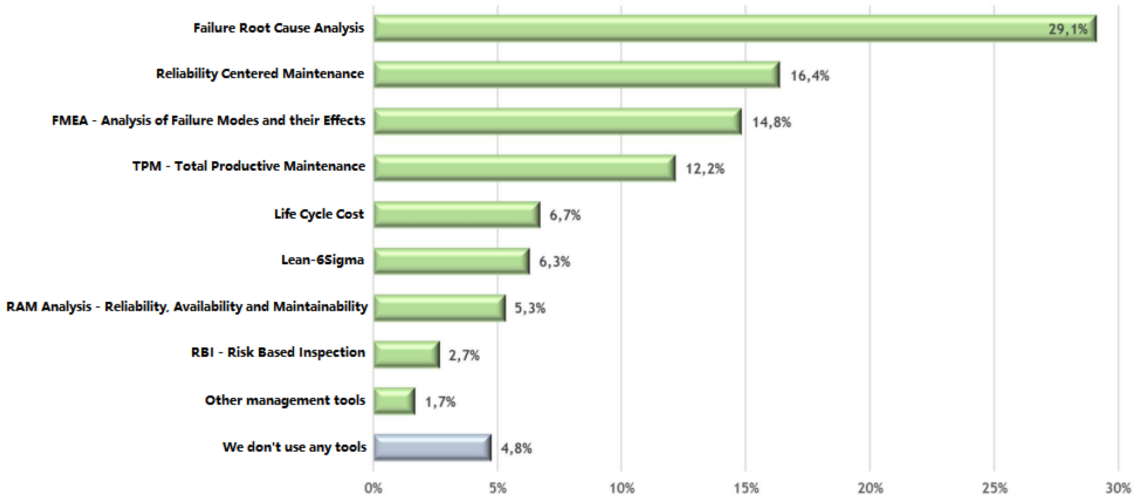

Figure 10. Tools and methodologies used in maintenance and reliability engineering - Documento Nacional.
Source: ABRAMAN (2022).

Thus, it can be interpreted that the current approach of identifying and prioritizing failure modes using business intelligence is still a concept or methodology with limited diffusion in the current Brazilian mineralogical scenario. It is also evident that this methodology is one among several options available in maintenance and reliability engineering. Therefore, its use is supported by the employment of advanced tools for data analysis and dashboard generation, allowing for integration with any of the other available methodologies for asset management and failure mode analysis.

4. FINAL CONSIDERATIONS

The present study aimed to increase the reliability and efficiency of the grinding stage in an ore beneficiation plant through the analysis of its failure modes. By using business intelligence, specifically Microsoft's Power BI, it was possible to identify and prioritize the resolution of faults, contributing to the reduction of production losses. The obtained results demonstrated that the proposed objectives were achieved, providing a more accurate and data-driven approach to decision-making. By explaining the production flow of grinding based on a real and summarized example of a mining operation, it was possible to understand the process stages more precisely and define the critical points of the process. Thus, the main loss profiles of the grinding process were identified, highlighting the main issues and recurring problems in the sector.

The mining industry is a highly challenging and complex sector, which requires a systematic and innovative approach to overcome obstacles and maximize operational efficiency. In this regard, the analysis of failure modes offers a promising solution to improve the performance of mining companies. By adopting data-driven approaches, companies have the opportunity to explore valuable insights and make informed decisions based on solid information, resulting in significant improvements in availability and reliability. The implementation of similar methodologies based on the analysis of failure modes will contribute to increased productivity and competitiveness in mining companies that adopt the practice of processing this type of information, leading to a reduction in production losses. All of this is facilitated by the effectiveness of problem prioritization provided by the business intelligence process. Therefore, this study provides solid foundations for enhancing the operation and maintenance of the grinding process, assisting various mining companies in achieving better results and defined goals.

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