Original Research

Development of a Condition Monitoring Plan for Detecting Equipment Failures in the Water Resources Area of a Mining Company

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Abstract

The project aims to design a condition monitoring plan for a mining company's water resources equipment to reduce the likelihood of unforeseen and catastrophic failures. The proposed solution is to use condition monitoring based maintenance, which consists of taking parameters periodically with specific instruments to identify changes that indicate signs of failure. Inspection techniques such as vibration analysis and infrared thermography can be applied, depending on the parameter to be monitored and the failure mode to be detected. To validate the solution, the maintenance area inspected selected equipment for anomalies indicating possible failures. The results obtained with the application of the off-line monitoring system in the water resources area were satisfactory, as it was possible to detect faults in both the electrical and mechanical parts. In the electrical part, five anomalies were identified, two of them critical, while in the mechanical part, three anomalies were detected, two of them critical.

Keywords – Mining; Maintenance; Water resources; Condition monitoring.

INTRODUCTION

In the realm of production plants, the seamless operation of process equipment stands as a fundamental prerequisite for achieving production targets. Maintenance, in this context, assumes a pivotal role, as highlighted in prior research [1]. The importance of maintenance costs is accentuated since it represents between 15 to 60% of total operating costs [2]. Under the current context, delivering the best product at the lowest cost remains a top priority for manufacturers [3].

Factory operations that embrace condition-based maintenance strategies have demonstrated substantial benefits. These approaches have shown to decrease maintenance expenditures by 25% to 30%, decrease failure incidents by 35% to 45%, and boost production efficiency and return on investment by 20% to 25% [4]. Consequently, the precise operation of process equipment within production facilities is pivotal in attaining production goals. Herein lies the pivotal role of maintenance, guaranteeing optimal performance of the organizational infrastructure. This mission is actualized through programs of prevention, predictive fault detection, repair, and continuous enhancement [5]. Considering this, the establishment of comprehensive plans addressing both corrective and preventative maintenance, as well as the deployment of condition monitoring, becomes imperative.

Condition-based maintenance stands out for its ability to discern early signals of anomalies and unusual operational conditions. This capability facilitates the implementation of anticipatory corrective measures to prevent unforeseen equipment failures. Furthermore, condition monitoring techniques distinguish themselves by their real-time data collection while equipment is operational, thereby circumventing production disruptions during data acquisition. Among the most utilized techniques in condition monitoring are vibration analysis, infrared thermographic, ultrasound, and acoustic emissions [6]. Given the array of options available, it is imperative to undertake meticulous analysis to determine the most suitable technique based on the specific failure modes of each process equipment. To this end, historical failure data provided by the maintenance department will be leveraged, enabling the identification of failure modes and the proposal of precise monitoring strategies for early detection and prevention of potential failures.

Within the framework of this issue and with the objective of ensuring the optimal operation of process equipment, this study focuses on designing a condition-based maintenance plan for a mining company. This mining company extracts potassium nitrate, specialized fertilizers, iodine, potassium and lithium processing. In particular, the issue is addressed in the area of water resources, which is responsible for the extraction of water for the process. The main objective is to reduce the probability of unforeseen and catastrophic equipment failures, which have caused partial interruptions in the extraction and conduction of water, in addition to high costs for the maintenance department. Consequently, the objective is to implement a system that allows early detection of anomalies, signs of failure or deterioration of equipment and components, helping to minimize such failures and avoid unplanned shutdowns.

The proposed solution entails creating a comprehensive inventory of process equipment and a criticality analysis to evaluate their impact on the overall process. Characteristic failure modes will be identified, and the most suitable inspection techniques, along with necessary devices and instruments for data collection, will be determined. Additionally, the matter of investment required to implement the condition-based maintenance approach will be addressed. The study is organized as follows. Section 2 discusses the theoretical framework. Section 3 presents the methodology used. Section 4 describes the proposed solution. Section 5 presents the main results obtained. Section 6 discusses the results. Finally, Section 7 presents the conclusions and future research.

THEORETICAL FRAMEWORKS

The mining company has five business lines, in all of which it is a world leader: Specialty Plant Nutrition, Iodine and derivatives, Lithium and derivatives, Potassium and Solar Salts. It also has 9 production plants distributed in the production of caliche ore and brine.

I. Summary of production process for obtaining nitrates

The caliche mineral deposits, are the largest ever discovered and the only commercially exploited source of natural nitrates in the world. Their geological origin is not clear. It is thought that the formation of calicheis the result of sediment deposits from an ancient inland sea or the accumulation of minerals as a result of erosion of the western face of the Andes. The caliche is underlain by a layer of overburden material ranging from 0.5 to 2.5 meters thick, in mineral strata that can range from 0.2 to 5 meters in thickness. Ore concentrations in the caliche vary from mine to mine. In total, this representative company extracts around 30 million tons of caliche annually. The caliche overburden is removed with bulldozers. Subsequently, with explosive charges, the ore is broken and loaded onto trucks by front loaders. At Nueva Victoria, the ore is leached in heaps, obtaining solutions destined primarily for iodine production. Subsequently, they are transported to solar evaporation ponds where salts with a high concentration ofnitrate are crystallized and transported by truck to the plants in the town of Coya Sur, where they are used as an input in the production of potassium nitrate. The nitrate production process is shown in Figure 1.

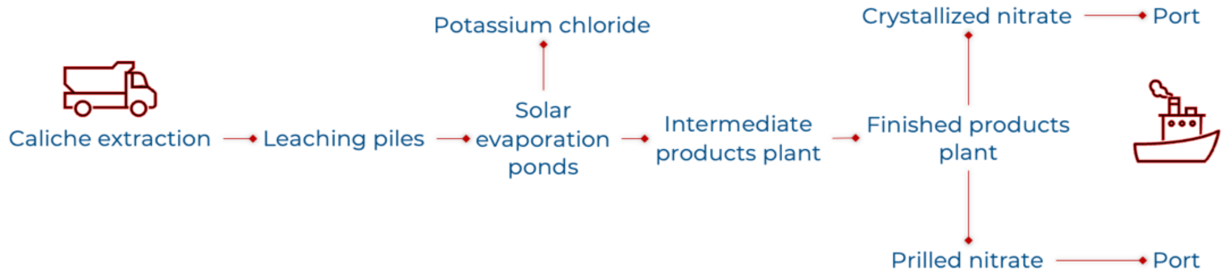

FIGURE 1
NITRATE PRODUCTION PROCESS

II. Summary of the process for obtaining iodine

The solutions obtained from the caliche ore leaching process are used at the plant to produce iodine from the iodate contained in them. Variations in the iodine content and other chemical components in the treated ore, in addition to other operational parameters, require a high level of specific knowledge to manage the process efficiently. Solutions from caliche leaching contain iodine in the form of iodate. Some of the iodate in solution is reduced to iodide using sulfur dioxide, which is produced by burning sulfur. The resulting iodide is combined with the rest of the original iodate solution to release elemental iodine. The solid iodine is then refined through a smelting and prilling process. The process of obtaining iodine is shown in Figure 2.

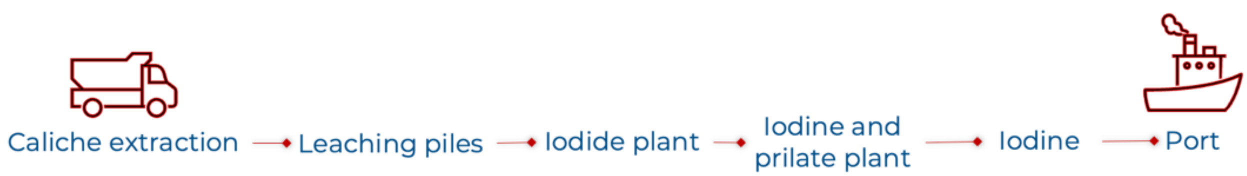

FIGURE 2
IODINE PRODUCTION PROCESS

An important part of the production process is leaching, which consists of heaps that are irrigated with water; all the water required for this process is obtained through deep wells by the water resources area.

One of the characteristics of the leaching process is that it uses only water as a leaching agent and recycled solutions from the leaching system. All solutions drained from the leaching heaps, duly waterproofed on the inside, flow by gravity in open troughs, planned and constructed in advance, to collection ponds; all irrigation and drainage flows are measured in real time.

III. Description of Water Resources Area

Water is required to irrigate the leach heaps, and the supply network used by mining company is through deep wells. The water is extracted from the desert groundwater by means of multi-stage submersible pumps that are located inside the well and can be installed at a depth of thirty to eighty meters in different sectors of the area. This water arrives directly to different pumping stations, which have large capacity tanks to store the water that will later be sent by the impulsion pumps to the different sectors where it is used for the leaching process.

The water resources area must comply with a water delivery flow rate of 2.225 m3/hr should be mentioned that the company has a maximum permitted groundwater extraction quota, which is monitored and supervised by the General Water Directorate. This is important because if equipment failure makes it impossible to extract the required water, the flow in the other equipment cannot be increased to compensate for the decrease in the system and meet the water delivery goals required by the process.

The company has six water extraction sectors (A, B, C, D, E and F), which are located at an average distance of 35 km from the iodine plant. The system is composed of thirty-five submersible pumps with their respective low voltage electrical system, eleven centrifugal pumps with low and medium voltage motors, which are highly critical for the water extraction process, in addition to three medium voltage substations with their respective power lines, six steel tanks and approximately 150 kilometers of steel and HDPE piping.

DESCRIPTION OF THE PROBLEM

The process equipment in the water resources area has had failures that have caused partial interruption of the water extraction and delivery process, in addition to generating high costs for the maintenance department. Therefore, the problem to be solved is to implement a system that allows early detection of anomalies, signs of failure or deterioration in the equipment and its components to reduce the probability of such failures occurring and avoid unscheduled equipment stoppages.

In order to make known the mechanical and electrical failures that can occur in the process equipment, below is information on six major failures that have occurred in the water resources area, these failures were recorded jointly by operations and the maintenance department and are being shared only to show the type of failures that have occurred in mechanical and electrical equipment in the last two rolling years (July 2020 to July 2022), the record presented is only an extract and does not correspond to the total number of failures that have occurred. The failures that occurred in the deep well pump motor set were excluded since the strategy used in such equipment is corrective maintenance, that is, when the equipment fails, it is replaced by a new one, since the intervention times are too long to apply another type of maintenance. Finally, a consolidated cost of equipment repair and production loss associated with the failures is sent. To obtain the repair cost, the sum of the individual repair costs of each piece of equipment was added up, as shown in Table I.

TABLE I
COST OF EQUIPMENT REPAIR DUE TO FAILURES (CHILEAN PESOS).

Equipment	Cost
A N°1 Pump	$30,000,000
F Impulsion Pump	$5,500,000
F Impulsion Pump	$1,200,000
C N°1 Impulsion Pump	$1,500,000
C N°2 Impulsion Pump	$9,000,000
Electric panel DE	$2,000,000
Total	$49,200,000

To obtain the cost of lost production, information provided by operations in the summary of failures is considered, which indicates a value associated with the loss of iodine production that occurs when a certain volume of water is not extracted, the relationship indicates that for each cubic meter of water that is not extracted, there is a loss of iodine production equivalent to eight thousand pesos. Table II shows the volume of water not extracted due to each of the failures detailed above, this value is multiplied by the unit loss factor and then the production loss value expressed in pesos is obtained for each of the failures that occurred, finally the sum of the individual losses is added to obtain the total loss.

TABLE II
COST OF LOST PRODUCTION (CHILEAN PESOS).

Equipment	Volume of water not withdrawn (m^3)	Cost production loss
A N°1 Pump	1,730	$13,840,000
F Impulsion Pump	1,075	$8,600,000
F Impulsion Pump	1,075	$8,600,000
C N°1 Impulsion Pump	547	$4,376,000
C N°2 Impulsion Pump	456	$3,648,000
Electric panel DE	870	$6,960,000
Total		$46,024,000

The total cost due to the six breakdowns mentioned above, taking into account the cost of repairing the equipment and the cost of lost production, amounted to $95,000,000. Considering that Iodine loss factor is 8,000 ($/m3).

INDUSTRIAL MAINTENANCE

To reduce the probability of equipment failure, industrial maintenance is used, which consists of the set of actions aimed at the conservation of machinery, equipment and facilities [7]. The main objective of industrial maintenance is to ensure the production in any industrial process, its quality and to maintain the correct functioning of the equipment, extending its useful life. According to the current concept, broadly speaking, there are two types of maintenance, the first is scheduled maintenance, in which interventions, resources and work to be performed on equipment that is operating normally are scheduled on a routine basis, and the second is unscheduled maintenance, in which emergency work is performed on equipment that has been stopped due to failure, usually these stops have already caused the total or partial stoppage of the processes [8]. Maintenance in a company has four objectives that must be achieved:

- Meet a certain availability and reliability [9].
- To ensure that the installation meets the projected useful life period.
- Achieve the above objectives without exceeding the allocated budget.

In order to carry out efficient maintenance, an implementation plan is proposed, which is understood as the set of maintenance tasks selected and aimed at protecting the function of an asset, establishing a frequency of execution of these tasks and the personnel assigned to carry them out [10].

Depending on the way, the objective and the opportunity in which the actions are performed, different types of maintenance can be identified, being the most used the corrective, preventive and predictive (condition monitoring) [11-13].

I. Corrective Maintenance

Corrective maintenance is the technical activity that is performed when a breakdown occurs and aims to return the asset to a state where it can function as intended, either by repair or replacement. This does not mean that corrective maintenance has little relevance to any other maintenance strategy, as it can be used as a strategy in its own right or in conjunction with other equipment maintenance strategies. However, there is insufficient time for optimal equipment maintenance [14].

II. Preventive Maintenance

Preventive maintenance consists of scheduling interventions or changes of some components or parts of the equipment according to predetermined time intervals. These procedures can be scheduled based on fixed times, by hours of resource utilization, by monitoring operating conditions, by failure analysis, by inspection routines, among others [15]. The objective of this type of maintenance is to reduce the probability of failure or loss of performance of a piece of equipment or installation, trying to plan and schedule interventions that are adjusted to the maximum useful life of the intervened element.

III. Predictive Maintenance (Condition Monitoring)

Maintenance based on condition monitoring is the process of periodically measuring one or more parameters in the machinery in order to identify changes that indicate malfunctions and/or failures in the components. Through this type of maintenance, once the deviations are detected, the corresponding repairs can be scheduled on the equipment, mainly avoiding downtime [16] and at the same time prolonging the life of the equipment. Maintenance based on condition monitoring is the most technological type of maintenance since its execution requires measuring instruments and advanced software. One of the main requirements for effective predictive maintenance is enough data from all parts of the manufacturing process [17]. As a result, it can decrease maintenance costs and downtime, and improve productivity and quality [20].

Some inspection techniques that are used and that will be explained in depth are those mentioned below.

- Vibration analysis
- Infrared thermographic
- Airborne ultrasound analysis
- Oil analysis
- Ultrasonic Thickness Measurement

METHODOLOGY

The methodology for the presentation of the work is based on five main stages [21]: information search, model, design, development, testing and documentation. The first stage focuses on the review of theoretical information through books, reports, scientific articles and websites on industrial maintenance and the mining company.

Subsequently, and in order to contextualize the problem, information provided by the operations and maintenance area regarding process equipment failures in the area of water resources is used. With this information, an analysis will be carried out, and a strategy based on maintenance by condition monitoring will be presented. In the design and validation of the solution, an inventory of the equipment to be treated will be carried out, followed by a criticality and failure mode analysis to propose a condition monitoring. The effectiveness of the proposed solution will be verified with the support of maintenance personnel from another area of the company. Finally, the results will be discussed, and the conclusions obtained, and future work will be presented.

PROPOSED SOLUTION

The solution proposed to reduce the probability of equipment failures is to designa maintenance plan based on condition monitoring, Figure 3 shows all the pointsthat will be developed.

First, an inventory of the process equipment that is exposedto failures will be made, considering the drive pumps and electrical panels, then acriticality analysis will be made for each equipment, considering the probability andthe consequence of the failure. Then, it is necessary to perform an analysis to determine which are the failure modes that may occur in the equipment, since withthis information a condition monitoring technique will be selected to detect signs of failure or anomalies, in this case the vibration analysis and infrared thermographic techniques were selected, for each of them a detailed description ofthe measurement methodology and how to perform the analysis will be made. Forlow voltage electrical equipment, it will be proposed to perform infrared thermography, which is done offline, i.e., the inspection is performed with a portable thermographic camera. For mechanical equipment it will be proposed to measure vibration and temperature parameters, with offline and online system in acomplementary way. The offline system uses portable equipment for data collection in the field and subsequent analysis in the office, while in the online system it is necessary to install sensors permanently in the motors and pumps, thesesensors instantly transmit vibration and temperature data to a website, the sensor system is quite useful because you can see the behavior of the equipment in real time, however, it does not have analysis tools as advanced as the portable equipment.

Other points considered in the study were to determine the costs associated with the implementation of the online and offline system, to create a schedule [22] with the periodicity of the measurements and to describe how the management of the information is done after the report is generated.

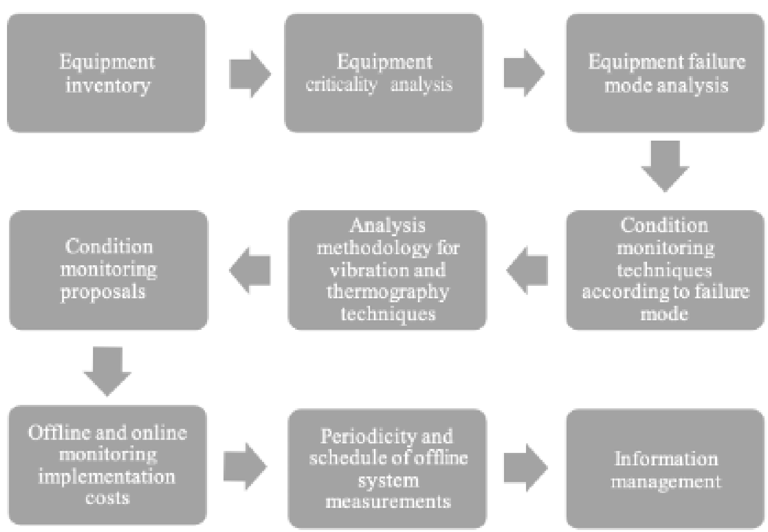

FIGURE 3
SOLUTION DEVELOPMENT STAGES.

I. Equipment Inventory

The equipment used in the water extraction and delivery system that can be inspected by condition monitoring are the motors and pumps that are on the surface and the low voltage electrical panels.

D motors and pumps were not considered for the analysis because, although monitoring technology exists, the most cost-effective strategy is maintenance upon failure to take advantage of their full useful life, nor were medium voltage power lines or substations considered since they have an effective associated maintenance plan that has allowed avoiding failures. In total, the study focuses on twelve mechanical equipment and thirty-two low voltage electrical panels.

II. Criticality Analysis

The existing methods for criticality analysis are grouped in different ways, and according to their type can be found as qualitative, semi-quantitative and quantitative, such methods are based on risk assessment and oriented to identify the critical equipment of a production system [23]. However, the individual impact on production, safety, product quality, environment and/or any other item considered relevant in the organizational context, when an undesired event or failure occurs, must also be considered, which allows classifying the equipment according to these impacts, generally represented in criticality matrices. The Ciliberti method will be used in the study, since it focuses mainly on the impact on production.

The criticality analysis will help determine which equipment has the greatest impact on the process, in order to subsequently define whether it is necessary to monitor the conditions of such equipment. As shown in the formula below, in the criticality matrices the risk is evaluated based on probability and consequence:

$$Risk = Probability \times Consequence$$

The probability is represented by the frequency in which the undesired event or equipment failure occurs, in this case referring to the total failure of the equipment. While the consequence refers to the impact as a result of the failure. The risk, being represented by semiquantitative criticality matrices, implies that both variables are evaluated in ranges of values.

For the analysis, the matrix shown in Figure 4 was used, based on the study carried out by [24], where one axis represents the frequency of failures and the other the impacts or consequences that the unit or equipment under study will incur if a failure occurs [25].

CONSEQUENCE	Very High	5	4	5	6	7	8
	High	4	3	4	5	6	7
	Medium	3	2	3	4	5	6
	Low	2	1	2	3	4	5
	Negligible	1	1	1	2	3	4
			1	2	3	4	5
			Negligible	**Low**	**Medium**	**High**	**Very High**
			PROBABILITY				

FIGURE 4
CRITICALITY ANALYSIS METHOD.

In order to perform the criticality analysis, the opinion of expert personnel from the maintenance and operations areas was requested. A complete criticality analysis of a production process includes various aspects, such as impacts on production, product quality, environment and safety. Each of these aspects was analyzed and it was concluded that for the study being carried out, none of the last three aspects apply, since there are no consequences associated with equipment failure; the study focuses mainly on reducing the probability of equipment failure and avoiding impacts on the process. The risk in the process is composed of the probability and the consequences that affect the production system, in the first instance the probability ranges are defined, based on the frequency of occurrence of the failures of each evaluated asset. It is important to mention that the evaluation scales must be adaptable to the frequency of failures presented by the equipment under analysis.

Finally, after obtaining the probability and consequence index, the criticality of each pump is obtained. The result of the study determines that the *E* drive pump is at a HIGH criticality level, pumps N°1 *A*, N°2 and N°3 *B*, N°1 and N°2 *C* drive and *F* drive are at MEDIUM criticality level and the puquios pump together with pump N°1 of *D* are at LOW criticality level, no equipment with very high or very low criticality level was detected, each criticality level is represented by a characteristic color.

TABLE III
CALCULATION OF CRITICALITY FOR MECHANICAL EQUIPMENT.

Equipment	Probability/Consequence/Criticality Index	Criticality
Pump N°1 A	3/3/4	Medium
Pump N°2 A	NA/NA/NA	
Pump N°2 B	3/3/4	Medium
Pump N°3 B	3/3/4	Medium
Pump N°4 B	NA/NA/NA	
Puquios Pump	2/2/2	Low
Pump N°1 C drive	4/2/4	Medium
Pump N°1 C drive	4/2/4	Medium
Pump N°1 D	3/2/3	Low
Pump N°2 D	NA/NA/NA	
E booster pump	3/4/5	High
F booster pump	4/2/4	Medium

III. Failure Mode Analysis

There are different methodologies to perform failure mode analysis, each methodology has a specific objective, in this study the failure modes that can be detected with condition monitoring techniques will be analyzed.

TABLE IV
INSPECTION TECHNIQUES FOR EACH FAILURE MODE.

Component	Abnormal condition	Condition monitoring technology
Motor - pump	Misalignment of shafts	Vibration analysis
Motor - pump	Flexible Base	Vibration analysis
Electric motor	Elevated housing temperature	Infrared Thermography
Electric motor	Motor mounted with lame foot	Vibration analysis
Electric motor	Static eccentricity in motor	Vibration analysis
Electric motor	Rotor unbalance	Vibration analysis
Electric motor	Bearing damage	Vibration analysis
Electric motor	Poor bearing lubrication	Vibration analysis
Electric motor	Mechanical looseness	Vibration analysis
Electric motor	Resonance	Vibration analysis
Mechanical coupling	Loose bolts	Vibration analysis
Centrifugal pump	High temperature bearings	Infrared Thermography
Centrifugal pump	Deformation of pump casing	Vibration analysis
Centrifugal pump	Impeller hydraulic unbalance	Vibration analysis
Centrifugal pump	Mechanical unbalance of impeller	Vibration analysis
Centrifugal pump	Bearing damage	Vibration analysis
Centrifugal pump	Poor bearing lubrication	Vibration analysis
Centrifugal pump	Mechanical looseness	Vibration analysis
Centrifugal pump	Resonance	Vibration analysis
Centrifugal pump	Cavitation	Vibration analysis
Centrifugal pump	Recirculation	Vibration analysis
Electric panel	High temperature cable	Infrared Thermography

The purpose of this analysis is to identify abnormal operating conditions in the equipment that will cause short, medium or long term a total or partial functional failure in the system, for example, a total functional failure in a pump is that it does not send any flow and a partial failure is that it sends less flow than required, a probable cause for the pump not sending flow may be that the electric motor is burned, the abnormal condition that will occur before this event occurs is that there is high temperature in the motor casing.

It should be mentioned that not all failure modes can be detected in advance with condition monitoring, there are failure modes that must be mitigated with preventive maintenance and there are even failure modes where none of the above strategies can be applied, and the only option is to be prepared in case the failure occurs.

Proposals for condition monitoring implementation

The condition monitoring proposal is composed of two systems that are complementary, the first is an offline monitoring system and the second is an online system, both systems and the associated instrumentation will be explained below.

I. Offline Monitoring System

Through this system, the person in charge of condition monitoring uses a thermographic camera and a portable vibration collector to perform an inspection route and take measurements in each of the equipment for a short period of time, the data obtained are only representative of the moment in which the measurement was performed, if at the next moment, the working condition of the equipment changes, the data cannot be recorded. The offline data collection process can be quite time-consuming, since it is necessary to prepare personal protection elements, charge the equipment batteries, load and unload measurement routes in the vibration collector, verify that the instruments and accessories are in good condition and also consider the travel time to the equipment, this last point is quite relevant in the water resources area since the most distant equipment is located at a distance of 40 km from the maintenance offices. It is necessary to define an inspection frequency, which depends on the criticality of the equipment and the availability of man-hours to perform the measurement. For the data collected by this method to be representative, the sensor must be installed in the same place for each measurement and the operating conditions must be the same.

II. Online Monitoring System

This online monitoring system uses wireless sensors, which are left permanently installed on the equipment to be monitored. The sensors measure and store vibration and temperature information at a specific point on the mechanical equipment; it is not possible to use these sensors to monitor the condition of the electrical panels.

Online equipment monitoring allows data to be captured in real time, without requiring displacement, time or effort of people in its collection, in an initial stage it is necessary to use personnel for the installation and configuration of the sensors and later, when the system is measuring, the condition monitoring engineer performs the analysis from a remote location. When accessing the web platform for the first time, the condition monitoring engineer must record data from each piece of equipment and configure alert and alarm levels. The sensors always capture the data and through the gateway it is sent and stored in the cloud, to be later analyzed and interpreted on the platform, finally the information about the equipment status is sent to operations and maintenance personnel. The data delivered by the sensors are very useful to know the general state of the equipment, since they measure vibration and temperature values, with which trends can be established, it is also possible to take more specific vibration data, such as velocity spectra, however, such data are not yet of such good quality compared to those taken by the offline vibration data collector equipment, therefore, the online system serves mostly to determine if there is a change in the condition of the equipment but not necessarily to provide an accurate diagnosis and establish the real cause of increased vibration, the same happens with the temperature measurement, the wireless sensor captures the value only at one point, while with the thermographic camera it is possible to visualize the heat distribution throughout the equipment and also to quantify its temperature.

The proposed system consists of installing wireless sensors in the motors and pumps to take vibration and temperature parameters, the sensors store the data in their internal memory and subsequently the data collection is done through a cell phone app or through a device called gateway, which is connected via Wi-Fi or network cable to transmit the data a web platform, Figure 4 shows the general operating diagram of the system and Figure 5 shows the flowchart of the implementation, later a description of the components will be delivered.

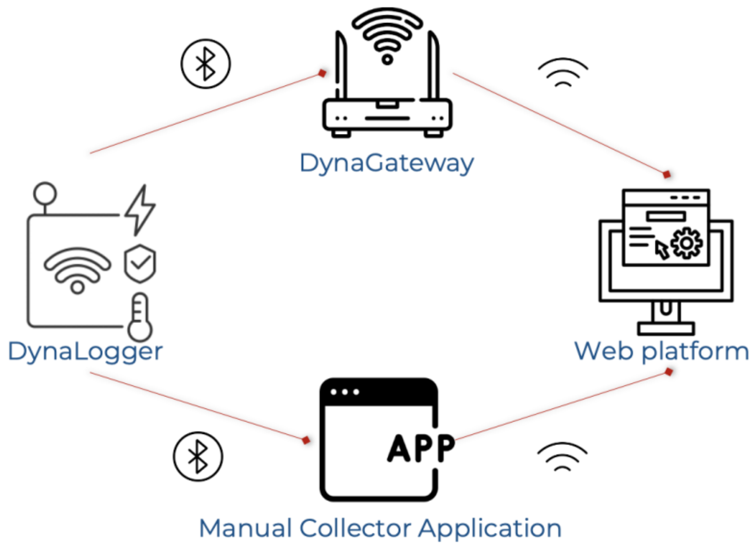

FIGURE 5
GENERAL SCHEME OF OPERATION OF THE ONLINE SYSTEM.

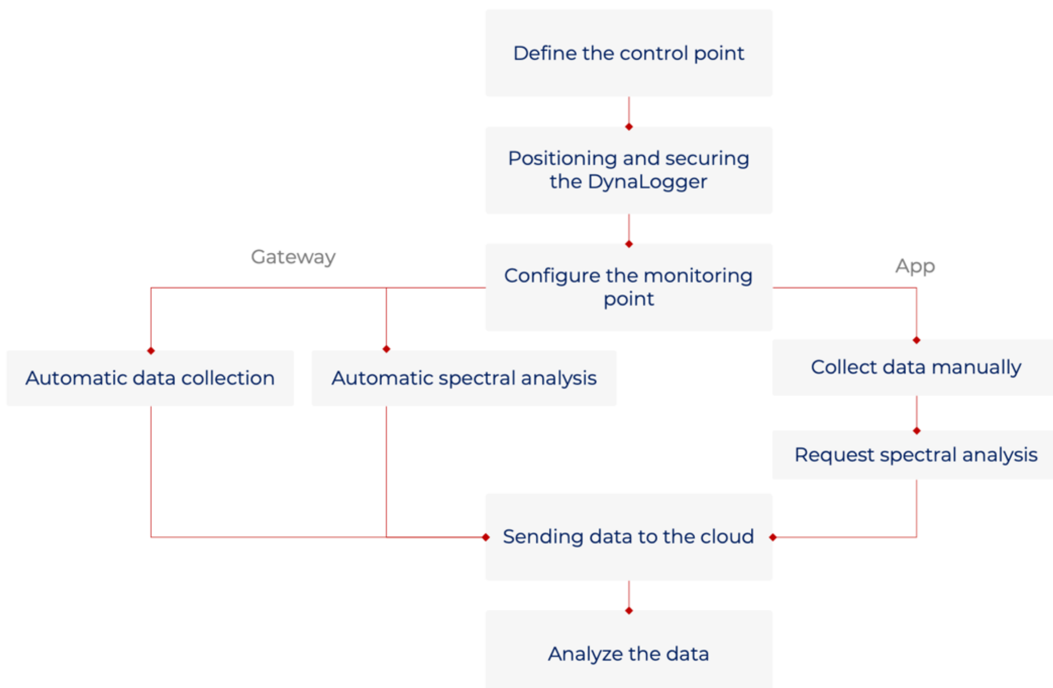

FIGURE 6
DYNAMOX SYSTEM IMPLEMENTATION FLOW DIAGRAM.

COSTS OF INSTRUMENTS FOR ONLINE AND OFFLINE MONITORING

The highest cost to form a condition monitoring department is the purchase of instruments and measuring devices, the most important costs are presented in Table V.

TABLE V
COST OF REQUIRED EQUIPMENT (CHILEAN PESOS).

System	Equipment	Total Cost
Offline	Fluke Model Ti480 Pro Thermal Imaging Camera	$12,000,000
Offline	CSI 2140 Vibration Collector (2-channel) and AMS Software License	$40,000,000
Online	Gateway	$2,600,000
Online	Dynamox Wireless Sensor	$7,200,000
Offline and Online	Notebook	$1,000,000
	Total	$62,800,000

RESULTS OBTAINED

The following is a summary of the results obtained, followed by the vibration and thermographic technical reports. In the inspection of electrical panels, carried out with the thermographic camera, five pieces of equipment were detected with anomalies, as shown in Table VI. In the mechanical inspection, carried out with the vibration collector, three pieces of equipment were detected with anomalies, as shown in Table VII.

TABLE VI
LOW VOLTAGE ELECTRICAL THERMOGRAPHY.

Area	Equipment	Priority
E	TC9 submersible well pump	1
E	CPC booster pump	2
E	CPC 4 submersible well pump	2
A	S6B2 submersible well pump	1
A	Brac submersible well pump	2

TABLE VII
VIBRATION ANALYSIS.

Area	Equipment (Vibration mm/s)	Priority
F Drive	*F*-well drive pump (16 mm/s)	1
H Impulsion	Pump N°1 Moderate damage (3 mm/s)	2
H Impulsion	Pump N°2 Advanced pump (12 mm/s)	1

- To validate the proposed online monitoring solution, the results obtained from the implementation of a pilot system in the iodine plant will be shown. The system is composed of five sensors installed in centrifugal pumps, four sensors are connected to a gateway, and one is outside the range of coverage of the gateway, therefore, in the latter it is necessary to download the data with the cell phone app.

- The first validation performed was to download, through the DynaPredict app, the data stored in the sensor that is out of range of the gateway, the connection between sensor and app was immediate and the approximate download time was three minutes, automatically the data was loaded on the web platform. In the app, it was possible to visualize the vibration and temperature values, as well as the vibration spectrum and waveform, as shown in Figure 7.

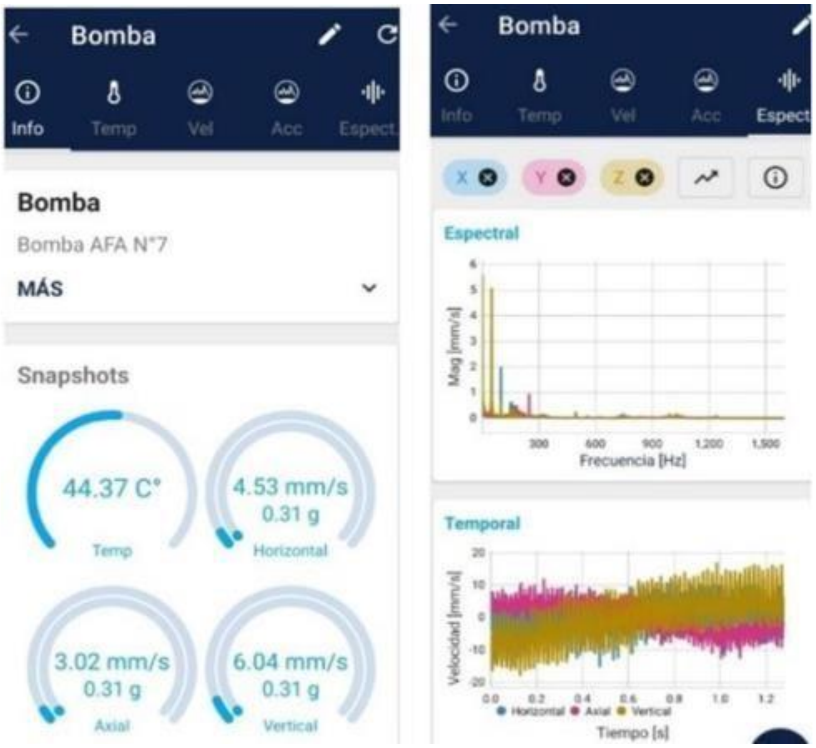

FIGURE 7
DYNAMOX SENSOR DATA VISIBLE IN THE APP.

- The second validation that was performed was to review the information of the equipment on the web page, it was corroborated that the display panel allows reviewing the status of the equipment at user level. To know the status of the equipment it is not necessary to be a specialist in condition monitoring, since through green and yellow graphics it is possible to know if the equipment is operating within the acceptable limits of vibration and temperature, as shown in Figure 8. In the web platform it is also possible to visualize more specific vibration analysis information, which is useful for the condition monitoring specialist, it was possible to visualize trend graphs, velocity spectra, waveforms, among others, as shown in Figure 9 and 10. The information from the sensors that were transmitting via gateway was updated every twenty minutes.

Estatus	Reporte	Máquina	Spot	Tendencia	Vel. mediana	Temp. mediana
A1		Bomba AFA N°7	Bomba		7,68	39,38
		Bomba Brine Reactor Planta 1	Bomba		3,82	22,32
		Bomba Brine Reactor Planta 2	Bomba		5,02	29,06
		Bomba Brine Torre Planta 1	Bomba		1,10	26,39
		Bomba Brine Torre Planta 2	Bomba		1,69	27,67

FIGURE 8
VISUALIZATION OF EQUIPMENT STATUS ON DYNAPREDICT WEB PLATFORM.

FIGURE 9
VIBRATION TREND GRAPH ON DYNAPREDICT WEB PLATFORM.

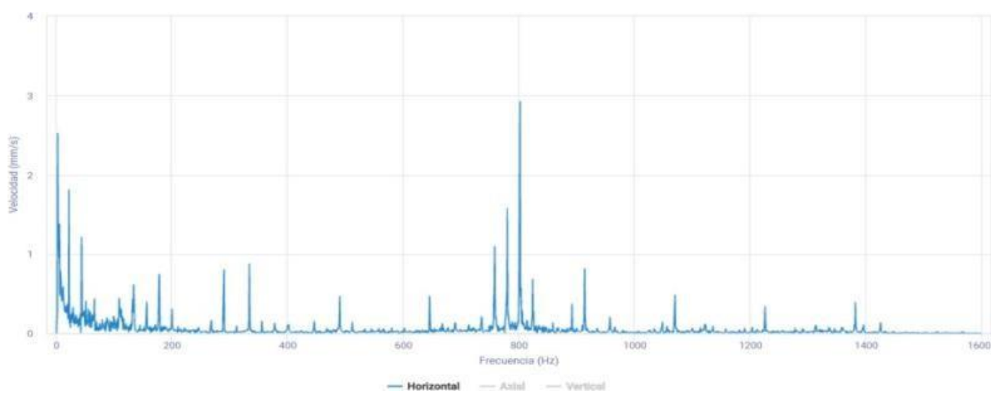

FIGURE 10
VIBRATION VELOCITY SPECTRUM IN DYNAPREDICT WEB PLATFORM.

DISCUSSION OF THE RESULTS

The results obtained through the application of the off-line monitoring system in the water resources area were satisfactory, as it was possible to detect faults in both the electrical and mechanical parts. On the electrical side, five anomalies were identified in the low-voltage electrical panels, two of them critical, while on the mechanical side, three anomalies were detected, two of them critical. With the measurements carried out, it was possible to verify that the selected inspection techniques, infrared thermographic and vibration analysis, can actually identify the failure modes, these anomalies represent a threat to operational continuity, therefore, it is necessary to carry out maintenance work to correct the condition.

Since the iodine plant maintenance personnel used the same thermographic camera and vibration collector to perform the measurements, it is also possible to validate that the instruments are suitable for failure detection. The thermographic report is quite easy to interpret, since by means of the different colors that can be seen in the thermal image, the temperature differences in each of the connections can be observed, in addition the report shows a photograph of the equipment where the faulty component is located, finally, the report provides a recommendation of the work to be carried out with a priority that indicates the time in which the repair should be carried out. On the other hand, the information provided by the vibration analysis is quite complete, there is a vibration value to evaluate the severity of the problem, also through the spectrum analysis, the condition monitoring engineer provides a diagnosis and based on that diagnosis a recommendation is given on the work to be done to correct the abnormal condition detected in the equipment. The vibration and thermographic reports received contain clear and accurate information about the anomalies of the inspected equipment. Therefore, by carrying out the recommended work, the objective of reducing the probability of equipment failure is achieved, maximizing its useful life and avoiding production losses due to unexpected failures caused by abnormal operating conditions. It should be mentioned that the measurement and analysis process must be carried out by personnel with the appropriate skills to be effective; otherwise, incorrect diagnoses could be given, or the wrong criticality could be assigned to a job.

Regarding the data reception and transmission system via gateway, it was verified that the data measured by the sensors are transmitted to the web platform with the established frequency, the web platform is constantly being updated with the vibration and temperature values. In the web platform it was possible to determine the general condition of the equipment status through the initial Dashboard of the system, where the equipment that is in normal condition, in alert and in alarm was visualized through green, yellow and red colors, such information is useful and can be interpreted by any person, in conclusion, the objective of delivering information of easy interpretation is fulfilled, this is achieved with the correct configuration of alert and alarm levels. The second part of the web platform is focused on a deeper analysis, which should be performed by the condition monitoring engineer.

According to the comments received by the condition monitoring engineer of the iodine plant, the system works quite well when measuring a vibration and temperature value, the measured value is in accordance with the actual operating status of the equipment and is also accurate in terms of the trend presented by these values, this part is quick and easy to visualize and interpret, however, in more advanced analysis tools such as speed spectrum review, the system becomes complex due to the resolution of the graphs and the slowness in the analysis, In conclusion, the data shown in the web platform are useful to perform a general analysis of the equipment condition, since it is difficult to interpret the data correctly to be able to deliver an accurate diagnosis of the equipment condition, which is achieved with the analysis of the data in a more advanced software such as AMS, described in previous chapters.

CONCLUSIONS

The water resources area is a vital area to produce iodine and nitrates at mining company, since if the volume of water required to irrigate the leaching heaps is not extracted and sent, there will inevitably be production losses, which will result in non-compliance in the production and delivery of the mentioned products to the clients; therefore, it is necessary to have a maintenance strategy to ensure operational continuity. The electrical and mechanical equipment that are part of the water resources area are exposed to failures because their components have a finite useful life, which could be further reduced due to abnormal operating conditions, with the study was able to identify the failure modes that can affect such equipment and select a type of maintenance that is effective to detect in advance such failure modes, with which it will be possible to provide recommendations to correct the condition, schedule interventions and prevent equipment from having sudden failures. With the information received from the history of failures and the associated downtime, the economic impact of all the stoppages occurred was quantified, the cost associated with maintenance was quantified, as well as the cost associated with loss of production.

The type of maintenance selected was condition monitoring, specifically using vibration analysis and infrared thermographic techniques. With these techniques, itis possible to detect many failure modes in low voltage mechanical and electrical equipment; the use of these techniques does not interrupt the operation of the equipment or alter the production process in any way. The proposed condition monitoring plan includes the use of offline and online equipment and instruments, which are available in the market and are effective for diagnosing the equipment and detecting abnormal operating conditions; however, the initial investment to acquire them is quite high, which could be a barrier for the implementation of the project. In conclusion, the main objective of the project was achieved, which was to design a condition monitoring plan to reduce the probability of occurrence of failures, which was validated and proved to be effective, its implementation will depend on the areas of operations and maintenance of water resources.

The prospects for the project are the presentation of the study to the water resources maintenance and operations areas, so that it can be evaluated and implemented. In the offline system, a database will be created in the AMS software with all the process equipment, in the database the measurement points will be created and configured, then the measurements will be taken with the frequency proposed in the study and then the analysis of the information collected in the field will be carried out to finally write a report with the condition of each of the equipment and report. In the online system the process equipment must be created and configured in the DynaPredict web platform, then the sensors must be mounted on the equipment and the gateway must be installed with the help of personnel from the instrumentation area, finally the configuration of each of the sensors will be performed and the information will be analyzed to evaluate the condition of the equipment and report.

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