Modal Failure Analysis and Effects in the context of Industry 4.0 – A case study in The Navigator Company

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Abstract

The "Maintenance" concept has been changing in recent years, imposing itself as a fundamental area in many companies and industries. With the growing increase in consumerism, the productivity of industries and the complexity of equipment, it is crucial that organizations achieve an effective and efficient performance of their activity at the lowest possible cost. Thus, it is essential to use maintenance methodologies that allow the optimization of processes and good practices.

Thus, in the scope of maintenance management, this dissertation aims to promote an improvement in the management of preventive maintenance actions for the equipment of The Navigator Company Group. This action aims at the future transition from the preventive logic currently used, to a predictive logic.

Also noteworthy are solutions that allow for better monitoring and analysis of the performance of preventive maintenance in pumping equipment of medium consistency. These will also serve as support for the construction of a Digital Twin of the study equipment and, in the future, categorization of equipment failure alarms.

In the case of the study carried out, an FMECA analysis is carried out (analysis of critical failure modes, causes and effects), taking into account factors such as the frequency of occurrence, detectability and severity that will allow a critical analysis of the assets' failures and the respective prioritization. The analysis carried out resulted in an FMECA table for a medium consistency pump, together with proposals for preventive action with the aim of restoring the reliability and availability of equipment of this type

1. Introduction

The paper sector is characterized for being of continuous work (24/7) where the availability of the infrastructures of the production process is crucial, leading the entity responsible for maintenance management to concentrate efforts on the adoption of good practices that allow to ensure a good performance of the its assets, at the lowest cost, with controlled risks, it is essential not to compromise the required service quality levels. This continuous use means that maintenance management is seen as a factor of great importance and a critical contribution to the continuous operation of the installations.

This work appears in the scope of asset management and maintenance, aiming to verify if the existing preventive maintenance plan for pumping equipment aims to mitigate its most critical failure modes. The development of this is based on a management method, which aims to ensure the reliability of the equipment through the analysis of critical failure modes and effects (FMECA - Failure Modes and Effects Critically Analysis). It also served as a knowledge base for the construction, in progress in the company, of a Digital Twin of the equipment (digital representation of a physical medium that has the objective of advanced analytics) and categorization of the equipment's failure alarms.

Thus, the objectives of the present work are:

• Analyze the maintenance status of the pumping equipment under study (notes and work orders);

• Study the operating conditions of the paper pulp circuit and the process control variables of the equipment;

• Study the FMECA analysis method;

• Analyze, identify and draw up a list of potential failure modes in pumping equipment;

• Quantify the criticality of potential failure modes;

• Analyze the existing maintenance plan and propose changes that aim to mitigate the most critical failure modes.

2. State of the art

2.1. FMECA Analysis

The FMECA methodology is "a procedure through which the potential failure modes of a system are analyzed to determine its results or effects on the system, to classify them according to their severity and order according to the combined influence of severity with its probability of occurrence" [1].

This methodology can be seen as an extension of Failure Modes and Effects Analysis (FMEA), through the inclusion of a criticality analysis, which is used to calculate the probability of failure modes occurring—considering the severity and detectability of its consequences. Thus, the priority falls on failure modes with a higher likelihood of occurrence and with more severe consequences, thus allowing the analysis to act in order to reduce the consequences of critical failures [2].

2.1.1. FMEA Analysis

FMEA analysis is a systematic analysis technique, of products or processes, to identify and minimize potential failures and their effects even in their design phase, with the primary objective of preventing problems, eliminating the dissatisfaction of the "customer" [3].

The development phases of an FMEA analysis are typical as follows [4]:

1. Analysis and hierarchy of the system;

2. Selection of the subsystem to be analyzed;

3. Functional study and selection of a functioning state;

4. Identification of a potential failure mode;

5. Identification of the respective causes;

6. Identification of the possible effects of the failure mode;

7. Identification of detection and prevention methods

2.1.2. Critical analysis

The FMECA risk assessment (risk associated with the potential problems identified) can be carried out using two methods [2]:

• Criticality index or Risk Priority Number (RPN, from English Risk Priority Number) [4], which corresponds to the IEC 60812 standard;

• Criticality analysis [1], which compares to MIL-STD-1629A.

One of the methods for the quantitative determination of criticality is the calculation of a criticality index or the RPN of each equipment for each function and its failure mode. To analyze RPN, the failure modes mentioned above are associated with a function of their probability of occurrence, severity, and detectability, and, based on this association, the intention is to rank the potential causes of failure, through their degree of risk. , to plan more effectively, the respective preventive and corrective actions [5].

To complete an FMECA, the following additional phases are developed [4]:

8. Estimate the severity of the failure mode under study (S);

9. Estimate the probability of occurrence of failure mode - (O);

10. Estimate the probability of detecting the failure mode - (D);

11. Criticality analysis.

The RPN (Phase 11) is calculated, according to the expression below, making the product of the three indices [5]:

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D} \quad (1)$$

The IEC 60812 standard [4] describes the FMEA analysis, as well as the FMECA analysis. Systematizes the design process developed by the engineering teams, in order to find possible problems and respective solutions, prioritized according to the failure hypothesis and its criticality.

Therefore, the calculation of the severity, occurrence and detectability indices of a failure mode are made based on the classification of this standard, of which for each index there is a table with a variable amplitude scale [6].
The application of FMECA analysis has demonstrated over the years that, in fact, they prolong the useful life of the equipment under analysis and improve its operational reliability, proving, therefore, that it is correct to apply this method to the analysis of operational reliability of a product. Above all, an FMECA is a living document and not merely an exercise on paper, it is an essential source of information, especially when introducing a new model/system/subsystem/component [3].

2.2. Industry 4.0

The creation of industrial value is shaped by development and sustainability towards the fourth stage of industrialization, called Industry 4.0 (I4.0). The need for this revolution is to convert ordinary machines into self-aware and self-learning machines capable of improving their overall performance and maintenance management with neighboring interaction [7]. I4.0 aims to build an intelligent and open production platform for the application of the information in an industrial network. It is best defined by the "smart factory" resulting from the merger of the virtual and physical worlds through Cyber-Physical Systems (CPS) and the merger resulting from technical and commercial processes [8].

2.3. Digital Twin Concept

The Digital Twin (DT) was originally presented by Michael Grieves in 2002, in the context of an industry presentation on a product's life cycle. In its original form, it is described as a digital informational construction on a physical system, created as an entity in itself, and linked to the physical system in question. The digital representation must include all information related to the system asset that can potentially be obtained from its inspection in the real world [9].

In terms of the production industry, the definition of DT consists of the virtual/digital representation of a production system capable of operating in different simulation disciplines characterized by the synchronization between the virtual and real system, thanks to detected data and connected smart devices, models mathematics and real-time data elaboration. This allows the representation to reflect the current state of the system and perform real-time optimizations, decision making, and predictive maintenance according to the conditions detected [10].

DT can be referred to as the total integration of data between the physical and the digital object, in both directions (Figure 1). In this combination the digital object can also act as a control station for the physical object. A change in the state of the physical object leads directly to a change in the state of the digital object and vice-versa.

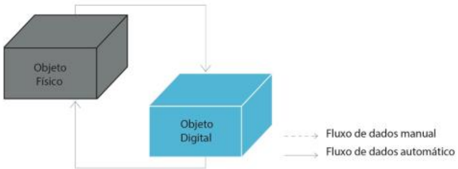

Figure 1 - Data flow in a DT, adapted from [11]

3. Case study

The case study that motivates the present dissertation is centered on the application of an FMECA analysis on a pump of medium consistency from The Navigator Company, whose function is the transport of cellulose pulp up to 16% of consistency, with the final objective of verifying if the existing maintenance plan aims to mitigate the most critical failure modes.

According to the internal procedure PG14 that mediates the process of analyzing and classifying the importance of industrial assets, the target pump of the case study (pump P049) was considered critical because it has a high number of operating failures with high production losses associated and with a low level of detectability, adding that when it is inserted in the area of Bleaching, the objective value of the availability of the functional area is 99.5%, which justifies the interest in deepening the knowledge about the equipment, its performance, and possible behaviors.

It was reported by the operations team, a degradation in the performance of this equipment as well as the existence of failures that led to unplanned stoppages (35 hours in the last three years), resulting in production losses in the order of 2275 tons of air-dried cellulose, justifying from the outset, the elaboration of an FMECA analysis to identify the most critical failure modes and subsequent mitigation proposals.

For this, an exhaustive study of the pump was carried out before proceeding to the FMECA analysis. This study included steps at the integral level of the pump, such as evaluation of the operating conditions and the function of the equipment and its subcomponents. In terms of maintenance, evaluation of orders and work notes, and verification of the existing maintenance plan for the pump. At the production level, assessment of downtimes (production losses associated with unplanned stops) and of the current process control variables and their variation over time.

Finally, the FMECA analysis is carried out, where, in the first phase, the identification of the modes, causes and effects of failure is made. Subsequently, they are classified according to a criticality index and the existing preventive tasks are identified for each component of the asset. Finally, a proposal is made to mitigate the failure modes, focusing more on the most critical failure modes.

3.1. Operational Context

The P049 medium consistency pump is located in the Bleaching circuit. Their choice is justified by the fact that this is a critical equipment, which demonstrated some inability and inefficiency in responding to inputs from the Production side.

The main objective of pulp bleaching, at a high level of whiteness, is to produce clean and stable pulp suitable for the production of high-quality white printing papers. Most of the time, cleaning can be more critical than whiteness, since to obtain a paste with high whiteness, a clean paste is necessary.

Another decisive factor for the study of this pump, in addition to having determined a critical industrial asset, is that in a perspective of replicability of the study, 4 pumps were identified in a similar operational context, in the Bleaching circuit.

3.2. Functional Analysis

With the contextualization of the operating mode of the P049 pump, it is possible to perform a functional analysis where it is intended to identify all the functions necessary to fulfill the operational requirements by the equipment, as well as the identification of the main components associated with those same functions. It is through the identification of these functions that it will be possible to carry out an analysis of failure modes, recognizing their loss of functionality.

The P049 pump having as main function the transport of cellulose pulp up to 16% of consistency, 7 main components of the equipment stood out, indispensable for the fulfillment of its function (Figure 2). The components are bearings, shaft, fixing base, mechanical seal, volute, rotor and coupling (not shown in the figure, as it is the component that connects the pump to the electric motor).

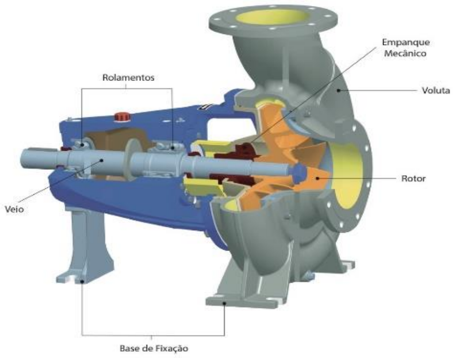

Figure 2 - Medium Consistency Centrifugal Pump

As for the identification of the primary functions adjacent to each of the pump's identified components, with the following being:

• **Volute**: Transform kinetic energy into potential energy;

• **Rotor**: Supply kinetic energy to the fluid;

• **Bearings**: Accommodation of axial and radial loads;

• **Mechanical seal**: Safety of the fluid seal;

• **Coupling**: Pump-motor connection;

• **Shaft**: Transmission of rotation to the rotor;

• **Fixing Base**: Reduction of vibrations.

Ensuring the necessary information for an FMECA analysis, the functional analysis allowed the identification of the functions that will be analyzed by this tool as well as the critical components responsible for the performance of those same functions.

3.3. Record Analysis

The analysis of existing information and data processing consists of obtaining all the useful history related to the P049 pump and then organizing it according to the final objective, carrying out the FMECA analysis. In order to filter the search for information, only a period of three years of history was counted, thus the time interval from June 2016 to June 2019.

3.3.1. Orders and Work notes

The organization of the list of orders and work notes was organized by type and type of component involved to identify some failure modes and which pump components are more likely to fail. Due to some lack of accuracy in filling out orders and work notes, it was not possible to identify specifically which mode of failure and which component failed, implying an uncertainty associated with the analysis and justifying the carrying out of an FMECA analysis to systematize the modes most likely and consequently more critical failures.

3.3.2. *Downtimes*

The term downtime is used to refer to the period that a given system was unavailable; that is, it is the period that a given system failed to perform its primary function.

The calculation was made to see the result of the cost of losses derived from stopping the P049 pump at around one million euros in the last three years. However, due to some lack of rigor in filling out orders and work notes, it was not possible to know the downtime of each of the interventions made on the equipment, but from a global perspective of the time span (3 years).

3.3.3. Process Flow Diagram

The Process Flow Diagram (PFD), flow process diagram, of which the P049 pump is inserted, was visualized through the company's operating system (DCS - Distributed Control System) and identified the operational variables measured in relation to the P049 pump, which are: Current intensity of the electric motor; Consistency of the paste; Paste flow; Control level of the standpipe upstream of P049.

3.4. Maintenance plan assesment

Equipment maintenance plans are obtained in SAP through the crossing of three objects (databases), which together formulate the maintenance requirements for a given Industrial Asset. The three objects referred to and their functions are:

• "MAINTENANCE PLAN" - It allows parameterizing the base calendar allocated to the maintenance plan, thus managing the dates for requesting maintenance routines;

• "MAINTENANCE ITEM" - Defines the Industrial Assets that will be the object of a set of maintenance actions as well as who performs these maintenance actions;

• "ROUTE GROUPS" - Defines the set of maintenance actions, their duration and their periodicity, related to the Maintenance Assets described in the Maintenance Item.

In addition to these three task lists as an integral part of the P049 pump preventive maintenance plan, lubrication and vibration routines are also taken into account

4. FMECA Analysis

Having defined the functions of each component that guarantee the proper functioning of the equipment and in turn the main function, it is then possible to identify the main failure modes associated with them, that is, how the function ceases to be performed, the causes which lead to the loss of the fulfillment of this function and what are its consequences (failure effects) for the infrastructure and the process. After consulting the preventive maintenance plan and the vibration and lubrication routines of the P049 pump, the tasks from the maintenance point of view on each component of the pump are checked. In a second phase, performed the FMEA analysis, the criticality analysis of each failure mode identified previously is carried out. Finally, a proposal for fault mitigation is made for each of the identified failure modes.

4.1. FMEA Analysis

The FMECA analysis started by identifying the most common modes, causes and effects of failure in centrifugal pumps of medium consistency through an empirical study always associated with the components and their functions previously identified. After this first step, there was a need to obtain the information and experience of the employees who had the most contact with the asset. Therefore, two meetings were scheduled, the first with the objective of carrying out the FMEA analysis and the second meeting for carrying out the criticality analysis, with those responsible for the areas of Production, Local Maintenance, Operations and employees who are members of Maintenance Engineering in the to complete the FMECA analysis.

The first of two meetings consisted of a review of the study previously carried out (identification of the generic failure modes, causes and effects in a centrifugal pump) and its enrichment through the inputs given by the people present at the meeting based on their experiences and knowledge of the asset in question. Thus, it was possible to determine the modes, causes and effects of failure of each function of the constituent components of the pump. Therefore, regarding each component and its respective function, 22 failure modes (Table 1) were identified, and subsequently, the causes and effects derived from those failure modes.

Table 1 - Failure Modes of Pump P049

Component	Failure Mode
Volute	Failure to contain fluid
	External contamination
	Fatigue
Rotor	Reduction of suction height
	Reduced compression pressure
	High discharge pressure
	Damaged rotor
	Corrosion
Mechanical Seal	Conducting process
	Type of mechanical seal
	Leakage through mechanical seal
	Lack of sealing liquid
Shaft	Rotation transmission failure
	Shaft deflection
	Shaft misalignment
Bearings	Misalignment of the pump-motor assembly
	Bearing failure
	Pump fixing defect
	Low oil level
	Inadequate shaft support
Coupling	Coupling failure
Fixing Base	Failure to fix the pump to the base

For the volute component, failure to contain fluid, external contamination and fatigue. For the rotor, reduced suction height, reduced compression pressure, high discharge pressure, worn or damaged rotor and component corrosion. Mechanical packing has as failure modes, the conduction of the process, type of mechanical packing, leakage through the mechanical packing and lack of sealing liquid. For the shaft there is a failure in the rotation transmission, shaft deflection and shaft misalignment. Bearings, misalignment of the pump-motor assembly, bearing failure, defective pump fixation, low oil level and inadequate support for the shaft. Coupling component has the failure mode only the coupling failure. Finally, the fixing base has failed to fix the pump to the base.

4.2. Existing tasks

After identifying the modes, causes and effects of failure, the section "Existing Tasks" was also filled in on each of the components according to the preventive maintenance plan and vibration and lubrication routines already observed (Table 2).

Table 2 - Existing tasks of Pump P049

Component	Existing task
Volute	--------
Rotor	- Visual Inspection - Vibration Analysis
Mechanical Seal	- Verification of cooling system
Shaft	- Verification and record of the alignment - Vibration Analysis
Bearings	- Vibration Analysis - Lubrification Routine
Coupling	- Vibration Analysis - Visual Inspection
Fixing Base	- Vibration Analysis

The volute has no indication of existing tasks incident on itself, however, when we refer to the rotor component, there is a preventive maintenance plan task that indicates for opening the pump and its inspection. This means that once the pump is opened, both the rotor and the volute inside it are inspected. Regarding the mechanical seal, the existing task is to check the sealing liquid circuit from the maintenance plan. The shaft is checked by vibration analysis and when it is aligned according to the maintenance plan. The bearings are checked for vibration and lubrication routines. The coupling includes the order of visual inspection and vibration analysis. Finally, the fixation base is checked by vibration analysis.

4.3. Critical Analysis

The second meeting, aimed at carrying out the criticality analysis of the previously reviewed and accepted failure modes of the first meeting, was held with the same employees present at the first meeting and the classification of the indices used to calculate the criticality index or RPN was carried out based on your inputs and experiences acquired on the asset in question, pump P049.

Once the failure modes have been classified according to their severity, occurrence and detectability indices, and the RPN is subsequently calculated, it is possible to draw some conclusions about the failure modes where to act more briefly. Therefore, Table 3 shows the classification of failure modes as to their criticality (the following table is an excerpt from the FMECA table).

Table 3 - Critical Analysis of Pump P049

Component	Failure Mode	RPN
Volute	Failure to contain fluid	81
	External contamination	9
	Fatigue	9
Rotor	Reduction of suction height	3
	Reduced compression pressure	3
	High discharge pressure	9
	Damaged rotor	27
	Corrosion	27
Mechanical Seal	Conducting process	27
	Type of mechanical seal	27
	Leakage through mechanical seal	9
	Lack of sealing liquid	3
Shaft	Rotation transmission failure	9
	Shaft deflection	27
	Shaft misalignment	27
Bearings	Misalignment of the pump-motor assembly	9
	Bearing failure	9
	Pump fixing defect	3
	Low oil level	9
	Inadequate shaft support	9
Coupling	Coupling failure	9
Fixing Base	Failure to fix the pump to the base	3

It is possible to verify that the failure mode with the highest risk is the failure to contain the fluid in the volute component and those with the lowest risk are varied since the rotor has failure modes, reduced suction height and reduced compression pressure. In the mechanical seal, the lack of sealing liquid. Bearings, defect in the pump fixing, and in the fixing base, the failure in fixing the pump to the base.

The reason that one failure mode only stands out for the negativity of all the others stems from how it was rated as serious in relation to the probability of seriousness, that is, the failure mode leads to real safety problems, and as to its detectability, it was evaluated as remote due to the control defined in the design failing to detect the potential cause of failure and subsequent failure mode, thus making an RPN value equal to 81 for the failure mode, failure in containing the fluid in the volute component.

It is concluded that the failure mode where more attention is needed is the problem of fluid containment, either because of the probability of gravity or because of the probability of detectability that the greatest risk of causing the P049 pump to become inoperative is obtained. Although this is the failure mode with the highest risk, the others should not be ignored, more specifically the failure modes with an RPN equal to 27 (indicated in orange in the table) and may also cause the pump to become inoperable or cause major damage.

4.4. Fail mitigation proposal

With the completion of the analysis, the assignment of the appropriate maintenance tasks for the equipment identified in the analysis process follows. The P049 pump, for having a continuous or frequent service, the group wants to keep the operational asset, available to act, whenever necessary.

The recommended action plan in order to optimize the asset maintenance plan and mitigate the failure modes identified through the analysis resolution was done through the study and analysis of case studies in the area, together with the support and experience of the responsible for the Maintenance Engineering of the group.

Table 4 - Proposal of maintenance tasks for Pump P049

Component	Proposal action	Frequency
Volute	Visual inspection (interior) and Non-Destructive Test – Penetrating Liquid.	1 year
	Surface treatment inside.	5 years
	Exterior visual inspection.	1 month
	Creation of a monthly report for condition analysis.	Single action
Rotor	Checking the pump operation by noise.	1 day
Mechanical Seal	Visual inspection of the sealing seats and sealing liquid.	1 year
	Setting of sealing liquid out alarms in the DCS.	Single action
	Placement of flow sensors in the sealing water circuit.	Single action
Shaft	Visual inspection and Non-Destructive Testing – Penetrating Liquid or Magnetic Particles.	1 year
	Checking the tightness of the bearing bolts according to the manufacturer's specification	1 year
Bearings	Training of a team responsible for the assembly of the bearings	1 year
	Visual inspection.	1 year
	Placement of temperature sensors on the bearings.	Single action
Coupling	Verification of clearances; if so, act accordingly.	15 days
Fixing Base	Checking the tightness of the electric motor to the base and the support points of the pump to the base.	1 year

Regarding the volume, it is advisable to indicate the task "Visual inspection of the volute" in the preventive maintenance plan and carry it out annually when the factory is stopped, in order to anticipate any external contamination or possible visible crack. It is also suggested the creation of a monthly report, where each person responsible for carrying out the external inspection can note the date that it was carried out, notes to collect information for the next inspection to be taken into account or also for the person responsible for the maintenance of the equipment to change any your maintenance plan procedure. The interior surface treatment and the non-destructive test, penetrating liquid, to prevent the occurrence of interior corrosion and cracking not visible to the naked eye on the outside.

The rotor component as to its causes of failure is well protected both by the vacuum pump and by the high suction height (standpipe level), effectively preventing the cavitation of the pump and many other causes of failure present in the FMECA table. Therefore, it is only proposed that a daily check of the pump is made for noise in case any abnormal noise is detected, and a vibration analysis is made.

As a recommended preventive maintenance action, the mechanical seal must be viewed annually in relation to the sealing seats and the sealing liquid. It must also be indicated in the preventive maintenance plan. Regarding the types of unique actions, it is proposed to place alarms of lack of sealing liquid in the DCS and to monitor the flow of the sealing liquid through the installation of flow sensors, so that any failure of the recovery system is detected. sealing waters, or the incorrect detection of the lack of sealing liquid, among other causes.

The shaft must be inspected annually in order to observe signs of corrosion and its indication must be included in the preventive maintenance plan. As a visual inspection aid, two types of Non-Destructive Tests (END) can be made, the penetrating liquid test or the magnetic particle test. A check of the bearing tightening should also be carried out on an annual basis and, if any tightening is necessary, carry out it according to the manufacturer's specifications. This will more effectively prevent a possible failure mode such as shaft misalignment or imbalance.

The bearings, despite not having any failure mode considered critical, have room for improvement. The misalignment of the motor-pump assembly results from inadequate assembly of the bearings, therefore, an annual training / workshop of the team responsible for its assembly is advisable. In the past, the placement of temperature sensors on the bearings comes with the purpose of being able to monitor and control the high temperatures that are felt in the bearings anticipating some excessive temperature causing the pump to stop. Its visual inspection should also be indicated in the preventive maintenance plan and carry out it according to its frequency.

Finally, as for the coupling and the fixing base, it is proposed to check for looseness in the coupling and to check the tightness to the base of the electric motor and the pump support points in order to prevent the causes of failure such as, vibration as a whole, shaft misalignment, looseness / looseness.

That said, it is necessary to take into account that the presentation of proposals for mitigation of failures is based on some rationing of time and money, as mentioned above, but also, where measures were proposed that could be carried out in practice and where it was also adapted the reasoning and knowledge acquired by the research and sharing of experience of the group's employees to the preventive maintenance plan of the equipment.

Once all this information about the equipment, its performance was collected, analyzed and systematized and the Maintenance plan was reevaluated, the company considered it a good opportunity to develop a pilot test on the concepts of predictive models and simulation of cyber-systems – DT, as it is part of the company's strategy to move from a corrective and preventive maintenance logic to reach predictive levels.

It is not the formal scope of this dissertation, but being a natural development of it, we propose a brief presentation, in the next chapter, of the concepts of DT and the predictive models tested.

5. Digital Twin

The main objective with the construction of a DT is the development of a proof concept for a predictive system in order to anticipate failure events in a critical equipment. Basically, allow the change from a preventive maintenance logic to predictive maintenance.

The results were very positive, having detected 6 events out of 7 possible within the time determined by Navigator. Of these 6 identified events, 15 alarms were triggered, of which 13 correspond to positives and 2 correspond to false positives. With the FMECA analysis carried out together with the survey of historical data, it is possible to begin to carry out a cataloging of alarms. That is, whenever a type of behavior is presented by the equipment on a certain date when the failure mode has already been known, it is possible to record its behavior that caused the alarm to be triggered and catalog it.

According to the FMECA table presented, it is possible to pay more attention to the most critical failure modes and alarms that may have been triggered directly by them and then try to catalog them according to those failure modes. Also, eventually to dynamically change the equipment maintenance plan based on the application of the model to the historical data of the past 3 years and its future use. In other words, if the model predicts that a certain failure mode considered to be critical is going to occur within 21 days, automatically change the maintenance plans or daily routines for the equipment, so that the maintenance team is notified and acts accordingly.

Finally, after years of history, refine the RPN values for each failure mode, updating the FMECA table and subsequent preventive actions to be taken. Figure 3 summarizes the next steps regarding the use of DT.

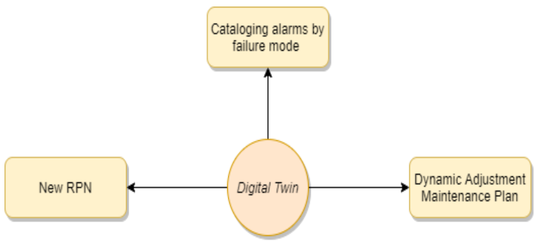

Figure 3 - Future work with DT

The survey that was done contributes decisively to the success of DT since it came to validate what were the outputs of DT in the identification of failures.

6. Conclusions

This dissertation aims to improve the maintenance plans for the pumping equipment of the industrial units of The Navigator Company.

Visual inspection, the creation of a monthly report, the surface treatment and the performance of a Non-Destructive Test (penetrating liquid) on the volute component were proposed in order to prevent the corresponding possible failure modes more effectively.

Regarding the rotor component, only a daily check of the pump was proposed, as it is well protected in terms of causes of failure.

It was also proposed to place alarms for lack of sealing liquid in the DCS and to monitor the flow of the sealing liquid through flow sensors in the mechanical seal component, in order to detect any failure of the sealing water recovery system and to avoid incorrect detection of the lack of sealing liquid.

It was suggested to the component an annual inspection, the application of two Non-Destructive Tests and the verification of the bearings tightness in order to prevent the corresponding possible failure modes more effectively.

As for the bearings an annual training was proposed for the team responsible for their assembly, placement of temperature sensors and annual visual inspection, in order to avoid improper assembly of the bearings and to control the high temperatures that are felt anticipating some excessive temperature causing stop the pump.

In the last of the components, the coupling, it was proposed to check for looseness and to check the tightness to the base in order to prevent causes of failure such as vibration in the set, shaft misalignment and loosenes.

This work allowed us to evaluate and assess the importance of the maintenance plan for pumping equipment in the pulp and paper production circuit in the sector. It was possible to detect problems related to the identification and quantification of potential failure modes, with the same typology as presented in this work and the impact that these failures can have on the security and global availability of the system.

The FMECA analysis, in addition to the fault mitigation proposals, was basically a critical analysis of what The Navigator Company contained and what it needed to act in order to mitigate the failure modes of the equipment. This served the purpose of generating knowledge.

It is concluded, then, that the data collection work allowed to have a good knowledge base about the equipment, both empirical knowledge and theoretical knowledge about the equipment and its surroundings. Thanks to the entire thorough study of the pump, from understanding its operation, to identifying failure modes and its criticality, it allowed this information to be transformed into knowledge of the equipment. In other words, without the case study carried out by the FMECA analysis, it would not be possible to start the construction of the DT.

It is concluded, in a global analysis of the results, that the categories of security and availability are affected, positively, with a study of this type, because when identifying which failure modes in which to act more quickly and with more intensity, there is no only the system's maintainability is increased, but also its security and availability. It was also possible to observe that maintenance management, constant investment in more efficient technologies and the creation of economic maintenance habits and policies, allow to increase the efficiency of the equipment under study. It is important to adopt more and better maintenance practices in order to reduce losses, allowing companies to increase their competitiveness and improve their maintenance plans, contributing to global sustainability.

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