https://doi.org/10.47456/bjpe.v9i3.41098

Brazilian Journal of Production Engineering

ORIGINAL ARTICLE OPEN ACCESS

APPLICATION OF RELIABILITY-CENTERED MAINTENANCE IN A STEEL MILL

APLICAÇÃO DA MANUTENÇÃO CENTRADA NA CONFIABILIDADE EM UM ALTO FORNO DE USINA SIDERÚRGICA

APLICACIÓN DEL MANTENIMIENTO CENTRADO EN LA CONFIABILIDAD EN UNA PLANTA SIDERÚRGICA

Filipe Carneiro Bastos [1] **& Roberto Tetsuo Fujiyama** [2*]

[1 2] Federal University of Pará, Belém-PA

[1] filipecarneirobastos@gmail.com [2*] fujiyama.ufpa@gmail.com

ARTICLE INFO.

Received: 30.05.2023
Approved: 03.07.2023
Available: 06.09.2023

KEYWORDS: Reliability-Centered Maintenance; Blast Furnace; Steel Mill.
PALAVRAS-CHAVE: *Manutenção Centrada na Confiabilidade; Alto Forno; Usina Siderúrgica.*
PALABRAS CLAVE: *Mantenimiento Centrado en la Confiabilidad; Alto Horno; Planta siderúrgica*

***Corresponding Author**: **Fujiyama, R. T.**

ABSTRACT

Technological development has provided numerous changes in the industrial process and has led to the need for maintenance improvement due to the importance of operational availability for companies' results. In this study, we sought to apply Reliability-Centered Maintenance (RCM) to equipment with high criticality indexes in a blast furnace of a steel mill and present the benefits obtained after implementation. As an initial sample, the electrostatic precipitators from the engine room were used due to the high number of corrective maintenance interventions and long downtime during failures. To apply the method, the 5 stages for implementation were followed, and finally, a comparison was made between maintenance plans before and after RCM implementation, presenting the gains achieved through a reduction in the number of corrective maintenance interventions during a specific analysis period. By applying RCM to equipment of class A criticality, a 91.7% reduction in corrective maintenance interventions was achieved in the year 2022, compared to 2021, along with increased MTBF and reduced MTTR for the studied equipment.

RESUMO

O desenvolvimento tecnológico vem proporcionado inúmeras mudanças no processo industrial e têm levado à necessidade do aprimoramento da manutenção, em face da importância da disponibilidade operacional para o resultado das empresas. Neste estudo buscou-se aplicar a Manutenção Centrada na Confiabilidade nos equipamentos com elevados índices de criticidade de um alto forno de usina siderúrgica e apresentar os benefícios obtidos pós-aplicação. Como amostra inicial, foram utilizados os eletrosopradores da sala de máquinas, devido ao elevado número de manutenções corretivas, além de longos tempos de paradas durante ocorrência de falha. Para aplicabilidade do método, as cinco etapas para implantação foram seguidas e, por fim, foi realizado comparativo entre os planos de manutenção antes e após a implantação da MCC e apresentado os ganhos obtidos através da redução do número de manutenções corretivas em determinado período de análise. A partir da aplicação da MCC nos equipamentos de criticidade A, conseguiu-se uma redução de 91,7% no número de manutenções corretivas no ano de 2022, ao comparar com 2021, além do aumento do MTBF e redução do MTTR para os equipamentos estudados.

RESUMEN

El desarrollo tecnológico ha proporcionado innumerables cambios en el proceso industrial y ha llevado a la necesidad de mejorar el mantenimiento debido a la importancia de la disponibilidad operativa para los resultados de las empresas. En este estudio, se buscó aplicar el Mantenimiento Centrado en la Confiabilidad (MCC) en los equipos con altos índices de criticidad de un alto horno en una planta siderúrgica y presentar los beneficios obtenidos después de la implementación. Como muestra inicial, se utilizaron los electrofiltros de la sala de máquinas debido al alto número de intervenciones de mantenimiento correctivo y largos tiempos de parada durante las fallas. Para aplicar el método, se siguieron las 5 etapas de implementación y, finalmente, se realizó una comparación entre los planes de mantenimiento antes y después de la implementación del MCC, presentando las mejoras logradas mediante la reducción del número de intervenciones de mantenimiento correctivo durante un período de análisis específico. A partir de la aplicación del MCC en los equipos de criticidad A, se logró una reducción del 91,7% en el número de intervenciones de mantenimiento correctivo en el año 2022, en comparación con el 2021, además del aumento en el MTBF y la reducción del MTTR para los equipos estudiados.

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International. ***Brazilian Journal of Production Engineering***, São Mateus, Publisher UFES/CEUNES/DETEC. ISSN: 2447-5580

Citation (APA): Bastos, F. C. & Fujiyama, R. T. (2023). Application of reliability-centered maintenance in a steel mill. *Brazilian Journal of Production Engineering*, 9(3), 206-223.

1. INTRODUCTION

In maintenance management, the use of specific structured tools can provide greater efficiency and equipment availability, lower maintenance costs, in addition to ensuring greater safety and quality of the production process. Teles (2019) states that the Fourth Generation of Maintenance, born in the 2000s, is marked by the increase in the maintainability of assets by manufacturers, by their levels of autonomy and by the adoption of World-Class Maintenance strategies.

Kardec and Nascif (2012) emphasize that with the increase in competitiveness between companies, there was a greater need for more reliable maintenance systems, which would guarantee the functioning of their assets.

The Reliability Centered Maintenance (RCM) is a maintenance policy that selects and structures the maintenance activities necessary to guarantee asset availability and consequently guarantee the reliability of the production process. Lafraia (2014) shows that the RCM defines what must be done to keep the asset in full working condition instead of leaving it in ideal condition.

The Blast Furnace, an essential sector for the steelmaking process, needs tools and studies that can update, modernize and expand the performance of the maintenance sector. The implementation of the RCM will contribute positively, leading to studies of asset failures and to the review of current maintenance plans in order to avoid failures, with periodicity of the relevant activities, for the purpose of guaranteeing the functioning of the asset.

This work has as its main theme the application of RCM in a Blast Furnace of a steel plant, aiming. Such implementation will guarantee a useful life and availability of the equipment, by carrying out a previous study, with predefined and sequenced steps, with the goal of identifying the main failures of the assets and their effects, through a structured Failure Modes and Effects Analysis (FMEA), aiming at the revision of maintenance plans based on data obtained from the previous steps, in order to guarantee a longer useful life and availability of equipment and consequent reliability of the production process.

2. THEORETICAL REFERENCE

2.1 Industrial Maintenance

Industrial maintenance is an ancient practice that dates back to the dawn of civilization, with the conservation and repair of equipment. The word “maintenance” originated in the military and means “to maintain”, referring to the maintenance of manpower and provisions in combat units (Wyrebski, 1997).

The evolution of maintenance began during the Second World War, when maintenance strategies were mainly focused on repairs after failures (Mata Filho et al., 1998). However, with the increasing of mechanization in industry after the war, maintenance became an essential function and a form of competitive advantage (Fernández and Márquez, 2012). According to ABNT NBR 5462 (1994), maintenance involves all technical and administrative

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International.

Citation (APA): Bastos, F. C. & Fujiyama, R. T. (2023). Application of reliability-centered maintenance in a steel mill. *Brazilian Journal of Production Engineering*, 9(3), 206-223.

measures aimed at maintaining or replacing an object, ensuring its proper performance. Maintenance encompasses the concepts of prevention and correction.

The generations of industrial maintenance represent different stages of development. The first generation, which occurred between the 1940s and 1950s, was characterized by a little mechanized industry, simple equipment and basically unplanned corrective maintenance (Kardec and Nascif, 2012; Siqueira, 2005). The second generation, which occurred between the 1960s and 1970s, brought the adoption of time-based preventive maintenance, due to increasing mechanization and the search for greater productivity (Kardec and Nascif, 2012; Lucatelli, 1998).

The third generation, between the 1970s and 1990s, was driven by market demands, focusing on reliability, availability, quality, safety and the environment (Lucatelli, 2002; Siqueira, 2005). The fourth and last generation, between 2000 and 2005, emphasized predictive maintenance techniques, condition monitoring and projects aimed at reliability and availability (Rosa, 2016; Dunn, 1998). These different generations represent the evolution of industrial maintenance over time, reflecting the needs and requirements of industries in each era.

2.2 Types of Failures

One of the main functions of maintenance is to prevent and repair failures. For this, they must be properly categorized, analyzed and catalogued. In other words, we need to understand how the system fails. For the application of RCM, failures are classified according to the effect they cause on a function of the system to which they belong.

Siqueira (2005) divides failures into two large groups: functional failure, as the inability of an asset to perform the function, and potential failure, as an identifiable condition for the subsequent occurrence of a functional failure.

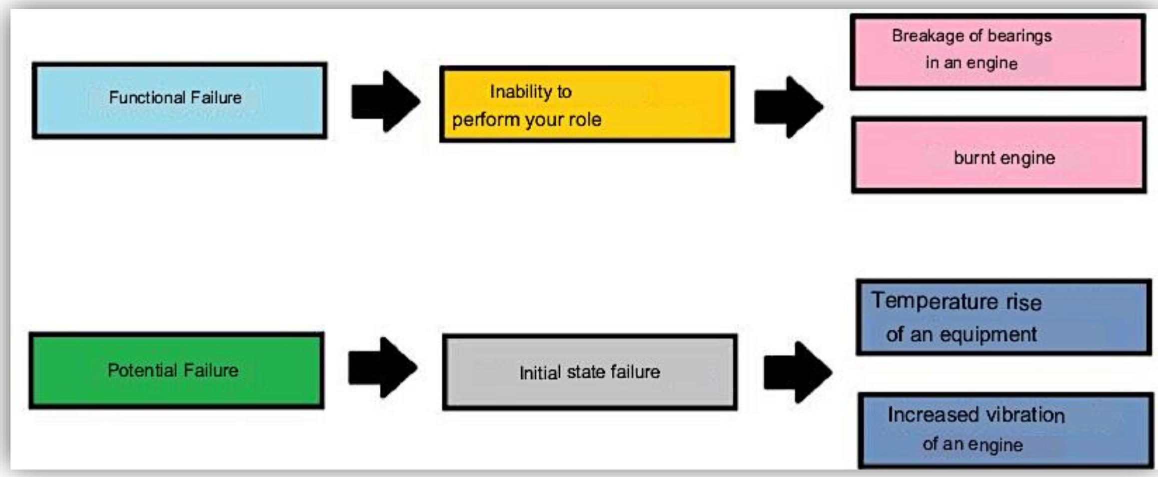
The potential failure is presented by Teles (2019) as the moment when the failure starts in the asset, not completely compromising the equipment, but decreasing its performance. As for functional failure, it is seen as the inability to function at the level of performance that was specified as satisfactory.

Figure 1 shows a diagram of the types of failures and some everyday examples.

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International. ***Brazilian Journal of Production Engineering***, São Mateus , Publisher UFES/CEUNES/DETEC. ISSN: 2447-5580

Citation (APA): Bastos, F. C. & Fujiyama, R. T. (2023). Application of reliability-centered maintenance in a steel mill. *Brazilian Journal of Production Engineering*, 9(3), 206-223.

Figure 1. types in flaws, concepts and examples



Source: Authors (2023).

2.3 Types of Maintenance

ABNT NBR 5462 (1994) presents corrective, preventive and predictive maintenance as the three main types of maintenance. Within each type of maintenance, other categories are derived.

2.3.1 Corrective Maintenance

Corrective maintenance is the oldest and most used by companies, regardless of their level of maintenance planning. It is essentially characterized by reactive actions, that is, curative, unplanned or emergency actions necessary to restore (Smith, 1993).

According to the NBR 5462 Standard, Corrective Maintenance is the maintenance carried out after the occurrence of a failure (or breakdown), and acts after the occurrence of a functional failure, in which the equipment has ceased to perform its function (ABNT NBR 5462, 1994).

2.3.2 Preventive Maintenance

Preventive maintenance is carried out at predetermined intervals and aims to reduce the probability of failures or degradation of the functioning of an item (ABNT NBR5462, 1994). Although it has a lower cost compared to corrective maintenance, it is still considered relatively expensive compared to other types of maintenance (Kardec and Nascif, 2009).

In establishing time intervals for preventive maintenance, it is common to adopt a conservative approach, resulting in shorter intervals than necessary, which can lead to interruptions and unnecessary parts replacements (Xavier, 2010).

2.3.3 Predictive Maintenance

Predictive maintenance, also known as maintenance under condition or maintenance based on the state of the equipment, seeks to predict the future state of an equipment or system through the analysis of data collected over time (Teles, 2019). This approach aims to detect irregularities, quantify the origin and severity of defects and establish limits for scheduling

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International.

Citation (APA): Bastos, F. C. & Fujiyama, R. T. (2023). Application of reliability-centered maintenance in a steel mill. *Brazilian Journal of Production Engineering*, 9(3), 206-223.

and executing repairs, with the aim of correcting potential failures before causing irreversible damage (Nepomuceno, 1989).

Predictive maintenance has significant benefits, such as minimal intervention on the asset and without the need to stop the equipment to perform it, which results in better outcomes (Kardec and Nascif, 2009). Examples of techniques used in predictive maintenance include thermography, vibration analysis and oil analysis.

2.4 Criticality Matrix

The criticality matrix is an important classification for the development of adequate maintenance policies, assessing the criticality of machines in terms of the impact of failures in the production process, safety, quality, among others (Maintenance, 2016).

It is a methodology whose purpose is to determine the criticality of an equipment based on pre-established criteria. It is also responsible for maintenance actions. Six elements, including security, quality and occupancy rate, are used in this algorithm to define which path to follow. Each element response is classified in A, B or C, and this classification will define the path to be followed in the algorithm. Table 1 presents the characteristics used for ABC classification.

Table 1. ABC criticality matrix table.

		CLASS		
		A	B	W
S	Potential risk of an accident when a failure occurs	High Risk	Medium or low risk	Risk discarded
Q	Risk of Losses, claims, rework.	High risk for waste and rework	Medium risk for losses and rework	Low risk or ruled out
O	Equipment operating time	24h/day	8 to 24h/day	<= 8h/day
IF	Process impact during equipment failure	Stops the entire production process	Does not interrupt process, but generates losses	There is no significant impact
F	Equipment failure frequency	Greater than 01 failure / 02 months	1 failure / 02 and 06 months	Less than 01 failure / 06 months
M	Mean Time to Repair (MTTR)	MTTR > 2h	0.5h< MTTR <2h	MTTR < 0.5h

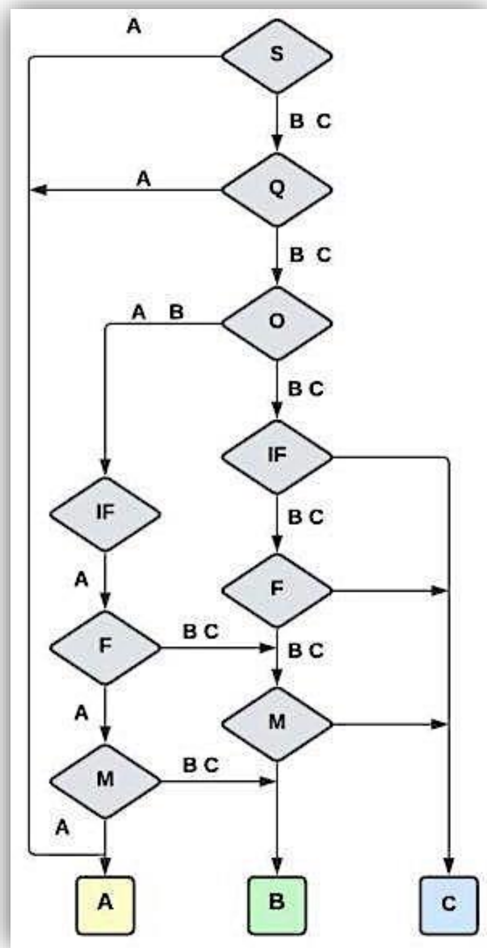
Source: Adapted in JIPM (1995).

The information in Table 2 must be analyzed and applied to the flowchart in Figure 2 so the criticality level of the asset can be defined.

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International.

Citation (APA): Bastos, F. C. & Fujiyama, R. T. (2023). Application of reliability-centered maintenance in a steel mill. *Brazilian Journal of Production Engineering*, 9(3), 206-223.

Figure 2. flowchart from the headquarters criticality ABC.



Source: Adapted in JIPM (1995).

2.5 Reliability Indicators and Metrics

Asset reliability measures, such as the MTBF and MTTR, are widely used in evaluating the efficiency and reliability of equipment and systems in various industrial sectors.

According to Pinheiro, Silva and Almeida (2016), MTTR can be used in conjunction with MTBF to assess reliability in production systems. These measures can be used to identify possible equipment failures and to improve preventive maintenance, helping to reduce costs and improve asset performance.

The MTBF calculation is based on the average operating time between two consecutive failures, considering the repair time and preventive maintenance. In this way, it is possible to assess the reliability of the equipment and to program preventive maintenance actions to avoid unscheduled downtime. The MTTR calculation is based on the average repair time between failures in the equipment.

According to Maiorky, Lima and Pereira (2015), the MTTR analysis can be performed by monitoring the equipment repair time. In addition, the use of MTTR in conjunction with MTBF can contribute to a more complete assessment of the reliability of industrial equipment and systems.

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International. ***Brazilian Journal of Production Engineering*** , São Mateus , Publisher UFES/CEUNES/DETEC. ISSN: 2447-5580

Citation (APA): Bastos, F. C. & Fujiyama, R. T. (2023). Application of reliability-centered maintenance in a steel mill. *Brazilian Journal of Production Engineering*, 9(3), 206-223.

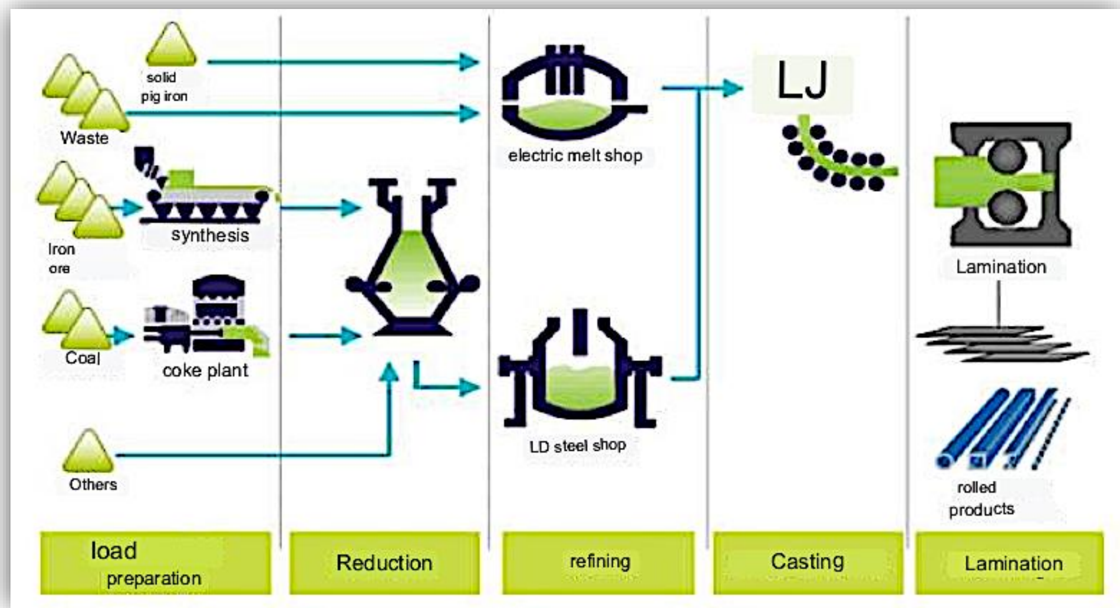
2.6 The steelmaking process

The technological evolution of the steel industry in the 20th century grew significantly, aiming at increasing productivity, returning on investment, and energy efficiency. The use of scrap as raw material for steel production is pointed out as a striking point of the current steel industry, according to CGEE (2009). Brasil (2009) divides steel mills into two groups: integrated and semi-integrated. The integrated ones produce steel from their raw materials, while the semi-integrated ones use scrap as a source of raw material. Mourão (2007) presents the main stages that follow the steel production process in an integrated plant, such as:

- Step 1 - Obtaining pig iron from raw materials (intermediate product);
- Step 2 - Conversion of pig iron into steel;
- Step 3 - Casting of the steel produced;
- Step 4 - Conformation of steel into final product (rolling).

In Figure 3, the phases of the production process of a melt shop are illustrated. The first reduction phase is present in the integrated mills, while the semi-integrated mills start their processes from the refining phase. An essential component in this process is the blast furnace, where complex processes for transforming iron ore into liquid pig iron take place.

Figure 3. Stages of the steelmaking process



Source: https://portalvirtuhab.paginas.ufsc.br/aco/

2.7 The Blast Furnace

The blast furnace is an essential component in the steel industry, where complex processes of transforming iron ore into liquid pig iron take place. According to specialists, “The blast furnace is a large structure with a cylindrical shape that allows the melting and reduction of iron ore, resulting in the production of pig iron” (Geerdes, 2004).

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International. ***Brazilian Journal of Production Engineering*** , São Mateus , Publisher UFES/CEUNES/DETEC. ISSN: 2447-5580

Citation (APA): Bastos, F. C. & Fujiyama, R. T. (2023). Application of reliability-centered maintenance in a steel mill. *Brazilian Journal of Production Engineering*, 9(3), 206-223.

The production process in the blast furnace involves charging iron ore, coke and fluxes. According to researchers, "Coke is used as a source of heat and carbon during the iron ore reduction reaction. Fluxes, such as limestone and dolomite, help melt the components and remove impurities." (Mourão, 2007).

Liquid pig iron, containing carbon and other impurities, is collected at the bottom of the blast furnace. As pointed out by researchers, "This liquid pig iron is later directed to other processes in the steel plant, such as the melt shop, where it is transformed into steel by removing impurities and adding alloying elements" (Geerdes, 2004).

2.8 Reliability-centric maintenance

Reliability-Centric Maintenance had its first steps taken in the early 1970s, after an event requested by the FAA- Federal Aviation Authority. Teles (2019) states that the main reason was the need for certification of the new Boeing 747 aircraft line, and it required a maintenance policy different from the usual ones due to the level of automation used.

Moubray (1997) presents the concept of RCM as a process that determines what must be done so that an asset continues to perform its function, within its operational context. Afefy (2010) states that RCM works to optimize preventive maintenance strategies, ensuring greater equipment reliability.

2.8.1 Deployment Steps

2.8.1.1 Operational Requirements - System Selection and Information Collection

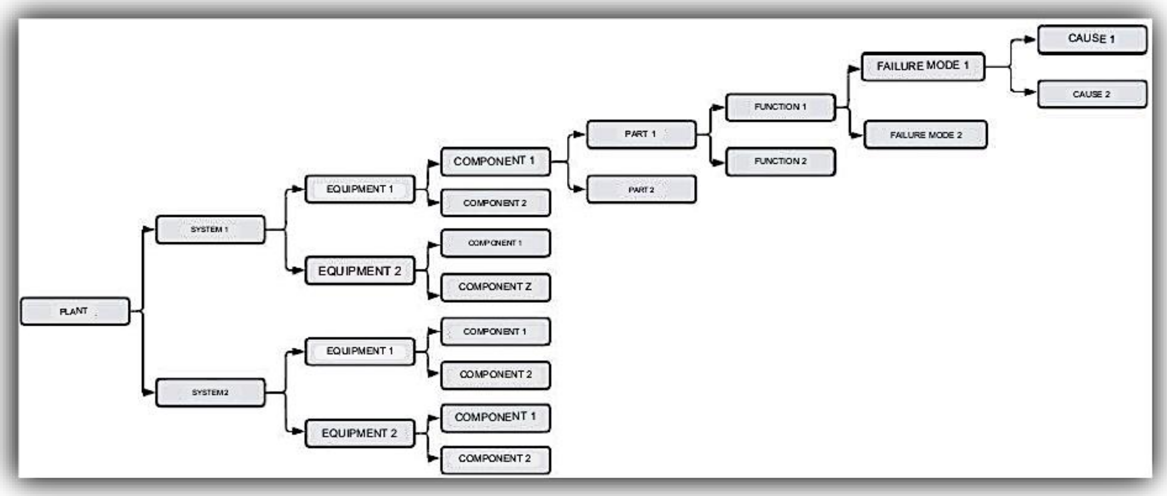
It will be the stage in which the operational requirements and their functions will be presented. To carry out this step, it is necessary to consult some information, such as:

- Manufacturers' manuals;
- History of equipment failures;
- Project specifications.

According to Siqueira (2005), the first stage of the RCM implementation process consists of understanding the operation and structure of the installation. Lafraia (2014) states that there is no ideal predefined level of analysis and that the experience of the implementation team and the monitoring of maintenance effectiveness are factors that determine the level of analysis to be performed. To determine this level, it is necessary to create process diagrams. Fogliatto and Ribeiro (2011) suggest the integration of a database to RCM systems to record failures and maintenance performed on assets. Figure 4 presents a process diagram model used in the RCM analysis.

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International. ***Brazilian Journal of Production Engineering***, São Mateus , Publisher UFES/CEUNES/DETEC. **ISSN: 2447-5580**

Figure 4. Model in Diagram in Process.



Source: Adapted in Lafraia (2014)

2.8.1.2 System Functional Analysis

In the previous stage of the RCM study, the Block Diagram was created, which allows identifying the assets involved in the process and their interactions. Now, in the second stage, it is possible to identify and define the functions of the assets and their respective functional failures, based on the desired quality and safety standards. According to Moubray (1997), the functions can be classified into primary and secondary, the first being those that justified the acquisition of the asset, and the second the extra functions that it can perform. It is important that the functions are specific to the operational context so that functional failures can be identified and measures can be defined to avoid them. Lafraia (2014) highlights the importance of identifying the functions of assets and their failures for the correct application of RCM.

2.8.1.3 Analysis of Failure Modes and Effects

The third stage for the application of RCM consists of the elaboration of the Failure Modes and Effects Analysis (FMEA), a tool that aims to analyze possible failures in industrial processes, identifying their causes, effects and measures to avoid them. Based on this analysis, it is possible to define corrective actions according to the criticality of the failure. According to Kardec and Nascif (2012), FMEA can also be used as a documented means of reviewing projects and industrial processes, allowing for possible changes. Fazle (2018) highlights that the tool requires the combination of technical knowledge with human experience for its proper application.

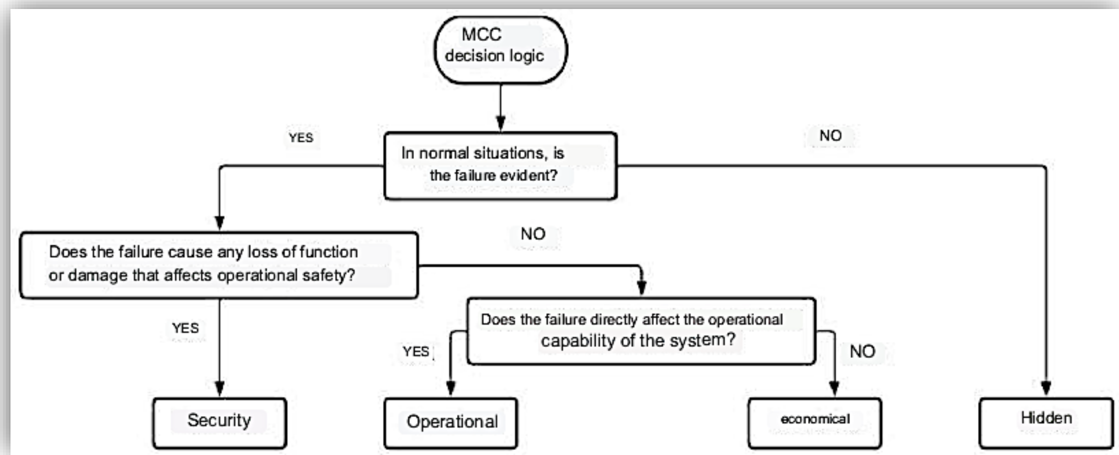
2.8.1.4 Selection of Tasks and Types of Maintenance to be Applied

After carrying out the FMEA, the maintenance tasks and the respective types of maintenance that they fit should be defined, and later they will be included in the maintenance plans. Deshpande and Modak (2002) show that RCM emphasizes how functions can fail in considerations based on priority of safety, economy and process, which identifies applicable and effective maintenance tasks. For this, the RCM Block Diagram is used. Figure 5 shows the RCM Block Diagram model.

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International. ***Brazilian Journal of Production Engineering*** , São Mateus , Publisher UFES/CEUNES/DETEC. ISSN: 2447-5580

Citation (APA): Bastos, F. C. & Fujiyama, R. T. (2023). Application of reliability-centered maintenance in a steel mill. *Brazilian Journal of Production Engineering*, 9(3), 206-223.

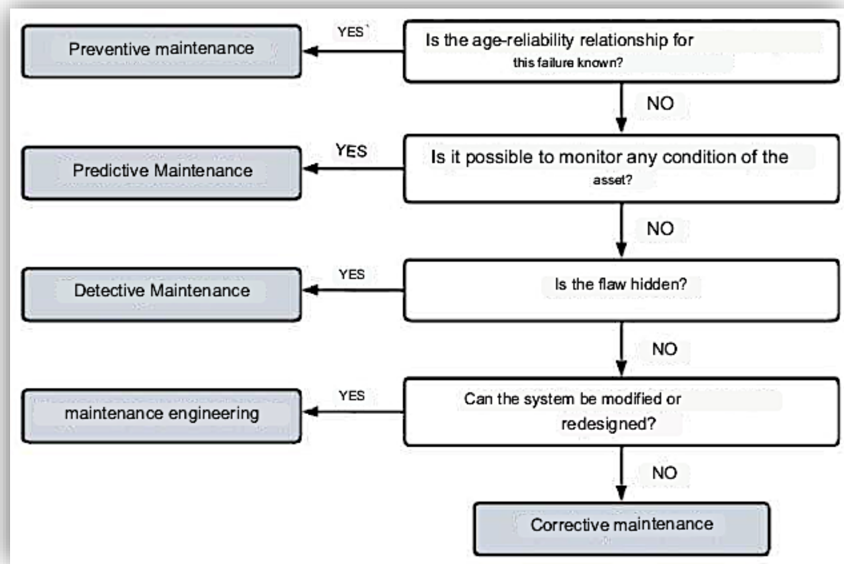
Figure 5. Diagram in Blocks from the RCM.



Source: Lafraia (2014).

After surveying the types of maintenance for each failure, the maintenance activity can be elaborated and later added to a maintenance plan. In their literature, Kardec and Nascif (2009) also present a decision diagram for the ideal types of maintenance to every way of failure, as shown in Figure 6.

Figure 6. Diagram in decision for types in maintenance.



Source: Adapted in Kardec and Nascif (2009)

2.6.1.5 Creation of Maintenance Plans

An effective maintenance plan must include the tasks to be carried out, the critical points that must be monitored, the responsibilities and the frequency with each task must be executed. According to Teles (2019), there are two possible ways to organize a plan of maintenance: per criticality or per area. A frequency of activities in maintenance should be determined based on the manufacturer's recommendations and the performance of the assets. In some cases, it may be necessary to adjust the frequency of activities to avoid occurrence in premature failures.

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International. ***Brazilian Journal of Production Engineering*** , São Mateus , Publisher UFES/CEUNES/DETEC. ISSN: 2447-5580

Citation (APA): Bastos, F. C. & Fujiyama, R. T. (2023). Application of reliability-centered maintenance in a steel mill. *Brazilian Journal of Production Engineering*, 9(3), 206-223.

3. METHODOLOGY

This case study investigated the application of the Reliability Centered Maintenance (RCM) concept in blast furnace equipment in a steel plant. The choice of this area was due to the high levels of corrective maintenance and the ease of initial implementation of the RCM in the plant under study, in comparison with other sectors of the steel plant.

Initially, a survey was carried out of all the information necessary to start the work, including the asset tree and its main functions, in order to delimit the scope of the research. Then, a diagram was drawn up dividing the area into subareas, their respective lines of action and, finally, the machines corresponding to each subarea.

After this stage, the equipment with the highest criticality (Class A) was selected, using an asset criticality matrix. The electric blowers in the machine room were chosen as a sample because they have a high rate of corrective maintenance and because they are fundamental to the blast furnace process. Then, the main functions of these assets were analyzed, aiming to identify their main functional failures.

For the detailed analysis of the failures, an FMEA study was carried out with the objective of identifying the failure modes, causes and effects of each component of the asset under study. At the same time, the Risk Priority Number index (RPN), which ranks potential failures according to their level of criticality. Based on the FMEA results, a maintenance plan was defined, including the appropriate tasks for each identified failure, considering the criticality of each specific task, as well as information from the manufacturer, installation location and previous experiences.

After the implementation of the maintenance plans, quantitative analyzes were carried out on the number of corrective maintenances in the first quarter of 2021 (before the implementation of the RCM) and in 2022 (after the implementation of the RCM), in order to assess the gains obtained in terms of occurrence reduction. In addition, the reliability metrics (MTBF and MTTR) were compared during these periods to verify the advances related to the times and amounts of asset failures.

4. RESULTS AND DISCUSSION

4.1 Selection of systems and collection of information

The analyzed maintenance plans are at the asset machine level. To select the systems that will participate in the RCM study, a survey was initially carried out on the plant's assets, presenting machines, their respective production lines and the subarea where they are installed, according to the hierarchical level of assets presented by Teles (2019). From the asset survey, an analysis was carried out, based on the ABC criticality of equipment. Table 1 presents the survey of the 34 assets of the Blast Furnaces plant and the level of criticality that each one presents, both for the process, as well as for safety and economy. For the RCM study, only the criticality A equipment shown in Table 2 will be considered.

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International. ***Brazilian Journal of Production Engineering*** , São Mateus , Publisher UFES/CEUNES/DETEC. **ISSN: 2447-5580**

Citation (APA): Bastos, F. C. & Fujiyama, R. T. (2023). Application of reliability-centered maintenance in a steel mill. *Brazilian Journal of Production Engineering*, 9(3), 206-223.

Table 2. Equipment in criticality A of the Blast Furnace.

Criticality ABC of Machines			
Sub area	**Line**	**Machine**	**Criticality**
Processing in Ore	Washing in Ore	Main Tc (Ore Gross)	A
Processing in Coal	Unloading in Coal	Tumbler Of Coal	A
Area High Oven 1	Living Room in Machines	Electric Blower Two	A
		Electric Blower 3	A
		Electric Blower 4	A
		Electric Blower 5	A
		Electric Blower 6	A
	High Oven	Hopper Rotary of Distribution of Loads	A
	Platform	Granulator in Slag	A

Source: Authors (2022)

Initially, the RCM will be applied to the electroblowers in the engine room, due to their higher rate of corrective maintenance compared to the other equipment shown in Table 2. Later, the other criticality A equipment will be included in this RCM study.

4.2 Analysis of functions and functional failures

For this step, a spreadsheet was filled out with the main functions and functional failures of the criticality A assets of the plant, obtained in the previous step, as shown in Table 3, which shows the functions and functional failures of the motor and monoblock bearing, the main equipment of the electroblower. Only the primary failures were considered, as they had a more significant influence on the process. Lopes (2001) presents a spreadsheet model similar to the one presented in Table 3, informing the equipment, functions and its functional failures.

Table 3. Analysis in functions It is flaws functional – Electroblower.

Functional Failure Analysis - MCC		
Sub-Area: Blast Furnace Area 01	Eletrosprador 02	Line: Machine Room Machine
Equipment	**Function**	**Failure functional**
Motor	Rotate the blower fan shaft	Fracture of the LA and LNA bearings
Motor	Rotate the blower fan shaft	Short circuit in stator windings
Motor	Rotate the blower fan shaft	Overcurrent motor trip
Motor	Rotate the blower fan shaft	disarm per overheating
monobloc bearing	Rotate the blower fan shaft	Fracture of the LA and LNA bearings

Source: Authors (2022)

4.3 Application of failure modes and effects analysis

From the FMEA application, the failure modes, their causes, and their effects for each functional failure presented in the previous step will be analyzed. From the data collected and analyzed in the FMEA, it will be possible to elaborate the activities of the maintenance plans that will be carried out in a later stage. The FMEA spreadsheet used in this work is shown in Table 4, where the modes, causes and effects of failures for the motor and monobloc bearing are presented, making it possible to carry out a risk assessment and calculate its RPN index (Risk Priority Number), which points out which failure modes require more priority and attention to be addressed. ROSA, 2016, similarly, applies the FMEA, and highlights the failure modes with the highest RPN's for priorities in their dealings.

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International. ***Brazilian Journal of Production Engineering***, São Mateus , Publisher UFES/CEUNES/DETEC. **ISSN: 2447-5580**

Citation (APA): Bastos, F. C. & Fujiyama, R. T. (2023). Application of reliability-centered maintenance in a steel mill. *Brazilian Journal of Production Engineering*, 9(3), 206-223.

Table 4. Analysis of Functions and Functional Flaws – Electric Blower 02.

SPREADSHEET FMEA										
No. FMEA: 01 Area: AF1			Date in elaboration: 05/29/2022 Line: Living room in machine machines				Responsible: Philip Ram : Electric blower 02			
Point in failure			Analysis from the failure			Assessment risk				Action preventive recommended
Equipment	Function of equipment	Component	Modes in failure (SYMPTOM)	effects of failure	Cause from the failure	Severity	Occurrence	Detection	RPN	
Motor	Rotate axle offan of electroblower	bearings	Temperature elevated	Fracture/Stop of machine	*Amount in lubrication inadequate; *Lubricant inappropria; *Contamination of lubricant; *Assemblyincorrect; *Charge excessive	6	7	6	252	
Motor	Rotate axle offan of electroblower	Bearing	Vibration excessive	Broken rolling/stopping from the machine	*Lubrication deficient; *Eccentricity of rotor; *Misalignment of axle in rotation; * Rings with breakdowns; *Contamination of lubricant;	7	7	8	392	
Motor	Rotate axle of fan of electroblower	stator	imbalance in voltage	Short circuit in between phases/stop from themachine	clearance in connectionsfrom the box in connection.	5	8	6	240	
Motor	Rotate axle offan of electroblower	stator	Temperature elevated in coils of stator	Short circuit in between phases/Stop of machine	Accumulation in sweat in the engine frame(fins)	8	6	6	288	
Motor	Rotate axle offan of electroblower	stator	Temperature elevated in coils of stator	Short circuit in between phases/Stop of machine	Ventilation forced/ self-ventilation inefficient	6	5	8	240	
bearing monoblock	Rotate axle offan of electroblower	Bearing	Vibration excessive	Broken rolling/stopping from the machine	*Lubrication deficient; *Eccentricity of rotor; *Misalignment of axle in rotation; * Rings with breakdowns; *Contamination of lubricant;	7	7	5	245	
bearing monoblock	Rotate axle offan of electroblower	Bearing	Temperature elevated	Broken rolling/stopping from the machine	*Amount in lubrication inadequate; *Lubricant inappropria; *Contamination of lubricant; *Assemblyincorrect; *Charge excessive	8	6	5	240	

Source: Authors (2022)

4.4 SELECTION OF MAINTENANCE TASKS

After implementing the FMEA in the previous step, it was possible to obtain data on the causes of failures for each failure mode, individually, and made it possible to carry out a survey of the recommended actions to mitigate each failure. The flowchart shown in Figure 5 was used to define the type of maintenance to be used based on the data obtained from the FMEA. In Table 5, the FMEA worksheet is presented with the recommended actions completed for each failure mode previously presented, according to each equipment.

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International. ***Brazilian Journal of Production Engineering*** , São Mateus , Publisher UFES/CEUNES/DETEC. ISSN: 2447-5580

Citation (APA): Bastos, F. C. & Fujiyama, R. T. (2023). Application of reliability-centered maintenance in a steel mill. *Brazilian Journal of Production Engineering*, 9(3), 206-223.

Table 5. Spreadsheet FMEA with recommended preventive actions – Electric blower 02.

SPREADSHEET FMEA										
No. FMEA: 01 Area: AF1			Date In Elaboration: 05/29/2022 Line: Living Room In Machine Machines				Responsible: Philip Ram : Electric Blower 02			
Point in failure			Analysis from the failure			Assessment risk				Action preventive recommended
Equipment	Function of equipment	Component	Modes in failure (SYMPTOM)	effects of failure	Cause from the failure	Severity	Occurrence	Detection	RPN	
Motor	Rotate axle offan of electroblower	bearings	Temperature elevated	Fracture/Stop of machine	*Amount inlubrication inadequate; *Lubricant inappropriate; *Contamination of lubricant; *Assemblyincorrect; *Charge excessive	6	7	6	252	Lubrication periodic according to specifications of manufacturer; Follow-up journal of temperature of work of component.
Motor	Rotate axle offan of electroblower	Bearing	Vibration excessive	Broken rolling/stopping from the machine	*Lubricationdeficient; *Eccentricity ofrotor; *Misalignment of axle in rotation; * Rings with breakdowns; *Contamination of lubricant;	7	7	8	392	Perform analysis in vibration periodically. Lubrication periodic according to specifications of manufacturer
Motor	Rotate axle of fan of electroblower	stator	imbalance in voltage	Short circuit in between phases/stop from themachine	clearance in connectionsfrom the box in connection.	5	8	6	240	To check grip of connections periodically
Motor	Rotate axle offan of electroblower	stator	Temperature elevated in coils of stator	Short circuit in betweenphases/Stop of machine	Accumulation in sweat in the engine frame (fins)	8	6	6	288	Accomplish cleaning at structure of motor. Accomplish follow-up from thetemperature of work of equipment.
Motor	Rotate axle offan of electroblower	stator	Temperature elevated in coils of stator	Short circuit in betweenphases/Stop of machine	Ventilation forced/self ventilation inefficient	6	5	8	240	Check cleanliness of deflector cap engine (engine self-ventilated); Accomplishmonitoring of temperature in work of equipment.
bearing monoblock	Rotate axle offan of electroblower	Bearing	Vibration excessive	Broken rolling/stopping from the machine	*Lubricationdeficient; *Eccentricity ofrotor; *Misalignment of axle in rotation; * Rings with breakdowns; *Contamination of lubricant;	7	7	5	245	Perform analysis in vibration periodically. Lubrication periodic according to specifications of manufacturer
bearing monoblock	Rotate axle offan of electroblower	Bearing	Temperature elevated	Broken rolling/stopping from the machine	*Amount inlubrication inadequate; *Lubricant inappropriate; *Contamination of lubricant; *Assemblyincorrect; *Charge excessive	8	6	5	240	Lubrication periodic according to specifications of manufacturer; Follow-up journal of temperature of work of component.

Source: Authors (2022)

4.5 Creation of Maintenance Plans

This step consisted of setting up the maintenance plan, using the recommended actions obtained in the previous step. The flowchart proposed by Kardec and Nascif (2012) and previously presented in Figure 5 was used to assess which type of maintenance is most appropriate for each failure mode, individually. The maintenance tasks presented in the previous step were used to prepare the maintenance plans. The periodicity of the plans was based on the manufacturer's recommendations and experience in the area, but considering the characteristics of the location where the asset is installed (dirt, high humidity, high temperature). The periodicities presented in the maintenance plans before the application of the RCM were also considered to define the periodicities of the activities of the new plans. Table 6 presents the revised maintenance plan, based on the RCM, for the electric blowers in the machine room.

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International. ***Brazilian Journal of Production Engineering*** , São Mateus , Publisher UFES/CEUNES/DETEC. ISSN: 2447-5580

Citation (APA): Bastos, F. C. & Fujiyama, R. T. (2023). Application of reliability-centered maintenance in a steel mill. *Brazilian Journal of Production Engineering*, 9(3), 206-223.

Table 6. Maintenance plan revised based on the RCM.

FLAT IN MAINTENANCE REVISED WITH BASE AT MCC - HIGH OVEN 01			
Code	**Description**	**Activity**	**Frequency**
	INSP. LIVING ROOM MACHINES 00-08	Accomplish cleaning at cover deflector of motor	Weekly
		Accomplish cleaning in the fins of the engines	
		To check fixation from the cover deflector of motor	
PRES/AF1-117	COL. ViIB HOME MAQ 00-08 AF1	Collect vibration through of point measuring	Daily
PRES/AF1-118	COL. VIB HOME MAQ 08-16 AF1	Collect vibration through of point measuring	Daily
PRES/AF1-119	COL. VIB HOME MAQ 16-00 AF1	Collect vibration through of point measuring	Daily
PRES/AF1-172	LUB. BEARINGS HOME MAQ AF1	MACHINE 02 - lubricate bearing side coupled of the bearing with 46g of grease diurea	Weekly
		MACHINE 02 - lubricate bearing side no coupled to the bearing with 46g in grease diurea	
		MACHINE 03 - lubricate bearing side coupled of the bearing with 46g of grease diurea	
		MACHINE 03 - lubricate bearing side no coupled to the bearing with 46g in grease diurea	
		MACHINE 04 - lubricate bearing side coupled of the bearing with 46g of grease diurea	
		MACHINE 04 - lubricate bearing side no coupled to the bearing with 46g in grease diurea	
		MACHINE 05 - lubricate bearing side coupled of the bearing with 46g of grease diurea	
		MACHINE 05 - lubricate bearing side no coupled to the bearing with 46g in grease diurea	
		MACHINE 06 - lubricate bearing side coupled of the bearing with 46g of grease diurea	
		MACHINE 06 - lubricate bearing side no coupled to the bearing with 46g in grease diurea	
PRES/AF1-111	COL. HOUSE TEMP MAQ 00-08 AF1	Collect temperature through of point in measurement	Daily
PRES/AF1-112	COL. HOUSE TEMP MAQ 08-16 AF1	Collect temperature through of point in measurement	Daily
PRES/AF1-113	COL. TEMP HOME MAQ 16-00 AF1	Collect temperature through of point in measurement	Daily
PRES/AF2-081	LUB. ENGINES HOME MAQ AF1	Lubricate engine machine 02 with 70g of grease for each point	Weekly
		Lubricate machine engine 03 with 70g of grease for each point	
		Lubricate motor machine 04 with 70g in grease for each point	
		Lubricate machine engine 05 with 70g of grease for each point	
		Lubricate machine motor 06 with 70g of grease for each point	

Source: Authors (2022)

4.6 Comparison Between Maintenance Plans

After completing step 5, it was possible to compare plans before applying the RCM and those that were implemented based on the RCM. As a sample, the preventive maintenance plan for electroblower 2, from the engine room, was taken. Table 7 shows the maintenance plan prior to the study for implementing the RCM. Lopes (2001) also presents a comparison of maintenance plans, before (using the SOM- Operation and Maintenance System) and after RCM, also showing the changes made to the plans.

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International. ***Brazilian Journal of Production Engineering***, São Mateus , Publisher UFES/CEUNES/DETEC. ISSN: 2447-5580

Citation (APA): Bastos, F. C. & Fujiyama, R. T. (2023). Application of reliability-centered maintenance in a steel mill. *Brazilian Journal of Production Engineering*, 9(3), 206-223.

Table 7. Maintenance plan before the implantation of the RCM.

FLAT IN MAINTENANCE BEFORE FROM THE IMPLANTATION FROM THE MCC - HIGH OVEN 01			
Code	**Description**	**Activity**	**Frequency**
LUBR/AF1-001	LUBRICATION HOME ENGINES IN MACHINES	LUBRICATE MOTOR MAQ-02 24G FOR EACH POINT	fortnightly
		LUBRICATE MOTOR MAQ-03 24G FOR EACH POINT	fortnightly
		LUBRICATE MOTOR MAQ-04 24G FOR EACH POINT	fortnightly
		LUBRICATE MOTOR MAQ-05 24G FOR EACH POINT	fortnightly
		LUBRICATE MOTOR MAQ-06 24G FOR EACH POINT	fortnightly
LUBR/AF1-002	LUBRICATION HOUSE BEARINGS IN MACHINES	LUBRICATE BEARING MAQ-02 70g FOR 2 POINTS	fortnightly
		LUBRICATE BEARING MAQ-03 70g FOR 2 POINTS	fortnightly
		LUBRICATE BEARING MAQ-04 70g FOR 2 POINTS	fortnightly
		LUBRICATE BEARING MAQ-05 70g FOR 2 POINTS	fortnightly
		LUBRICATE BEARING MAQ-06 70g FOR 2 POINTS	fortnightly
PRE/AF1-007	PRES. SYSTEM HOME INMACHINES	TO CHECK NOISE STRANGE	Daily
		TO CHECK FIXATION IN ELEMENTS	Daily
		TO CHECK LEAKS PIPING	Daily
		TO CHECK LUBRICATION OF DAPER	Daily
		TO CHECK TEMPERATURE LA/LNA BEARING	Daily
		TO CHECK TEMPERATURE THERE MOTOR	Daily
PRE/AF1-008	PRES. SYSTEM HOME INMACHINES	TO CHECK NOISE STRANGE	Weekly
		TO CHECK FIXATION IN ELEMENTS	Weekly
		TO CHECK LEAKS PIPING	Weekly
		TO CHECK LUBRICATION OF DAPER	Weekly
		TO CHECK TEMPERATURE LA/LNA BEARING	Weekly
		TO CHECK TEMPERATURE THERE MOTOR	Weekly

Source: Authors (2022)

After analyzing the plans in Table 7 (before the implementation of the RCM), some considerations were raised:

- Absence of predictive plans for vibration analysis;
- Long periodicity of plans that include temperature collection of the motor and monobloc bearing of each machine;
- Absence of engine preservation activities (cleaning of the deflector cover and fins), which are factors responsible for the increase in engine temperature;
- The periodicity of the lubrication plans for the motors and monobloc bearings was fortnightly, being considered a long period, due to the criticalities of the installation site (high temperature and dirt).

In comparison with the plans before and after the implementation of the RCM study, the following considerations were obtained:

- Inclusion of predictive vibration analysis plans, with periodicity at each shift;
- Reduction of the frequency of maintenance plans for the temperature of the motor and monoblock bearing for each machine for each shift;
- Creation of maintenance plans that address engine preservation activities (cleaning the deflector cover and fins);
- Reduction of the periodicity of the lubrication plans for the motors and monobloc bearings to once a week due to the criticality of the installation site.

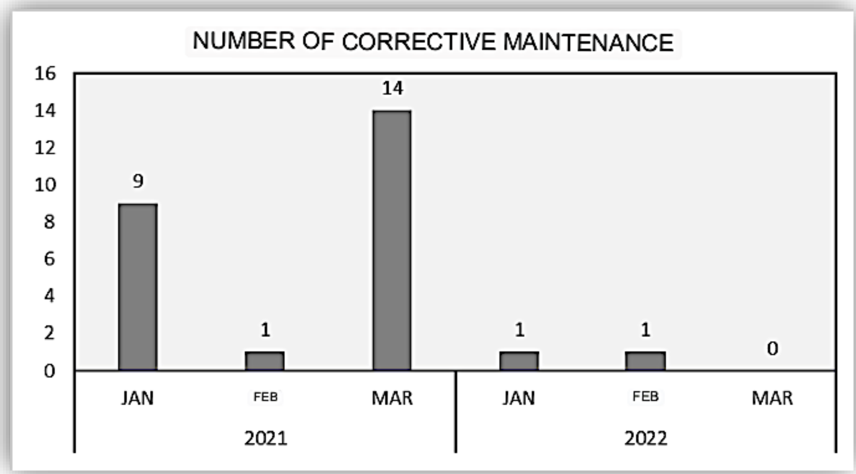
4.7 Results Achieved

When problems related to functional failures in the equipment occur, maintenance notes are opened, and they are characterized as corrective maintenance. After implementing the plans based on the RCM, a comparison was made of the number of open corrective

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International.

maintenance via the ITSS app for the electroblowers in the machine room. In Figure 7, a comparison was made between the first quarter of 2021, in which plans based only on technical experience were used, and 2022, when the plans were updated and revised by RCM.

Figure 7. Comparative for number in maintenance corrective



Source: Authors (2022)

With the maintenance data obtained in SAP PM for the years 2022, the MTBF AND MTTR values were also calculated, selecting the corrective maintenance values for the years 2021 and 2022, as shown in Table 8. Rosa (2016) shows similar gains for MTBF and MTTR after the implementation of the RCM.

Table 8. Comparative for number in maintenance corrective

Metrics in Reliability - Electric Blower 02			
Pre-MCC Values (2021)		Values Post -MCC (2022)	
MTBF	177.46	**MTBF**	301
MTTR	2.71	**MTTR**	2.27

Source: Authors (2022)

Analyzing the data, it was observed a ratio reduction of 91.7% of the number of corrective maintenances between 2021 and 2022. As for the reliability indices, there was an increase of 69.6% in relation to the MTBF, which ensures greater equipment availability. On the other hand, the MTTR had a decrease of 16.23% after the installation of the RCM, which shows the decrease in the equipment repair time.

5. CONCLUSION

The objective of this study was to increase the reliability of blast furnace equipment in a steel plant, applying the Reliability Centered Maintenance (RCM) methodology and addressing the following steps: (i) Team selection and training; (ii) system selection and information gathering; (iii) analysis of functions and functional failures; (iv) analysis of failure modes and their effects; (v) determination of the maintenance plan.

The blast furnace equipment was selected according to its level of criticality, using the criticality matrix, with the objective of particularizing the equipment classified as level A, so

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International.

Citation (APA): Bastos, F. C. & Fujiyama, R. T. (2023). Application of reliability-centered maintenance in a steel mill. *Brazilian Journal of Production Engineering*, 9(3), 206-223.

that the RCM was initially applied. Among the criticality A equipment, electroblowers were selected as the initial sample, due to their high rate of corrective maintenance and long equipment downtime during failures.

The partial results obtained by the application of the RCM in the criticality A equipment of the blast furnaces, selected from the ABC criticality matrix, showed the importance of such a method. A greater understanding of the process and functions of its assets was provided, in addition to enabling carrying out a more detailed assessment of the actions to be implemented to guarantee the design function of its main assets.

After applying the RCM to the machine under study (electric blower), a reduction of approximately 92% in the number of corrective maintenances was obtained, in addition to the optimization of reliability metrics (MTBF and MTTR), achieving an increase of 69.6% for o MTBF- Mean Time Between Failures and a 16.23% reduction in MTTR- Mean Time to Repair.

REFERENCES

Afefy, I. (2010). *Reliability-Centered Maintenance Methodology and Application: A Case Study*. Engineering, 02. https://doi.org/10.4236/eng.2010.211109

Associação Brasileira de Normas Técnicas (ABNT). (1994). *Confiabilidade e Mantenabilidade – Terminologia*, NBR 5462. Rio de Janeiro.

Deshpande, V. S. & Modak, J. P. (2002). Application of RCM to a medium scale industry. Reliability Engineering & System Safety, 77(1), 31-43. https://doi.org/10.1016/S0951-8320(02)00011-X

Fazle, R. M. (2018). Assessment of fuzzy failure mode and effect analysis (FMEA) for reach stacker crane (RST): A case study. *International Journal of Research in Industrial Engineering,* 7(3), 336-348. https://doi.org/10.22105/riej.2018.140970.1050

Fernández, J., & Márquez, A. (2012). *Maintenance Management in Network Utilities: Framework and Practical Implementation*. London: Springer. Retrieved from https://www.researchgate.net/publication/314041265_Maintenance_Management_in_Network_Utilities

Fogliatto, F. S. & Ribeiro, J. L. (2011*). Confiabilidade e manutenção industrial* [recurso eletrônico]. Rio de Janeiro: Elsevier ABEPRO.

Geerdes, M., Vliet C., Toxopeus H., & Medeiros F. (2004). *Práticas modernas para operação de alto-fornos*. [S. l.: s. n.]. 128p.

Kardec, A. & Nascif, J. (2009). *Manutenção: Função Estratégica* (3a ed.). Rio de Janeiro: Qualitymark Editora.

Kardec, A. & Nascif, J. (2012). *Manutenção: Função Estratégica* (4a ed.). Rio de Janeiro: Qualitymark Editora.

LaFraia, J. R. B. (2014). *Manual de Confiabilidade, Mantenabilidade e Disponibilidade*. Rio de Janeiro, RJ: Editora Qualitymark.

Manutenção. (2016). *Manutenção em Foco. Classificação ABC de Máquinas e Equipamentos*. Retrieved from https://www.manutencaoemfoco.com.br/classificacao-abc/

Siqueira, I. (2005). *Manutenção centrada na confiabilidade: Manual de implementação*. Rio de Janeiro: Qualitymark.

Smith, A. M. (1993). *Reliability-Centered Maintenance*. USA: McGraw-Hill, Inc.

Teles, J. (2019). *Bíblia do RCM – O guia completo e definitivo da Manutenção Centrada na Confiabilidade da era de indústria 4.0*. Brasília: Engeteles.

Vidal, R., Guay, M., Tremblay, P., Dion, J., & Gagné, M. (2019). *A study of the performance of the furnace lining in an iron-making blast furnace*. Journal of Ironand Steel Research, International.

Wyrebski, J. (1997). *Manutenção Produtiva Total -Um modelo adaptado*. Dissertação de mestrado, Universidade Federal de Santa Catarina. Retrieved from https://repositorio.ufsc.br/xmlui/handle/123456789/158161

Xavier, J. (2010). *Indicadores de Manutenção*. Retrieved from http://www.univasf.edu.br/~castro.silva/disciplinas/MAN/indicadores_manutencao.pdf

This work is licensed under a *Creative License Commons* Attribution-NonCommercial-Share Alike 4.0 International. ***Brazilian Journal of Production Engineering*** , São Mateus , Publisher UFES/CEUNES/DETEC. ISSN: 2447-5580