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Reliability-centric maintenance applied to an ROV system

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ABSTRACT

The ROV – Remotely Operated Vehicle is one of the most used subsea equipment in the world oil and gas industry, it is to maintain a good operational efficiency is necessary a concise and efficient maintenance plan. Among the maintenance applied to the subsea robot are corrective, preventive and predictive maintenance. Therefore, the general objective of this work is to analyze the main operational failures presented by the vehicle and propose the application of MCC - Reliability Centered Maintenance, to indicate the critical failures and optimize the maintenance performed on the equipment, reducing costs, labor and increasing the availability of the same. For this, a bibliographic survey on the subject and documentary analysis was carried out to identify the technical data. The pareto diagram tool was applied to prioritize the recurrent failures, after that, the root causes were raised, with the application of the analysis of effects and failure modes and the fault tree and, finally, a reliability study of the equipment used in the vehicle was carried out. With the results analyzed, it was proposed the use of MCC by the company in its maintenance plan.

Keywords: ROV, Failures, Reliability Centered Maintenance.

1 INTRODUCTION

The international oil industry began to live with strong fluctuations in the price of a barrel of oil from the year 2014, with the trend of declining prices, the companies operating in the sector engaged in a drastic revision of their exploration and production strategies, resulting in the restructuring of projects and cost reduction. The expenses resulting from the lack of maintenance on the equipment or an efficient maintenance plan, made this subject become one of the main focuses of management to improve operational performance.

According to Kardec and Nascif (2009), maintenance has the sense of reestablishing the original conditions of equipment and systems, as well as maximizing production with lower cost and higher quality, following the safety standards proposed by the company, without causing damage to the environment.

The company studied in the present work, offers inspection and intervention services in subsea equipment using the ROV. This equipment is widely used in the phases of exploration and production of oil, especially in areas where the environment is hostile to human presence, because the work of divers is limited to the depth of 300 meters and due to the high depth of work, from the well to the production platform, with water depths ranging from 2000 to 3000 meters deep, the maintenance of ROVs becomes increasingly critical and essential to obtain adequate operational performance and reliable equipment.

2 RESEARCH METHOD

The research methodology of this article has a qualitative-quantitative character, due to the collection of critical data of corrective maintenance. Thus, it was possible to elaborate a presentation with numerical and statistical data that determined which equipment suffered the most unexpected stops and had the greatest impact on operational time. And qualitative, because through the interpretation of these data and the identification of the current maintenance plan in force in the organization, its characteristics were delimited and its classification was possible according to the FMEA tool.

The research is classified as exploratory, and through the documentary analysis was carried out the survey of historical data made from the records of the company's maintenance book, between the years 2018 and early 2022, generating more information on the subject in question. This type of research is recommended when there is little knowledge about the subject and is intended to formulate and develop new research (CERVO; BERVIAN, SILVA, 2007).

According to Gil (2002) it is possible to classify documentary research as a type of bibliographic research, because some documents have already been analyzed and reviewed, such as technical reports of the company and statistical tables.

The bibliographic survey helped in the understanding of the theme about industrial maintenance and reliability studies, allowing a clearer view of the problem and delimiting the subject addressed, thus being complemented by documentary analysis.

In order to account for the proposed theme, a case study was developed, which was carried out in a subsea services company, focusing on the area of underwater robotics. Thus, it was possible to identify probable factors that were influenced by the maintenance performed during the period studied, analyzing the entire maintenance system adopted, historical data of failures, availability of spare parts, available and qualified labor to perform the activity and, from the data obtained, it is possible to raise the failure data that occurred more frequently, applied the FMEA and FTA, calculated the MTTF and reliability, including proposing improvements in the maintenance plan.

3 LITERATURE REVIEW

3.1 MAINTENANCE, FAULT AND RELIABILITY CONCEPTS

According to NBR 5462 (1994), maintenance can be understood as a combination of all technical and administrative actions, including supervision, aimed at maintaining or replacing an item in a state in which it can perform its primary function. These activities may include fault handling such as detection, repair, investigation of the root causes, and establishing control measures against their recurrence.

Also according to the NBR 5462 (1994) standard, the concept of failure can be understood as the termination of the ability of an item to perform a required function, which may result in dangerous and unsafe conditions for people, significant material damage or other unacceptable consequences. According to the same standard, the concept of reliability is understood as the probability that a component, equipment or system will perform its function without failure, for a certain predicted period, acting under the specified operating conditions.

Thus, CCM (reliability-centered maintenance) is a process used to determine what needs to be done to ensure that any physical item continues to fulfill its desired functions in its current operational context (GURSKI, 2002).

MCC addresses reliability measures to determine the likelihood of maintenance occurring. The first calculation addressed is the MTTF (*Mean Time To Failure*) or average time between failures, which is given by the average sum of time to failure, divided by the number of failures occurred. According to Lafraia (2001), it is understood as time until failure that moment that a unit is put into operation until its first failure. By integrating the MTTF it is possible to determine the risk function:

$$MTTF = \int_0^\infty R(t)dt = \int_0^\infty e^{-\lambda t}dt = \frac{-1}{\lambda}[e^{-\lambda t}\Big|_0^\infty = \frac{-1}{\lambda}(0-1) = \frac{1}{\lambda}$$

The reliability function represents the cumulative probability of success as a function of a given time *(t)*. Mathematically it can be expressed through the integral, arriving in its summarized form according to the formula below (LAFRAIA, 2001):

$$R(t) = \int_t^\infty f(u)du = \int_t^\infty \lambda e^{-\lambda u}du = -e^{-\lambda u}\Big|_t^\infty = \left[0-\left(-e^{-\lambda t}\right)\right] = e^{-\lambda t}$$

3.2 QUALITY TOOLS

For the survey, treatment of data and improvement of the way of visualization of the maintenance that occurred between the years of 2018 and beginning of 2022 in the ROV system of the company studied, the Pareto Diagram was used, whose objective is to identify the problems of greatest importance, allowing a quick visualization and greater deepening so that the improvement effort is directed to those who have priority (BALLESTERO-ALVARES, 2010).

Fault handling techniques emerged and were quickly absorbed by maintenance engineering. Many of them are related to monitoring the functional condition of the equipment, without the need to dismantle or deactivate the item for inspection. In the methodological field, research in the areas of reliability and maintainability, as well as mechanisms and equipment failures, gave rise to the techniques of Analysis of Failure Modes, Effects and Criticality – FMEA (SIQUEIRA, 2014).

Once the possible failures in a system have been identified, the next step towards prevention or correction consists in the characterization of how they occur, that is, the modes of each failure. Mode characterization is useful for identifying failures that can be corrected, such as those that can be prevented, and for consistently identifying failures that should be monitored.

According to Siqueira (2014), the failure mode can be defined as an event or physical condition that causes a functional failure or one of the possible failure states of an item, for a given required function.

The FMEA addresses the choice of preventive and corrective actions to minimize or mitigate the impacts of failures on the system, installation and environment. The failure effect results from the failure mode in the operation, function, or status of the item. This concept is applied in the impacts of failure modes on the functions of an equipment (FOGLIATTO and DUARTE, 2011).

The effects of failure can be classified quantitatively through the risk analysis of the indices of severity (S), occurrence (O) and detection (D).

The severity (S) is the measure of the little severe effect, which minimally affects the operation up to a maximum scale of very severe effect, and may even compromise the safety of the vessel. The severity applies exclusively to the effect of the failure.

Occurrence (O) relates to the probability that an analyzed failure may occur. The evaluation of the occurrence is also performed using a qualitative scale, in which the higher the number of classification, the greater the probability of occurrence of failure.

Detection (D) refers to an estimate of the ability of current controls to detect causes or potential modes of failure before the component or subsystem malfunctions. To reduce the score, it is necessary to intensify the program of maintenance, inspection and functional testing of the equipment.

The Risk Priority Number (NPR) is a mathematical product of classifying the failure effects discussed above. This number is used to define the priority of corrective and improvement actions of the project according to its presented risk. Through the indices of severity, occurrence and detection, it is possible to determine it by multiplying "S x O x D" (FOGLIATTO and DUARTE, 2011).

For better application of the tool, a form can be used in order to guide the process of identifying the flaws. After identification, the occurrence score is performed, as well as the definition of controls and detection score. Finally, the NPR calculation and the taking of actions were taken. Thus, the analysis of the FMEA ends up helping the identification of preventive and corrective actions.

The FTA – *Failure Tree Analysis* tool or as it is known Fault Tree was used in conjunction with FMEA, for mapping and prioritization of problems.

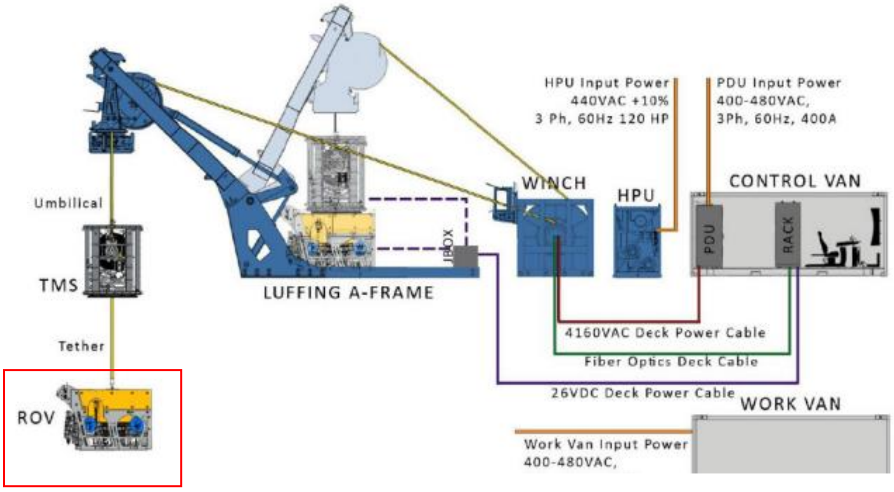
3.3 ROV - *REMOTELY OPERATED VEHICLE*

The ROV or translated to Remotely Operated Vehicle is widely used as an underwater vehicle, serving a range of military, commercial and scientific needs. Using a range of thrusters, these vehicles are highly manoeuvrable and safely operated by a qualified professional on the surface. A communication cable carries power and control signals to the vehicle, as well as video signals, measurements, other sensory and positioning data. Most ROVs have manipulable arms to assist in underwater operations at depths considered to be of risk to human life (CAETANO; SOUZA, 2012).

Currently, it can be stated that the ROVs are fundamental equipment for the extraction and production of oil at sea, and also a critical item for the maintenance and continuation of operations in deep waters, being essential for the advancement in the exploration of oil of the pre-salt layer of the Brazilian coast, where there are oil wells being explored at a depth of 3000 meters (MORAES, 2011).

As the ROV began to work in adverse pressure conditions, greater availability and reliability is required of it, and its maintenance is no longer seen as something secondary and has become a priority in the companies providing this service.

FIGURE 1 - General drawing of the ROV system.



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The ROV system basically consists of the components, as shown in Figure 1:

- *Control Van,* the control cabin where the computers responsible for communicating the surface with the underwater vehicle, the control panel and the pilot's chair are located;
- *Work Van,* is the workshop where maintenance is performed on the vehicle;

- LARS – *Lauching and Recovering System*, the vehicle launch and retrieval system, which consists of the EHPU (*Electric-hydraulic Power Unit*), the winch drum that accommodates the umbilical reinforced cable responsible for powering the system and the optical communication fiber and the *A-Frame* lifting structure that transports the ROV to the board of the vessel; and
- TMS – *Tether Management System*, also known as cage due to its shape, is the ROV communication cable management system that has the outer layer composed of float.

ROV classes are determined by their size, power capacity and functionality. The IMCA - International Marine Contractors Association *or International Association of Marine Contractors*, classifies the vehicles as class I, class II, class III, class IV and class V. Further details can be seen in the work of Ribeiro (2022).

4 APPLICATION OF RELIABILITY-CENTRIC MAINTENANCE

In this topic is presented the case study applied in the company, in which were statistically presented the most frequent failures that occurred in the ROV system observed class III. This work consisted of raising all unplanned corrective maintenance performed within the period of data collection, verifying the causes of their failures and proposing improvements in the project.

The application site of the case study was an ROV system installed on a drilling rig, operating in the Brazilian pre-salt region. The operation and maintenance of the ROV is done by the on-board team which consists of 1 supervisor and 2 technical operators.

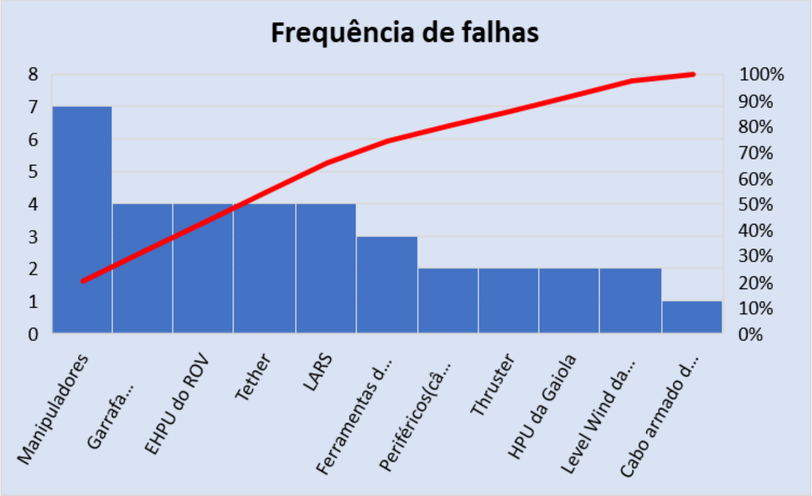
4.1 DATA COLLECTION

The maintenance data was obtained through the management software that the company itself developed. This software contains information such as inventory, team reports, security files, as well as the history and maintenance plan.

The company has a robust preventive maintenance plan, in which dozens of daily maintenance activities are sent to be performed by the on-board team, including inspection and intervention in the equipment of the entire ROV system.

For this research, data from the history of unplanned corrective maintenance were used, since the failure that occurred made the equipment unavailable until the maintenance was completed. The data collected was from the beginning of 2019 to the beginning of 2022 and the maintenance information was compiled and separated according to their categories of equipment and, with this, it was possible to determine the amount of failures that occurred in the observed period. The Pareto Diagram tool was applied in order to identify the priorities, according to the sub-item categories of the system and presented in graph 1.

GRAPH 1 – Pareto diagram applied to the frequency of failures.



Source: Own authors (2022).

According to the graph, it is possible to observe that the subitems that presented the highest recurrence of failures were the manipulators or popularly known as the ROV arms, indicating that it is a component that needs to be prioritized in corrective actions.

Table 2 was prepared according to the hours of unplanned corrective maintenance of each equipment.

TABLE 2 - Time used in corrective maintenance.

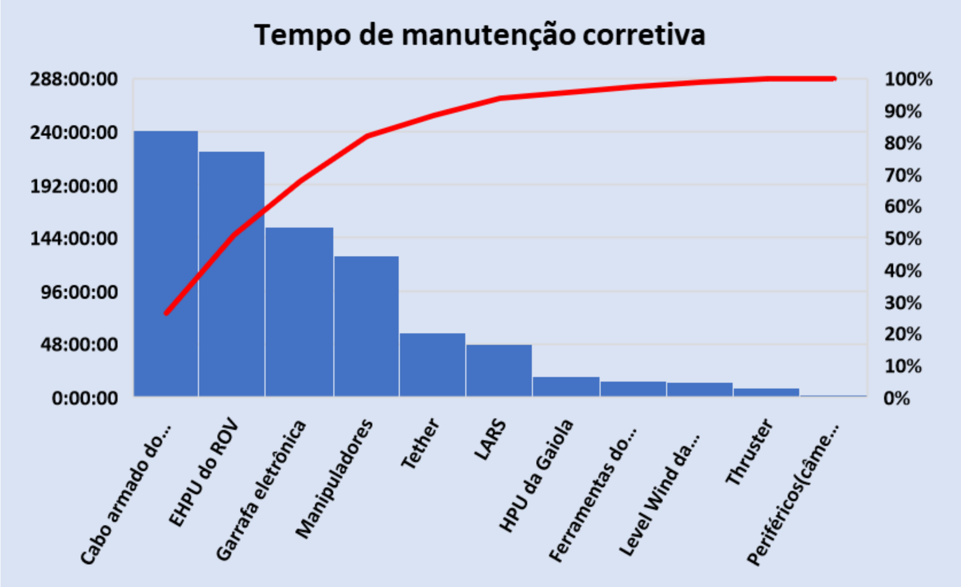
Equipment	Maintenance (hours)
Handlers	127:48:00
Electronic bottle	153:31:00
EHPU to ROV	222:00:00
Peripherals (camera, sonar)	2:00:00
Thruster	8:30:00
Tether	58:10:00
ROV Tools	14:30:00
LARS	47:37:00
Cage HPU	19:10:00
Cage Wind Level	14:00:00
Armed winch cable	240:53:00
TOTAL	**908:09:00**

Source: Own authors (2022).

With the application of the Pareto Diagram in the corrective maintenance time data, it is possible to verify that the exchange of the winch reinforced cable was the activity that required more time to be performed. However, this elapsed time is not only due to the maintenance task, it was found that there was no other armed cable available for immediate replacement. This activity is something very unlikely to happen, so it is not financially feasible to keep a spare reinforced cable on board, in addition to being a high-risk activity that requires the support of a crane for cargo handling, operational and safety planning.

Thus, the analysis of the second item was prioritized, which presented more recurrence of failures and had a considerable time to perform corrective maintenance, which was the EHPU of the ROV, as can be seen in graph 2.

GRAPH 2 – Pareto diagram applied to maintenance time.



Source: Own authors (2022).

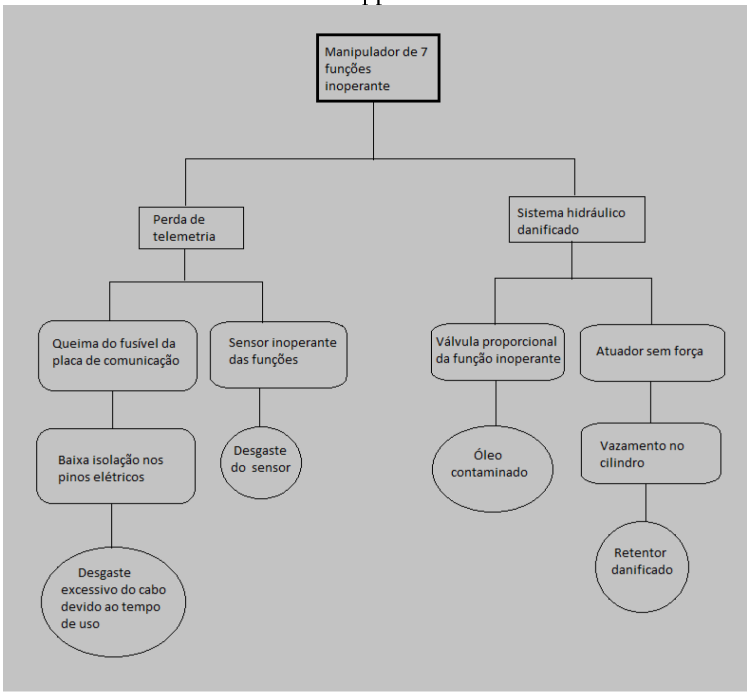
The EHPU is formed by the electric motor and the hydraulic pump that distributes the oil flow using pipes and hoses for the other hydraulic components of the vehicle. Analyzing precisely what actually occurred to require intervention, it is concluded that the main cause of the failure was the electric motor of the ROV.

4.2 APPLICATION OF FMEA AND FAULT TREE

In order to better understand the functions of the handler and the EHPU and relate to their functional failures and respective effects, Annex A of FMEA was elaborated. In this annex it is possible to verify the failures that had the highest NPR and indicate the prevention controls, improvement actions and the person responsible for performing such activities. In conjunction with FMEA, the fault tree was applied to determine the root cause of the failures that led to the unwanted event.

According to Annex A, the failure mode that presented the highest NPR was the loss of telemetry of the handler. To identify the root cause, the Fault Tree was used as shown in Figure 2 and the unwanted event was excessive wear due to fatigue of the manipulator's communication cable.

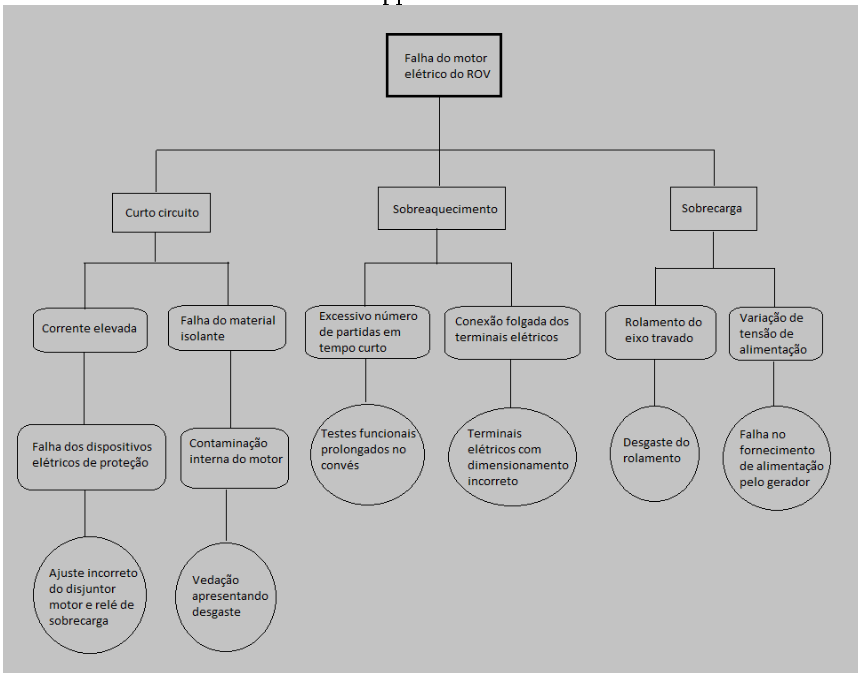
FIGURE 2 – Fault tree applied to the ROV handler.



Source: The authors (2022).

The FMEA and FTA tools were also applied to the EHPU of the ROV, as can be seen in Annex B. It was concluded that the failure mode with the highest NPR was the short circuit caused in the electric motor and due to its severity for operation and occurrence, triggered this high risk index.

FIGURE 3 – Fault tree applied to the ROV electric motor.



Source: The authors (2022).

According to Figure 3, it is concluded that the root cause was the incorrect adjustment of the motor circuit breaker and the overload relay that did not work correctly to protect the circuit, in addition to the seal that presented wear, culminating in the internal contamination of the insulating oil of the engine and failure of the insulating material.

To develop the reliability calculations of the system, the MTTF of the manipulator was used as an example, based on the beginning of the maintenance history of table 3 until the last failure presented and the value of the risk function was calculated as 29.2 x 10-5.

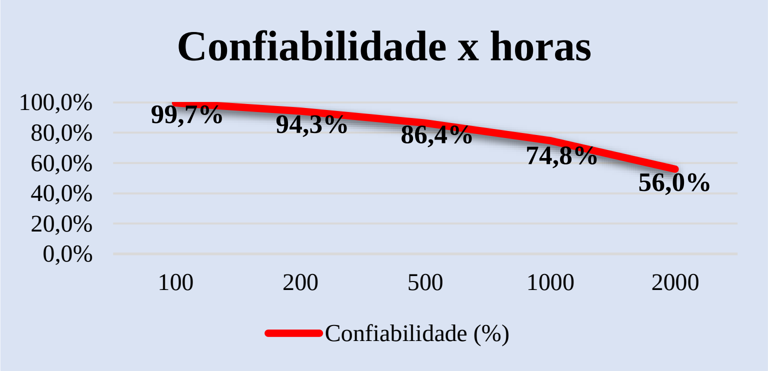
TABLE 3 – MTTF of the history of failures.

Beginning	**Final**	**Time to failure**
17/01/2019	15/02/2019	696:00:00
15/02/2019	26/06/2020	11928:00:00
26/06/2020	14/11/2020	3384:00:00
17/11/2020	29/03/2021	3168:00:00
29/03/2021	14/04/2021	384:00:00
14/04/2021	23/05/2021	936:00:00
25/05/2021	18/10/2021	3504:00:00
TOTAL		**24.000 hours**
MTTF		**3.428 Hours**

Source: The authors (2022).

With the value of the risk function defined, it was possible to estimate the reliability of the manipulator's performance, using suggested time measures. Through the formula for calculating the reliability value R(t) in relation to the operating time, graph 3 is presented.

GRAPH 3 – Reliability x time.



Source: The authors (2022).

5 ANALYSIS OF RESULTS

Graph 3 exemplifies how the actuation reliability of the handler can reduce according to the number of hours, decreasing from a value close to 100% reliability in 100 hours of operation to 56% in 2000 hours. With this estimate the company can plan according to the strategic objectives adopted, how much it is willing to invest to maintain a high level of reliability in the equipment.

During the case study, it was observed that the company follows the preventive maintenance plan suggested by the equipment manufacturer, as well as tasks proposed by its own history. Most maintenance tasks are based on the operating time of the equipment, but it is seen that even with the current plan, there are still operational failures in the system.

6 FINAL CONSIDERATIONS

This work presented the main concepts related to the area of maintenance and subsea robotics, through a case study applied in an ROV system of a company operating in the oil and gas sector.

The application of the quality tools Pareto Diagram, FMEA and FTA and the concept of equipment reliability can be a great differential for the company and of profound contribution to new projects, in addition to allowing the development of strategies to prevent operational failures, but it is necessary managerial effort, investment in technological resources, training and qualification for personnel.

The study showed that with the application of the CCM, it is possible to direct the efforts of the workforce to those components of the ROV that presented the most critical failures.

Thus, all the content produced in this article can serve as a basis for future work focused on the area of subsea equipment, underwater robotics, offshore tools in general and serve as a starting point for improving the maintenance plan of companies operating in the same field.

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ANNEX A – FMEA applied to the ROV handler

FMEA - Análise do Modo de Falhas e Efeitos

Empresa: X

Setor: ROV

Prepar[redacted]ibeiro

Responsável pelo projeto: Engenheiro de manutenção

Item / Função	Modo potencial de Falha	Efeito	Severidade	Causa	Ocorrência	Controles de prevenção	Detecção	Risco(NPR)	Ação	Responsável
Manipulador de 7 funções do ROV	Perda de telemetria	Sem comunicação eletrônica da superfície com o equipamento no fundo do mar	8	Queima do fusível da placa de comunicação	8	Teste funcional	4	256	Verificar peças sobressalentes para troca rápida da placa em caso de queima	Engenheiro de manuntenção/Equipe de bordo
				Sensor inoperante das funções		Teste funcional e limpeza da conexão do sensor			Instensificar inspeção e testes do sensor, para manter histórico de utilização	Equipe de bordo
				Baixa isolação nos pinos elétricos		Megagem do cabo e teste de continuidade			Realizar constantemte medição de resistência entre condutores e continuidade	Equipe de bordo
				Desgaste excessivo do cabo	8	Inspeção no conector e na capa externa do cabo.	3	192	Intensificar checagem, teste funcional e troca preventiva	Equipe de bordo
	Sistema hidráulico danificado	Sem movimentos do manipulador	9	Válvula proporcional da função inoperante	7	Teste funcional	2	126	Reduzir periodicidade para retirada e limpeza das válvulas propocionais.	Engenheiro de manuntenção
				Vazamento no cilindro		Teste funcional e inspeção diária			Verificar novos fornecedores de retentor	Engenheiro de manuntenção
			9	Óleo contaminado	6	Inspeção e retirada de amostra	2	108	Retirar e enviar amostras do óleo para análise em laboratório. Realizar a troca preventivamente do óleo e filtro.	Equipe de bordo/Engenheiro de manuntenção

ANNEX B – FMEA applied to the electric motor of the ROV

FMEA - Análise do Modo de Falhas e Efeitos										
Empresa: X										
Setor: ROV										
Prepar[redacted]										
Responsável pelo projeto: Engenheiro de manutenção										
Item / Função	**Modo potencial de Falha**	**Efeito**	**Severidade**	**Causa**	**Ocorrência**	**Controles de prevenção**	**Detecção**	**Risco(NPR)**	**Ação**	**Responsável**
Motor elétrico do ROV	Curto circuito	Não fornece energia suficiente para componentes hidráulicos	10	Curto entre fases do enrolamento trifásico	6	Megagem dos motores de acordo com plano de manutenção	4	240	Implementar sistema de manuntenção preditiva no circuito do motor elétrico, como medidor de corrente e resistência entre fases	Engenheiro de manuntenção
				Contaminação interna do motor		Coletar amostras de óleo do motor			Enviar amostras coletas para serem analisadas em laboratório	Equipe de bordo
				Falha do material isolante		Realizar troca do óleo isolante do motor			Reduzir a periodicidade de troca do óleo isolante do motor	Engenheiro de manuntenção
			10	Falha dos dispositivoes de proteção do circuito elétrico	7	Checagem e teste dos dispositvos de proteção	3	210	Intensificar checagem e teste dos dispositivos de proteção	Equipe de bordo
	Sobreaquecimento	Circuito de proteção não permite a partida	8	Excessivo número de partidas em tempo curto	6	Planejar teste funcional par reduir o número de partidas do motor	3	144	Implementar novo procedimento para teste funcional no convés	Engenheiro de manuntenção
				Conexão folgada dos terminais elétricos		Manutenção preventiva			Implementar sistema de manuntenção preditiva como medição de temperatura dos condutores	Engenheiro de manuntenção
Fornecer torque para partida do circuito hidráulico	Sem rotação de partida do motor	Motor travado sem rotação inicial	10	Rolamento travado não permite a rotação	6	Teste funcional	3	180	Troca do rolamento de acordo com o tempo de utilização	Equipe de bordo
	Circuito elétrico com conexão incorreta	Rotação invertida do motor, não fornece energia para a bomba hidráulica	8	Falta de procedimento de instalação	6	Elaboração de procedimento de instalação e testes	2	96	Revisão de documentos e procedimentos	Engenheiro de manuntenção
			8	Erro no manual de montagem	6	Revisão de manual	4	192	Treinamento da mão de obra	Setor de treinamentos
			8	Identificação inadequada de fios e conectores	6	Revisão de procedimentos	3	144	Treinamento da mão de obra	Setor de treinamentos