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Increased Availability Risk-Based Maintenance ROV's Hydraulic System

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Abstract

In the contemporary landscape characterized by heightened competitive pressures, adept maintenance management assumes a pivotal and strategic role in cost mitigation and profit augmentation. This paper applies the risk-based maintenance (RBM) methodology to the hydraulic system of a remotely operated vehicle (ROV) owned by an oil and gas services company. To achieve this, it was necessary to gather information on the system failures, followed by determining the critical subsystems. By analyzing the frequency and severity of identified failures, a risk matrix could be constructed. Using the "5 Whys" technique, an analytical framework was used to uncover the root causes of the failures observed in the handlers and propellant subsystems. Subsequently, a risk matrix is formulated again after the implementation of the RBM and the mitigation measures adopted by the authors to elucidate the discernible impact of the maintenance methodology on improving the availability of the ROV and the incidence of failures outlined in the study.

Keywords: RBM, ROV, Failures, Availability

1. Introduction

Petrochemicals is the most expressive and dynamic branch of the multi-faceted national and international chemical industry. It is clear that oil represents the world's main energy source, accounting for around 31.5% of the matrix [1]; when we think of Brazil, this average remains close at around 33.1%. Oil is conceived as a fundamental good for the development of society. Within this context, the management of oil and petrochemical production is quite broad and challenging because it correlates several processes, such as input control, equipment management, and personnel training.

Maintenance activities have become one of the most important areas of the industry because of their remarkable participation in the achievement of objectives in an increasingly competitive environment. This increase in competitiveness implies an even greater need to establish appropriate strategies for the security of processes in force in modern industry that take into account factors such as the reliability and availability of these systems [2]. Adequate maintenance can ensure a satisfactory level of operability for systems and equipment over a certain period [3].

Experts from various fields have been discussing better maintenance strategies that, in addition to being able to reduce their costs, are also able to assess system conditions to manage factors such as reliability, safety, and availability of their assets [4]. The increasing use of fault management-focused maintenance strategies can reduce costs, increase productivity, and maintain the high reliability, availability, and safety of critical systems [5]. One of the approaches that has been discussed in the literature and industry is risk-based maintenance (RBM).

RBM analyses the probability and consequences of failures to prioritize maintenance actions [6]. RBM is a quantitative analysis methodology guided by financial aspects and aimed at continuous improvement, as well as at defining opportunities for the abovementioned process improvement.

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The approach is capable of analyzing financial risks given the occurrence of a failure, as well as assessing the cost/benefit of its elimination. The concept of RBM was developed to inspect high-risk components and to achieve acceptable risk criteria. The proposed methodology provides a tool for maintenance planning and decision-making to reduce the probability of equipment failure and the consequences of failure [7].

One of the equipment used in the exploration and production of oil and gas, which was the object of this study, is a remotely operated vehicle (ROV). This equipment consists of a robot responsible for performing underwater interventions and assisting in activities such as equipment installation and de-installation, inspection, and monitoring. As important equipment for exploration activities, there is a need for the ROV to have maximum availability and to meet the needs of the client, which reinforces the importance of an efficient maintenance plan [8].

These underwater vehicles supervise the preparation and installation of oil exploration and production equipment in depth [9]. The underwater ROV enables the remote contemplation of the ocean floor and underwater structures. An umbilical cord allows two-way communication (between operators and machines) and the transmission of energy to the ROV.

Hydraulic failures are critical because, in addition to resulting in considerable damage to the equipment, there is a great chance that oil will leak into the sea. That is, in addition to the cost of the asset being unavailable, fines and downtime may occur due to environmental damage. Professional ROV pilots can also engage in safety operations, underwater engineering inspections, and underwater rescue missions; therefore, they assist in the work of these professionals, especially when there is a risk [10].

The high time for the completion of maintenance, the various operational failures due to inadequate maintenance management, the delay in the treatment of recorded anomalies, the low availability of ROV, and the slow acquisition of spare parts are just some of the challenges encountered in the practical management context of these pieces of equipment. The objective of this study was to apply a RBM methodology to the critical subsystems of ROV systems.

2. Theoretical Reference

Maintenance management was conceptualized simply as planning and resource management based on the expected workload. Currently, the concept has expanded, and the maintenance organization is focused on managing and solving production problems, which makes a company remain competitive in the market. Maintenance is a structured activity of the company that is integrated into other activities to provide solutions that maximize results [11].

To achieve more efficient maintenance management, it is necessary to perform a consolidated fault analysis, which allows the root causes of unwanted events to be searched. Failure is when the operation or performance of a particular asset is interrupted at various levels: system, subsystem, and components [12]. Failures occur for different reasons. An example is that machines can break due to design errors, customer actions, supplier issues, and product manufacturing process difficulties, and so on [13].

Regarding the classification of failures, [14] stated that it is possible to observe failures from various aspects, such as their origin, time, extent, and criticality. For reliability, failures are classified according to their effect on a function of the system to which they belong. The root cause of failure analysis is a method performed in equipment to search for the causes of problems and determine specific actions to prevent their recurrence [11]. By prioritizing resources to deal with those who have higher operational risks, the maintenance team can achieve more satisfactory financial and safety results [3].

The RBM methodology provides a tool for maintenance planning and decision-making to reduce the probability of equipment failure and the consequences of failure [7]. Maintenance optimization is a possible technique to reduce maintenance costs while improving reliability. Companies must seek to implement new strategies for more effective maintenance techniques and programs to manage inspections and maintenance activities.

The RBM aims to select maintenance policies in the most different areas by using risk analysis concepts and techniques. In recent decades, maintenance engineering has experienced several profound changes that have integrated RBM into the full planning of industrial activities. Such changes began with the addition of reliability concepts in maintenance planning in the 1980s, and these changes are known as the "third generation of maintenance". As a subsequent phase of maintenance management development, there was the integration of risk analysis concepts, which is known as the "fourth generation of maintenance" [15].

In the final opinion of a given project or process, a risk mitigation decision is made by adding factors such as cost [16]. When the process of this step is included, this concept is capable of denoting RBM. Figure 1 shows the general RBM procedure in detail.

Figure 1 illustrates the main steps of the RBM methodology, which begin with the collection of failure data. Subsequently, consequences and probability must be assessed to prioritize the risks present in the analyzed system. The development

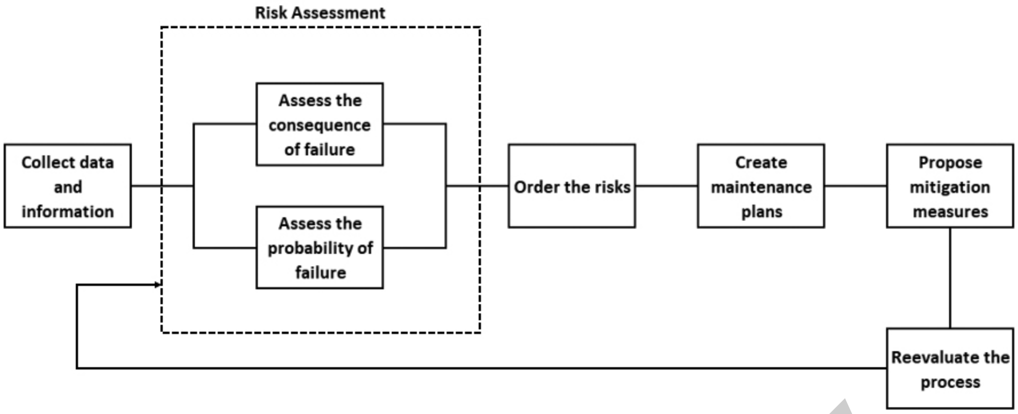

Figure 1. *RBM steps*

Adapted from Sakai [16]

RBM: Risk-based maintenance

of a maintenance plan along with proposals for mitigation measures is necessary so that a new evaluation of the process can be conducted to compare the current state after the implementation of the RBM steps with the state before the application of the methodology. These steps were used during this article and form the basis of the work conducted by the authors.

For ROV systems, there is a planned maintenance system, with emphasis on preventive techniques, developed according to the manufacturer's guidance, to reduce the possibility of failures before the expected or unnecessary disassembly of equipment still in good operating condition. However, even with a manufacturer-driven maintenance plan, significant corrective maintenance is performed, which may result in deviations from the maintenance plan used.

3. Methods

The classification of this article in terms of its nature is applied because it aims to aggregate practical knowledge used to solve problems. As to how the problem is addressed, the article is classified as quali-quantitative; quantitative, since the data of the failures were represented in numbers and classified to identify the subsystems with the highest level of criticality; and qualitative, due to the subjectivity and interpretation of the data obtained with the approach used to identify the root causes of the events that occurred.

A temporal cut-off was performed limiting the data collection period and the interval was established between June 2019 and June 2021. The work was carried out in an oil and gas sector company located in the city of Macaé, state of Rio de Janeiro (Brazil), presented here as "Delta". The Pipe Laying Support Vessel (PLSV) type vessel is also highlighted, where the ROV is installed is called "Deep X", even following a preventive maintenance plan based on the manufacturer's specifications, representing a significant period of unavailability.

Figure 2 shows the four steps responsible for characterizing the proposed method.

The ROV hydraulic system was defined and later divided into subsystems (Step 1) to collect and classify the data of the obtained failures (Step 2), which made it possible to organize the data using the analysis of Pareto. From this organization and application of the Pareto analysis, we were able to prioritize the critical ROV subsystems that presented the greatest occurrences of failure (Step 3). Subsequently, a risk matrix was developed to classify the risk of failure present in each subsystem. The subgroups that presented the highest risk were submitted to root causes of failure analysis (Step 4), and with the solution found, a new risk matrix was created to support the discussion of the results.

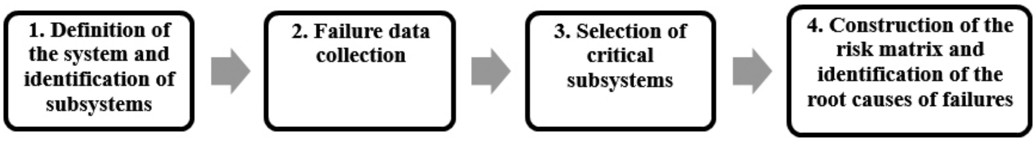

Figure 2. *Method steps*

4. Development

4.1. Description of System Analyzed

ROVs are submersible vehicles operated remotely by an operator, either on land or on a vessel. The submarine is an unmanned submarine whose main objective is to support oil well operations. These underwater vehicles supervise the preparation and installation of oil exploration and production equipment in depth [9]. The underwater ROV enables the remote contemplation of the ocean floor and underwater structures.

The use of ROVs allows long-term operation in deep water, which is not feasible in the case of diver use. It can also be operated in contaminated water, which poses a threat to the health and life of a diver, for example. ROVs are also widely used in underwater research, including shipwreck research and underwater archeological research [10].

ROVs have several classes and models that vary according to the type of operation. On the Deep X vessel, the ROV installed was class 3, and the model was Triton XLX (Figure 3) from the manufacturer Forum Energy Technologies extracted in [17]. The hydraulic, main, and auxiliary systems work essentially in the same manner; that is, a hydraulic pump coupled to an electric motor generates pressure on the system components and valves. For example, the pump supplies pressure to the manifold control valves. These valves provide pressure for various controlled components (thrusters, hydraulic tools, handlers, Pan&Tilt, etc.). The control valves on the manifolds are actuated by a surface control system through a local valve controller (LVC) plate located on each manifold. The LVC provides an electrical control interface with the valves.

Figure 3. *Triton XLX [17]*

A command is sent from the surface to the LVC that properly acts by controlling the valves that control the thrusters, tools, or other components. When any device is activated, there is an increase in the hydraulic pressure demand and consequently a pressure drop in the system. This drop is "felt" by the pump control circuits. The pump control circuits act so that there is an increase in the flow, which increases the system pressure, bringing it back to balance. The pump control system works continuously to balance the flow and pressure so that the output reaches the demand as it increases or decreases.

The main functions of the ROV hydraulic system served as a reference for this research by creating categories for the classification of faults that occurred. Name: (1) Thrusters, which are responsible for the ROV displacement; (2) handlers, which are the hands and arms of the submarine robot capable of lifting, connecting, and disconnecting; (3) Pan&Tilt, which provide movement to the cameras; (4) Motor/pump, which provide hydraulic power to the entire system; (5) Manifolds, which is the place where the control valves are installed; (6) reservoirs, where hydraulic fluid is stored; and (7) filters, which are responsible for keeping the fluid in healthy operating conditions.

4.2. Data Collection and Organization

The data collection process was carried out by Delta, specifically in a ROV installed in a PLSV vessel called Deep X. With one of its operational bases located in the city of Macaé, Brazil, Delta is a world leader in projects, technologies, systems, and services for the oil and gas industry. The company is capable of offering everything from individual products and services to fully integrated solutions, providing experience across the segments: Subsea, onshore/offshore, and surface projects.

To maintain asset functionality, the ROV has a strict preventive maintenance plan based on the manufacturer's specifications that indicates the replacement of parts, checking the wear of specific items, and hydraulic fluid conditions used. All system maintenance is managed by software called InforEAM© which is used for enterprise asset management to optimize maintenance operations and maximize equipment reliability. In addition to maintenance, the software has inventory control along with the purchasing system, simplifying procurement processes. The failure data recorded between June 2019 and June 2021 were exported from the software to a spreadsheet, classified according to subsystem, and quantified.

4.3. Quantification of Faults and Analysis of Pareto

From the hydraulic system division into 7 subsystems (Propellers, Handlers, Pan&Tilt, Motor/Pump, Reservoirs, Manifolds, and Filters), the exported failures of the InforEAM© software, comprising the period June 2019 to

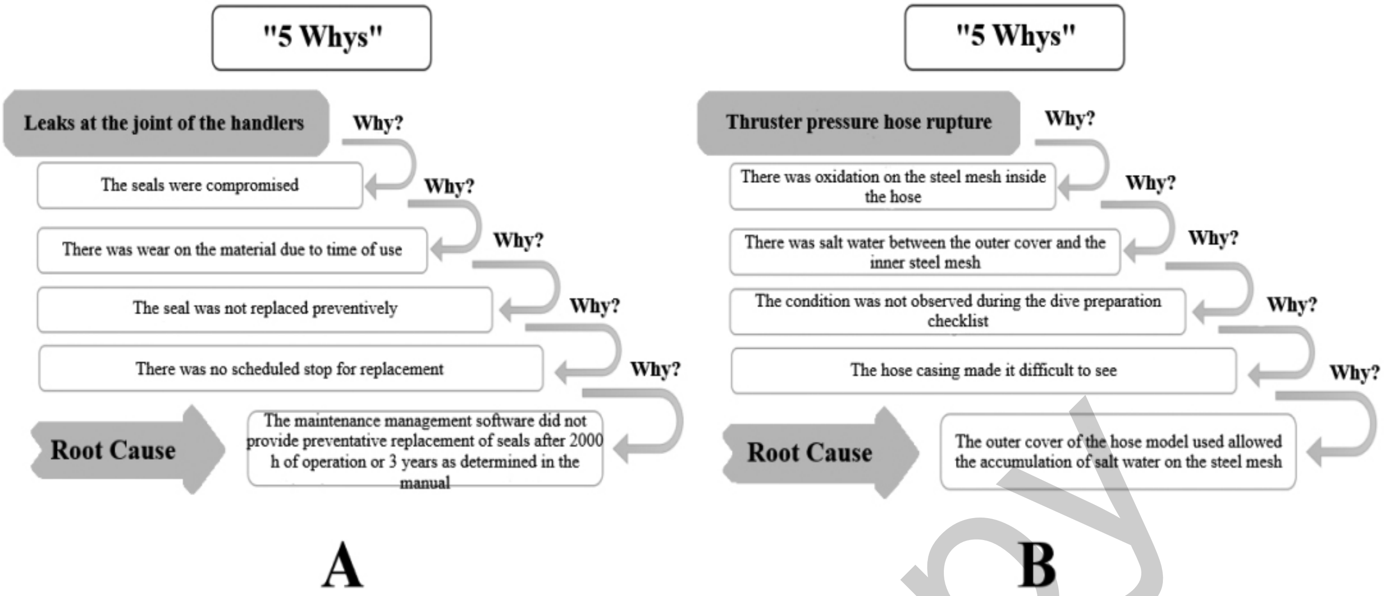

***Figure 4.** Whys "Handlers (A)/Propellants (B)"*

June 2021, the relative and accumulated percentages for each subsystem shown in Table 1 below are also shown and classified according to their respective subsystem, together with the classification:

With the help of the table, it was possible to observe that in the period a total of 56 hydraulic failures occurred, and 73.21% of the events belonged to the subsystems of the manipulator and thrusters, thus representing the main causes of ROV unavailability due to hydraulic problems with a total of 41 of the 56 occurrences. All failures involving the hydraulic system were addressed by the ROV sector of the Deep X vessel in a corrective manner [18]. Dividing the system into categories and organizing the data combined with the risk matrix helped illustrate the impacts.

4.4. Criticality Analysis and Construction of A Risk Matrix

The risk matrix was developed to classify groups based on the relationship between the frequency of analysis failures and their severity. Table 2 lists the severity levels adopted in this study. The severity levels are described in Appendix A. Such levels of frequency and severity were determined in collaboration with ROV specialists from the operation and maintenance department of Delta Co.

Categories A, B, C, and D in Table 3 represent each level of criticality, i.e., how critical the respective group is for the hydraulic system, given its representativeness regarding the total number of events that occurred due to severity. Table 3 lists the criteria for each category.

***Table 1.** Rov subsystems pareto analysis*

Description	Subsystem	Qty.	%Rel	%Acum
Handlers' failures	Handlers	28	50.00%	50.00%
Failures of thrusters	Propellants	13	23.21%	73.21%
Failures in Pan&Tilt	Pan&Tilt	4	7.14%	80.36%
Failures in the valve control block	Manifolds	3	5.36%	85.71%
Failures in the reservoirs	Reservoirs	3	5.36%	91.07%
Failures in the filtration system	Filters	3	5.36%	96.43%
Failures in hydraulic power generation systems	Motor/pump	2	3.57%	100.00%
	Total	**56**		

Source: Elaborated by the authors

4.5. Analysis of Root Cause of Failure in Selected Subsystems

In the risk matrix, the Pan&Tilt, Manifolds, Reservoirs, Filters, and Motor/Pump subsystems were positioned at level C in the criticality category, i.e., they are tolerable and, without additional measures required, can only be monitored according to the preventive maintenance plan already carried out by the ROV industry and as approached [19]. On the other hand, the subgroups of the handlers and thrusters were at level A, which represents the need for intervention to fall into acceptable categories.

***Table 2.** Frequency category*

Level	Designation	Description
5	Very high	Represents over 50% of all failure occurrences
4	High	Represents 20-50% of all failure occurrences
3	Moderate	Represents 15-20% of all failure occurrences
2	Low	Represents 10-15% of all failure occurrences
1	Very low	Represents less than 10% of all failures
Source: Elaborated by the authors		

***Table 3.** Criticality category*

Level	Designation	Criteria
A	Intolerable	Alternative methods must be considered to reduce the probability of occurrence and its consequences so that the criticality can be reduced to acceptable categories.
B	Undesirable	Additional measures should be evaluated to reduce criticality by implementing measures considered practicable.
C	Tolerable	No additional measures are required. Monitoring is required to ensure that criticality is maintained.
D	Negligible	No additional measures are required.
Source: Elaborated by the authors		

The 28 failures that occurred in the handler subsystem during the aforementioned period were arranged in a spreadsheet. According to the observed data, the events that occurred were due to leaks in the seals of the joints of the arms. To find the primary cause of these leaks, the technique used to analyze the root cause of failure [11].

The 13 failures in the thruster subsystem were also arranged in a spreadsheet. Based on the observed data, the events occurred mainly due to rupture of the pressure hoses connected to the propellers.

Based on the technique described by [20], to verify that the analysis was performed well, it is possible to replace the "Why" with "then" in the opposite direction, i.e., the root cause of the problem, and thus check the consistency of the analysis. The 41 failures in the handler and thruster subsystem during the period mentioned in the method section were arranged in a spreadsheet. According to the observed data, the events that occurred were due to leaks in the seals of the arms joints (case of the manipulators); and to find a primary cause of these leaks, the technique used was analysis of the root cause of failure [11].

Defined the parameters for the development of the risk matrix, each subsystem was classified, and for the Handlers group, the analysis of Pareto represented 50% of all hydraulic failures. The frequency and severity analysis resulted in level A (represented by "X") in the category of criticality, which can be observed in the risk matrix shown in Figure 5.

On the other hand, the Propellants subsystem represented 23.21% of the total occurrences in the frequency category, where it obtained level 4. Regarding severity, the group also obtained level 4, resulting in category A of criticality (represented by "X" too), as shown in Figure 5.

RISK MATRIX - HANDLERS

FREQUENCY \ SEVERITY	1	2	3	4	5
5	C	B	A	A	A
4	C	B	B	~~A~~	A
3	C	C	B	B	A
2	D	C	C	B	B
1	D	D	C	C	B

RISK MATRIX - PROPELLANTS

FREQUENCY \ SEVERITY	1	2	3	4	5
5	C	B	A	A	A
4	C	B	B	~~A~~	A
3	C	C	B	B	A
2	D	C	C	B	B
1	D	D	C	C	B

***Figure 5.** Risk matrix of "Handlers and Propellants"*

RISK MATRIX - HANDLERS

SEVERITY / FREQUENCY	1	2	3	4	5
5	C	B	A	A	A
4	C	B	B	A	A
3	C	C	B	B	A
2	D	C	C	B	B
1	D	D	C	~~C~~	B

RISK MATRIX - PROPELLANTS

SEVERITY / FREQUENCY	1	2	3	4	5
5	C	B	A	A	A
4	C	B	B	A	A
3	C	C	B	B	A
2	D	C	C	B	B
1	D	D	C	~~C~~	B

Figure 6. *Post RBM risk matrix: Handlers and Propellants*

RBM: Risk-based maintenance

Since hydraulic failures represent a high severity scale, the solution according to the risk-based maintenance methodology was to reduce the frequency at which these events occur, such as what happens in the filter group, so the risk matrix exposes a high severity of failure. Nevertheless, because the frequency is low, this group occupies category C in the risk scale, without the need for intervention, and only for monitoring.

When dealing with the two subsystems that had the greatest occurrence of failure and were more critical, it was possible to identify the two primary causes that were directly related to the high frequency of the failures. For the Handlers subsystem, the root cause was the failure to perform preventive maintenance as provided for in the manufacturer's manual, which states that the seals of the joints must be replaced every 2000 hours of operation or every 3 years.

The root cause of the Propellants subsystem was the type of hose used by the system. The hoses installed in the pressure lines were of a model that allowed the accumulation of salt water in the internal steel mesh, which caused oxidation in the mesh and broke with hydraulic pressure. The solution proposed for this failure was to replace the hose with a rubberized external cover that did not allow water to enter. In addition, this replacement and the check for corrosion or water accumulation in the hose should be inserted into the pre-operation checklist, and if there is still a propellant in the old hose, it should be replaced with a new one.

To illustrate the improvement in the RBM implementation, Figure 6 shows the new risk category of the Handlers and Propellants group.

5. Conclusion

This article aimed to apply the RBM methodology to the hydraulic failures of ROVs, and to achieve this objective, a case study developed for a Delta company vessel that operates in the oil and gas sector was used. Data extracted from the InforEAM© software were recorded in a spreadsheet, organized with the help of a Pareto chart, and classified according to the risk matrix. The ROV hydraulic system was detailed and divided into subsystems, where the elaborated matrix highlighted two subsystems with high levels of risk. With the analysis of the failures, it was possible to determine the root causes.

The solution found by the analysis resulted in a jump in the risk category in the two subsystems, and the proposal to improve the pre-operation checklist and update the preventive maintenance plan for the handlers has reinforced the importance of RBM for the company by highlighting the decrease in the frequency of failure occurrence. Due to the complexity of the other systems that make up the ROV, this research was based on only the hydraulic system. With this in mind, it is suggested for future studies that all ROVs be mapped according to the risks and analyses, and that maintenance plans and checklists be updated not only with the manufacturer's specifications but also with the RBM methodology.

The proposed solution for the failures identified in the handlers was to insert a 2000-hour preventive measure in the maintenance plan and a half-yearly inspection independent of the operating time to identify possible wear that the seals may present. With this proposed solution based on the RBM methodology, the authors expect that there will be a reduction in the number of failures that occur with fences. This implies an increase in the availability of the ROV of the Deep X vessel and a reduction in the costs that the Delta company has for the non-operability of the system. On the propellers, the solution proposed by the authors went through the replacement of the hose commonly used by another model with rubberized external cover, which was capable of blocking the water inlet, thus reducing the existence of corrosion in the equipment.

Authorship Contributions

Concept design: L. Braga, P. A. D. S. Pereira, M. C. Amaral, and. R. Cardoso, Data Collection or Processing: L. Braga, Analysis or Interpretation: L. Braga, and P. A. D. S. Pereira, Literature Review: L. Braga, I. D. S. Pinto, and P. A. D. S. Pereira, Writing, Reviewing and Editing: L. Braga, I. D. S. Pinto, and P. A. D. S. Pereira.

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References

[1] EPE, “National Energy Matrix”, *Empresa de Pesquisa Energética*, 2018. [Online]. Available: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-2018. [Accessed: Oct. 2, 2021].

[2] Y. Jiang, and S. Yin, “Recent advances in key-performance-indicator oriented prognosis and diagnosis with a MATLAB toolbox: DB-KIT”, *IEEE Transactions on Industrial Informatics,* vol. 15, pp. 2849-2858, May 2019.

[3] P. A. de Souza Pereira, “Risk-based maintenance applied in subsea equipments”. *Brazilian Journal of Development*, vol. 9, pp. 18178-18197, May 2023.

[4] V. Atamuradov, K. Medjaher, P. Dersin, B. Lamoureux, and N. Zerhouni, “Prognostics and health management for maintenance practitioners - review, implementation and tools evaluation”. *IJPHM*, vol. 8, pp. 1-31, Nov 2020.

[5] D. Galar, M. Palo, A. Van Horenbeek, and L. Pintelon, “Integration of disparate data sources to perform maintenance prognosis and optimal decision making”. *Insight - Non-Destructive Testing and Condition Monitoring,* vol. 54, pp. 440-445, Aug 2012.

[6] J. Lima, A. Santos, and R. Sampaio, “Sistemas de gestão da manutenção - Uma revisão bibliográfica visando estabelecer critérios para avaliação de maturidade.”, *Enegep*, Oct 2010.

[7] N. S. Arunraj, and J. Maiti, “Risk-based maintenance—Techniques and applications”. *Journal of Hazardous Materials*, vol. 142, pp. 653-661, Apr 2007.

[8] P. Pereira, M. Amaral, R. Bella, and L. Ribeiro, “Reliability centered maintenance applied to an ROV system”. *Brazilian Journal of Development*, vol. 9, Jul 2023.

[9] G. Lorosa, “*Sistemas elétricos de um veículo de operação remota (ROV): análise técnica funcional e operacional*”, 2015.

[10] N. Bouchonneau, et al. “Study of expanded polymers water absorption for buoyancy modulus development of a submarine mini-robot”. *Polimeros,* vol. 20, pp. 181-187, 2010.

[11] A. Kardec and J. Nascif, *Manutenção: função estratégica*. Rio de Janeiro: Qualitymark Petrobras, 2013.

[12] NASA, “Reliability centered maintenance guide for facilities and collateral equipment”. *National Aeronautics and Space Administration,* Final, Sep 2008. [Online].

[13] N. Slack, S. Chambers, and R. Johnston, *Administração da Produção*. São Paulo: Atlas, 2002.

[14] P. Siqueira, *Manutenção Centrada na Confiabilidade: Manual de Implementação*. Rio de Janeiro: Qualitymark Editora, 2014.

[15] F. I. Khan, and M. Haddara, “Risk-based maintenance (RBM): A new approach for process plant inspection and maintenance”, *Process Safety Progress*, vol. 23, pp. 252-265, Nov 2004.

[16] S. Sakai, “Risk-based maintenance”. *JR East Technical Review,* Tokyo, 2010.

[17] ROV Solutions for Power & Telecom, “ROVOP: Global ROV specialist”. *ROV Solutions for Power & Telecom*, 2019. [Online]. Available: https://www.rovop.com. [Accessed: Jun 5, 2023].

[18] M. Pereira, *Engenharia de Manutenção – Teoria e Prática*. Rio de Janeiro: Ciência Moderna Ltda., 2009.

[19] M. Pego, *Fundamentos da Engenharia de Manutenção. [S.l]*: *[S.n],* 2018.

[20] E. Bassan, *Gestão da Qualidade: Ferramentas, técnicas e métodos*. Curitiba: Clube de Autores, 2018.

Appendix A. *Severity category*

Level	Designation	Assets	Environment	Customer	Operability
5	Catastrophic	Material damage whose economic values for repair actions are very high compared to acquisition costs.	Environmental impact is difficult to reverse, even with mitigating actions, and of great magnitude and extent (beyond the limits of the enterprise) with the potential to affect stakeholders.	Direct impact on customer relationship. Contract interruption.	More than 24 hours of average downtime.
4	Critical	Material damage whose economic values for repair actions are high compared to acquisition costs.	Impact of great magnitude, reversible with mitigating actions, but restricted to adjacent areas of the unit.	Direct impact on customer relationship. Project shutdown.	Between 12 and 24 hours of average downtime.
3	Moderate	Material damage whose economic values for repair actions are moderate compared to acquisition costs.	Impact of considerable magnitude, but reversible with mitigating actions, affecting only internal areas of the unit.	Possible impact on the customer with a chance to affect the project and other operations.	Between 6 and 12 hours of average downtime.
2	Marginal	Material damage whose economic values for repair actions are reduced compared to acquisition costs.	Impact of negligible magnitude, but reversible with mitigating actions, affecting only internal areas of the unit.	Possible impact on the customer with a chance to affect the project.	Between 1 and 6 hours of average downtime.
1	Negligible	Material damage whose economic values for repair actions are negligible compared to acquisition costs.	Impact of negligible magnitude for the environment/restricted to the occurrence site, fully reversible with immediate actions, does not affect stakeholders.	No impact on the customer.	Up to 1 hour of average downtime.