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MODELING DYNAMIC MAINTENANCE PRIORITIES IN WARSHIPS – A DATA DRIVEN APPROACH

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Abstract

This research was developed in the scientific field of Military Sciences with a focus on technologies, or more specifically in Maintenance Management and Data Management of naval military ship equipment. The proposed theme of the thesis is *Modelling dynamic maintenance priorities in warships – a data driven approach*. This research presents: the object and objectives of the study, the justification of the topic under investigation, a state of the art on applied theories, methods and methodologies that can be applied in achieving the objectives of the thesis. This thesis aimed to develop a methodology that brings together several data sources, the FMECA, specifically modified to integrate equipment condition monitoring data and the threat state, FMECA-H-CM, which serves as a decision support system for maintenance on military ships. Within the scope of the conception and development of this concept, the database structure that feeds the FMECA-H-CM and factors related to cybersecurity were taken into consideration. With the results of the FMECA-H-CM, it was possible to improve its performance using the contribution of other experts, humanizing the responses to the method. Finally, a method and a software language were developed to demonstrate the possibility of defining automatically the risk, the priority of maintenance activities for a diesel propulsion engine and also give options of maintenance. On that way it is suggested whether it is appropriate to perform maintenance activities on other equipment related to the first if its condition determines it and this is the final option taken by maintenance managers. With the developed methodology, it may be feasible to decide on ship missions based on risk, so that decision-making bodies know the performance status of equipment and systems, indirectly revealing the degree of success of a mission on military ships.

Keywords: Dynamic Maintenance, FMECA, Condition monitoring, Data Management, Priority, Warships.

Resumo

A presente investigação foi desenvolvida no âmbito científico das Ciências Militares com foco nas tecnologias, ou mais especificamente na área de Gestão da Manutenção e Gestão de Dados de equipamentos de navios militares navais. O tema proposto da tese é Modelling dynamic maintenance priorities in warships – a data driven approach. Nesta investigação são apresentados: o objeto e objetivos do estudo, a justificação do tema sob investigação, uma pesquisa sobre o estado da arte e teorias aplicadas, métodos e metodologias passíveis de serem aplicadas na concretização dos objetivos da tese. Esta tese teve como objetivo o desenvolvimento de uma metodologia congregadora de várias fontes de dados, a FMECA, especificamente modificada para integrar os dados de controlo de condição de equipamentos e ainda o estado de ameaça, FMECA-H-CM, que sirva como um sistema de apoio à decisão sobre manutenção em navios militares. No âmbito da conceção e desenvolvimento deste conceito foi tido em conta a estrutura da base de dados que alimenta a FMECA-H-CM e ainda fatores relacionados com a cibersegurança. Com os resultados do FMECA-H-CM foi possível melhorar a sua performance utilizando o contributo de outros peritos, humanizando as respostas ao método. Por fim foi desenvolvido um método e linguagem de software de forma a demonstrar a possibilidade de definir automaticamente o nível de risco e a prioridade sobre as atividades de manutenção de um motor diesel propulsor, onde são igualmente dadas opções de ações sobre a manutenção. Neste sentido é ainda sugerido se é oportuno realizar atividades de manutenção de outros equipamentos relacionado com o primeiro, caso a sua condição o determine e seja essa a opção final tomada pelos gestores da manutenção. Com a metodologia desenvolvida pode ser viável a decisão sobre missões dos navios baseada no risco, de forma aos órgãos decisores conhecerem o estado de performance dos equipamentos e sistemas, sendo revelado indiretamente o grau de sucesso de uma missão nos navios militares.

Palavras-chave: Manutenção Dinâmica, FMECA, Monitorização da Condição, Gestão Dados, Priorização, Navios de Guerra.

List of abbreviations, acronyms and symbols

Abbreviations/Acronym	**Meaning**
AA	- Arsenal do Alfeite
AI	- Artificial intelligence
AIS	- Automation identification system
ANN	- Artificial neural network
AR	- Auto-regressive
ARIMA	- Auto-regressive integrated Moving Average
ARL	- Average run length
ARMA	- Mix of AR e MAd
BT	- Blockchain technology
CARM	- Planned maintenance card (*carta de manutenção*)
CBM	- Condition based maintenance
CDB	- Consolidated database
CINAV	- Naval Center Research (*Centro de Investigação Naval*)
CL	- Center line
CMa	- Maintenance cycle
CMMS	- Computerized maintenance management system
CMV	- Condition monitoring - vibrations
CMP	- Condition Monitoring - Parameters
CMT	- Condition monitoring - thermography
CMText	- Condition monitoring - text
CN	- Naval Command (*Comando Naval*)
CNN	- Convolutional neural network
CODOG	- Combined diesel or gas
CSMP	- Current ship´s maintenance project
DA	- Supply Direction (*Direção de Abastecimento*)
DatN	- Necessity date (*Data da necessidade*)
DB	- Database
DBMS	- Database management system
DN	- Ship Technical Directorate (*Direção de Navios*)
DNN	- Deep neural networks
DOD	- Department Of Defense
DSM58	- Requests and reports about interventions document
DSM59	- Functioning hours, marine gasoil and oil consumption document
DSM60	- Spare parts request document
DSS	- Decision support system
Electro pump	- Electrical pump
EMA	- Armed General Staff (*Estado Maior da Armada*)
EN	- European norm
ENS	- Surface Ship Squadron (*Esquadrilha de Navios de Superfície*)
FaC	- Fragility and criticality
FMEA	- Failure mode and effects analysis
FMECA	- Failure mode, effects and critically analysis
FMECA-H	- Failure mode, effects and critically analysis - humanized

FMECA-H-CM	- Failure mode, effects and critically analysis-humanized - condition monitoring
FN	- False negative
FuN	- Functional number
GR	- Extended (big) revision (*grande revisão*)
FP	- False positive
GFS	- Google File System
HAUIM	- High average-utility itemset mining
ID	- Intervention Description
LCL	- Lower control limit
MD	- Diesel propulsion engine (DPE, *motor diesel*, main diesel)
MDP	- Markov decision process
MLGF	- Multilevel grid file
MLPNN	- Multi-layer perceptron neural network
MMHS	- Military messaging handling systems
NATO	- North Atlantic Treaty Organization
NI	- Not identified
NN	- Neural network
NNA	- National supply number (*Número nacional de abastecimento*)
NDT	- Non-destructive testing
PCA	- Principal component analysis
PCT	- Principal component thermography
PLAMANCURT	- Maintenance plan of short duration (*plano de manutenção de curta duração*)
PLAMANLONG	- Maintenance plan of long duration (*plano de manutenção de longa duração*)
PROGMAN	- Maintenance progman (*programa de manutenção*)
PR	- Small revisions (*pequena revisão*)
PS	- Port side (*bombordo* – BB)
Q	- Kerenage (querenagem)
RA	- Assisted revision (*revisão assistida*)
RAM	- Reliability, availability and maintainability
RI	- Intermediary revision (*revisão intermédia*)
RMS	- Root Mean Square
RPM	- Revolutions per minute (*rotações por minuto*)
SB	- Starboard (*estibordo* – EB)
SGM	- Maintenance management system (*Sistema de Gestão da Manutenção*)
SLI	- Integrated logistic system (*sistema logístico integrado*)
SIL	- Shipyard intervention list (*lista de fabricos*)
SM	- Materials Superintendency (*Superitendência do Material*)
SMP	- Planned maintenance system (*sistema de manutenção planeada*)
SoE	- State of the equipment
SQL	- Structure query language
SRTD	- Data collection and treatment system (*sistema de recolha e tratamento de dados*)

SVD	- Singular value decomposition
TFH	- Total functioning hour
TM	- Maintenance type (*tipo de manutenção*)
TN	- True negative
TP	- True positive
TPOT	- Tree pipeline optimization tool
TS	- Threat status
UC	- Unit code
UCL	- Upper control limit
WWW	- World web sites

1. Introduction

1.1. Framework and justification of the topic

In Maintenance terms, when the topic of performance and quality is addressed, there is a set of relevant questions that are the object of investigation, such as: Should the implemented maintenance be preventive or corrective? Which equipment's can be under maintenance? When to do maintenance activities? How to do the maintenance process? What is the most adequate decision model for deciding maintenance?

Given a complex system, the respective temporal sustainability is expressed by the absence of catastrophic failures/breakdowns that imply operational risks, for people or of an economic nature, that cause the respective credibility to be lost. For this, the operation of a maintenance system is required, which is associated with a monitoring system that collects data regarding events relevant to decision-making and that, in general, aim at the detection, identification, characterization and follow-up of deterioration/damage processes before they translate into catastrophic breakdowns. In the more specific scope of complex military systems such as a ship or military industrial installations, the context is characterized by great complexity of the systems, generation of large masses of observational data through sensor networks (Big Data) of very high dimension in which it concerns the data. Many frequent situations are characterized by insufficient data, requiring adequate inference techniques, such as those of a Bayesian nature. Some research work in maintenance highlights the relevance of the application to the field of monitoring associated with conditional maintenance, namely in the military environment. Some of these works will be referred to in the preliminary literature review chapter of this thesis project.

The development of methodologies for monitoring and processing data to study possible systems failure processes, so that timely decision-making is possible, avoiding or limit the consequences of catastrophic failures, can be the solution for the elimination of unexpected failures and breakdowns in ships' electromechanical systems, increasing their lifetime and operational availability. In the present investigation, historic, procedures and continuous flow of data produced by sensors will be observed - including human perception of a possible failure due to non-compliance of a pre-defined maintenance action, to carry out a continuous assessment of the risk of potential damage as well as the consequences and effects of decisions (causality) made on Portuguese Navy ship equipment, as well as maintenance records. With the observation and processing of these data, through the development, application, and simulation of an integrative model, it is intended to obtain suggestions for decision-making and prioritization of maintenance interventions in ship equipment´s. In the present investigation, the main objective is the development of a maintenance methodology based on data of planned maintenance system, maintenance and operation parameters database, condition monitoring and the threat analysis applied to warship, where the decision to intervene on equipment is based on quantitative methodologies.

The central problem of the investigation is the need to optimize maintenance with the objective of reducing costs and optimizing Navy resources. To achieve this goal, an improvement in data collection, storage and processing methods through statistical techniques will be proposed. Based on these, the mode for deciding on the maintenance to be carried out will be further developed. And it is intended to contribute to the improvement of monitoring methodologies and maintenance methods in a Naval Military environment.

The theme of the thesis is: "Modelling dynamic maintenance priorities in warships - a data driven approach", and in Portuguese: "*Modelação de prioridades de manutenção dinâmica em navios de guerra - uma abordagem baseada em dados*".

1.2. Object of study and its delimitation

The object of study of the proposed thesis is the development of methodologies for processing data from Navy ships that can be a way to obtain a decision support system (DSS), considering the implemented planned maintenance system (SMP), the severity of it on the security/ environment/ equipment/ personnel / operations, the frequency of the occurrence, the ease of detection and the condition monitoring variables (for example: vibration measure, thermodynamic parameters, analysis of text in DSM58), and also the threat level environment. The suitability of alternative database management systems that guarantee the necessary flexibility in an environment in constant and rapid change on equipment state will be investigated and evaluated from the standpoint of the DSS, and the dynamic management of maintenance. Evaluate the adequacy of Database Management Systems (DB) performing integrated data simulation, observing the data flow and its interactions will be made with the application of Failure Mode, Effects and

Critically Analysis (FMECA), to define the prioritization of the systems intervention. In this investigation, the main objective will be the development of methodologies for equipment monitoring and processing its data to obtain a DSS in the execution of maintenance actions on warships, also evaluating the associated risk of not performing preventive, predictive and condition maintenance. For this, it is necessary to identify, evaluate, plan, and control the execution, considering the necessary resources, for implementing a Failure Mode and Effects Analysis (FMEA) system and finally including it on a Critical Analysis, FMECA.

1.3. Specific research objectives

The specific objectives are as follows:

a. Development of a maintenance database covering preventive maintenance needs complemented with condition monitoring of equipment and the threat environment.

b. Develop a methodology to supply online information about equipment and systems state and prioritize maintenance its interventions, evaluating the opportunity of maintenance of others equipment´s.

These specific objectives should make it possible to generate, at each moment, the inventory of maintenance needs already identified and quantified from the point of view of the effects on availability, risks and immobilizations and operational limitations that their execution implies, as well as the prioritization of execution.

1.4. The problem and the central question

The central problem of this investigation is the inexistence of a data analytics system associated to maintenance data collection and processing system in the Portuguese Navy, related to surface ships, which may configure a dynamic decision support system with prioritization of interventions. For this it is necessary to evaluate new DB models that allow greater flexibility and easy and quick establishment of multiple relationships between involved entities as well as the incorporation of data types such as images (e.g.: thermography), measurement records such as vibrations, digital photography and text without limitations. The specific problems that make up and drive the topic to be investigated are as follows:

a. Scarcity of material resources;
b. Personal shortage and instability;
c. Imperative ship missions;
d. Very specific naval resources;
e. Scarcity of financial resources;
f. Bureaucratic burden;
g. Partner shipyard with difficulties in human and financial resources.

Given the framework of the thesis and the problem that gave rise to the inspiration for this thesis, the following central question is proposed: "Can a dynamic maintenance system manage intervention priorities in Portuguese Navy ships?"

Derived questions:

QD1: Can a dynamic maintenance system be an asset in the operational management of military ships?

QD3: How to develop the system for prioritizing interventions in a maintenance system?

QD3: What are the variables to consider in the decision support system algorithm for ship maintenance?

1.5. Research methodology

The methodology to be followed in this research will be action-research (Fonseca, 2012) in the sense that it intends to contribute to the improvement of the maintenance system implemented in Portuguese Navy surface ships, identifying a problem and contributing to its future resolution, to try to minimize the impact of the lack of material and human resources. During the development of the investigation, maintenance data on Portuguese Navy ships will be collected and analysed to develop thinking and methodology for monitoring, forecasting anomalies and prioritizing interventions. Thus, it is intended to evaluate maintenance processes quantitative and qualitative data to be studied using statistical modelling methodologies, leading eventually to an artificial intelligence system to support decisions. With the collection of quantitative data and the application of statistical methodologies, several hypotheses will be formulated, which will be analysed to create algorithms to support the decision support system, contributing to the creation of dynamic manufacturing lists. As steps in the investigation (Figure 1) the following is proposed:

- Collection of SMP data from the ship 3;
- Collection of data from selected equipment's, and how the data is being processed at the Ship Technical Direction (DN);
- Choice of variables and information to be monitored;
- Construction of a database and definition of its structure;
- Comparison of acquired data, simulations;
- Develop a Failure Mode and Effects Analysis based on Planned Maintenance System (SMP);
- Creation of a Failure Mode, Effects and Critically Analysis to build decision making model;
- Test the developed FMECA model;
- Development of a dynamic model that relates SMP data, condition monitoring data, data from existing database, threat environment and the relation between them (Figure 2);
- Analysis and conclusions;
- Proposal for future work.

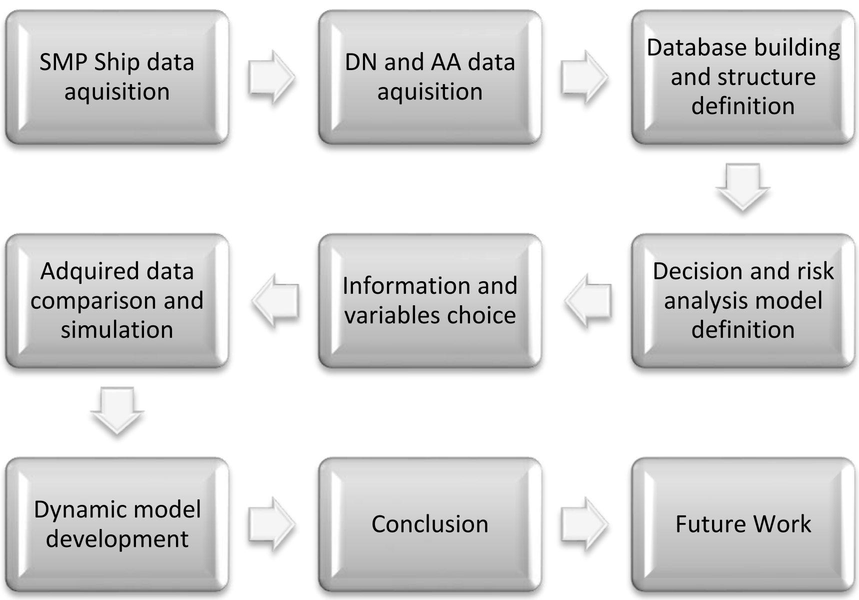


Figure 1 - Steps of research

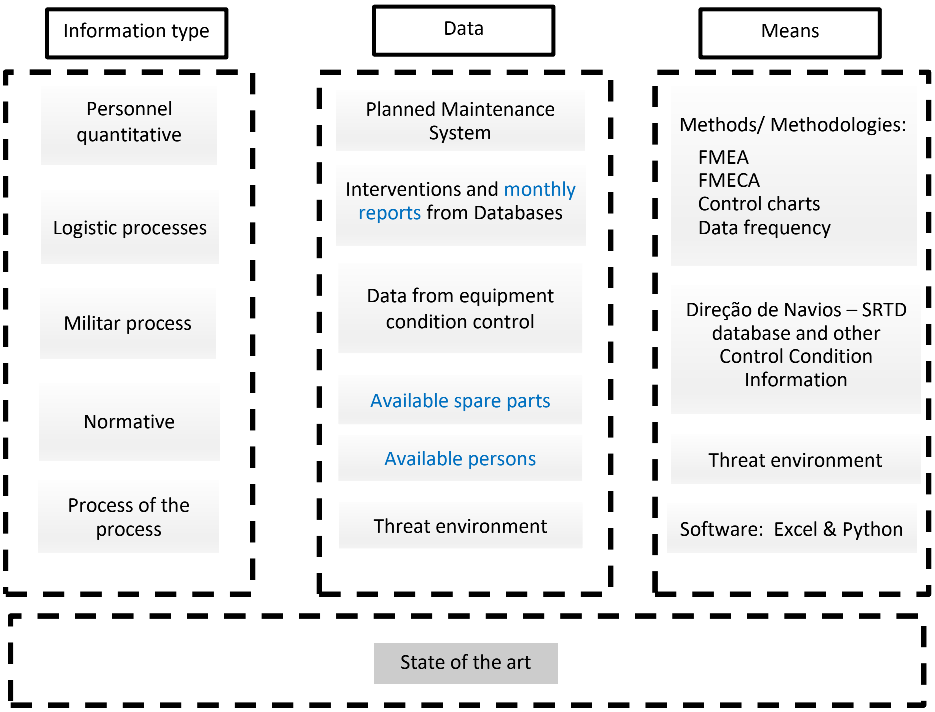


Figure 2 - Information type, data and means used in the present investigation

For reasons of limiting study only the information from SMP, Requests and reported maintenance interventions on SRTD, data from condition monitoring and threat state was used for modelling the proposed decision model.

The research design proposal, where the basic information of research work is summarized, is presented in Table 68 of Appendix A. In terms of timing in Table 69, also on Appendix A, can be observed the 5 years of thesis work, presenting the milestones and the report balance considering the various task to accomplish this research.

Figure 2 presents some of the data, processes and means that are intended to be used during this investigation in the field of Military Science Technologies. In this way, the maintenance processes that are in force relating to the following sub-processes are analysed: Personnel involved in maintenance, the logistical and economic processes, the military conjecture linked to naval military maintenance, the regulations, the process of the process itself. The data will be collected from the SRTD implemented on surface ships, from existing databases on DN (in terms of maintenance itself, personnel involved and costs). As a method, it is intended to use Failure Mode, Effects and Critically Analysis, considering also measures from sensors and threat environment, defining a methodology with various integrated methods and software, using excel, Python and the platform of Google Colab, to prove the functionality of the developed methodology.

1.6. Thesis organization

The thesis is organized in seven Chapters, Chapter 1 is the introduction then on Chapter 2 and Chapter 3 are made respectively a state of art considering maintenance management and data from databases, chapter 4 is where the methodologies and methods for data analysis are presented. On Chapter 5 it is where is presented the equipment´s on study and is presented the condition monitoring data and the database structure. On Chapter 6 it is applied FMEA and FMECA to the various equipment´s and system´s and presented some extracts of the developed software language and it is made an analysis of results. On Chapter 7 is presented the conclusions including research limitations, recommendations and future studies. Following the Chapters there is the bibliographic references, 1 Annex which has the scientific work developed by the author along the last 5 years. And finally, the 3 Appendix´s, where Appendix A has the research design and work chronology along the 5 years, Appendix B with data from SRTD and Appendix C with the results of FMECA-H-CM for each equipment.

The detailed thesis organization are as follows:

Cap. 1 – Introduction

- 1.1 Framework and justification of the topic
- 1.2 Object of study and its delimitation
- 1.3 Specific research objectives
- 1.4 The problem and the central question
- 1.5 Research methodology
- 1.6 Thesis organization

Cap. 2 - Maintenance management

- 2.1 Chapter introduction
- 2.2 Condition based maintenance
  - 2.2.1. Vibration measure and analysing
  - 2.2.2. Condition monitoring based in thermodynamic parameters
  - 2.2.3. Thermography measure and analyse
    - 2.2.3.1. Principal Component in Thermography
    - 2.2.3.2. Neural network in thermography
  - 2.2.4. Condition monitoring based in text
- 2.3. Maintenance management in military environment & others

2. Maintenance management

2.1. Chapter introduction

Maintenance in EN13306:2021 is described as "all activities of the management that determine the maintenance requirements, objectives. strategies and responsibilities, and implementation of them by such means as maintenance planning, maintenance control, and the improvement of maintenance activities and economics maintenance objectives" (EN, 2021).

The maintenance can be preventive or corrective, Figure 3. The preventive maintenance can be scheduled based on data, systematic or by demand. The corrective maintenance can be deferred or immediate (EN, 2021).

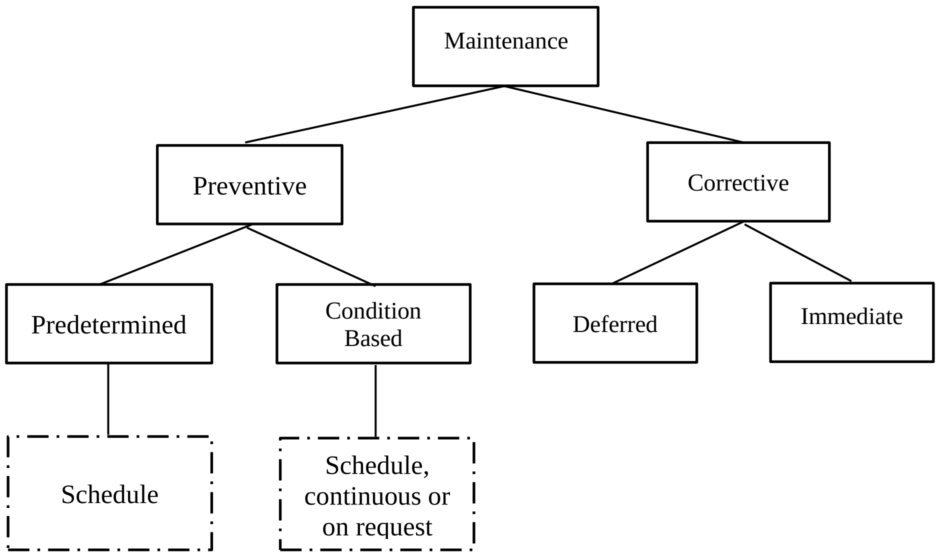


Figure 3 - Types of maintenance

Source: adapted from EN13306 (2021)

Other organizations and standardization organizations, National or International, may present similar concepts of maintenance management, further the attention will be centred on Portuguese Navy maintenance concepts.

Maintenance Systems in Portuguese Navy has been originally inspired in the 3M concept of the USA Navy (DOD, 2021). Nowadays it is believed there is space for enhancement of the implemented system allowing equipment condition and data decision based maintenance.

On Machine Learning area, although not specifically applied on the present research, the steps of the method can be framed on it, considering decisions support based on the steps of applying data-driven (MIT, 2021). To procced the present research the obtained data was perceived, then using a selected algorithm it was tried to predict future, defined actions to be taken, analysed results, identified potential errors, defined the principles and defined an application system considering continuous improvement and better decision-making in the future, Figure 4 (MIT, 2021).

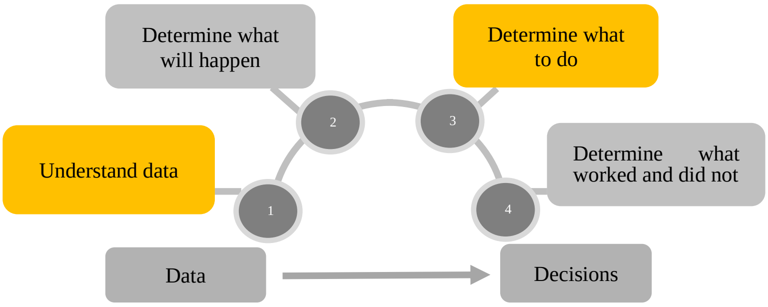


Figure 4 - Steps of machine learning

Source: adapted from MIT (2021)

To determine future outcomes, predictive analyses can be performed using classification techniques, regression models, artificial neural networks or other data-driven methodologies. Decision-making should be supported by data and may need to be carried out under conditions of uncertainty.

For a better understanding of maintenance requirements, it is important to identify variables that can be collected from equipment in a consistent and repetitive manner, such as temperature, oil analysis, pressure measurements, vibration levels. However, defining the most appropriate database structure and configuration is often a challenging task.

During the development of a pilot maintenance system, the database requirements may not be fully understood. In many cases, only after analysing the behaviour of the collected data through mathematical or statistical methods is it possible to develop algorithms capable of integrating multivariate data and support maintenance decision-making. Consequently, the selection of the programming environment and the design of the database architecture frequently become clear as the system development progresses and the relation between variables are better understood.

In this chapter will be presented some parameters and methods that may be used to determine a performance condition of an equipment or system, considering vibration measure and analysing, thermography, parameters like oil pressure and temperature, and finally use some registered text to evaluate the system state. Then will be present some state of the art of maintenance management in military environment, the maintenance that is applied in Portuguese Navy Surface Ships. And finally, the subchapter that present intelligent and dynamic maintenance which will refer the methodology bases that inspire the development of the present proposed methodology and that allows to integrate, not only a FMEA data, but also condition monitoring data.

2.2. Condition based maintenance

Condition based maintenance (CBM) is a type of preventive maintenance. In this maintenance the equipment intervention is decided based on data collected usually from non-destructive analysis like sensors measures, observation, fluids analysis and others (Li et al., 2020).

A procedure for implement CBM can be choosing the equipment for monitoring, use its sensors, processing signal, do the condition monitoring, made the diagnosis, the prognosis, acquire knowledge from the previous information and finally proceed to the maintenance considering reparation or replacement, Figure 5 (Shin & Jun, 2015).

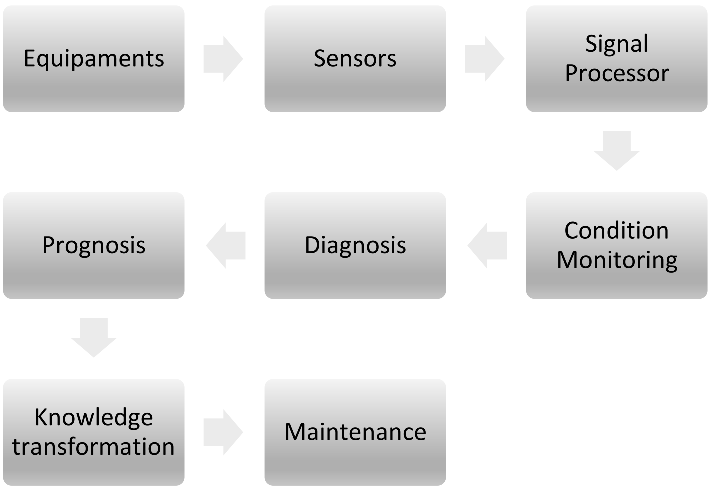


Figure 5 - Procedure for CBM approach
Source: adapted from Shin & Jun (2015).

A difficulty on Condition Based Maintenance is an equipment diagnosis and health prediction based in data (Shin & Jun, 2015). The data will be the base to define when to proceed to a maintenance action before an unexpected anomaly occur, so the chosen sensors value to study should be representative of equipment performance (Shin & Jun, 2015).

In a CBM a failure prediction approach based in data and dedicated algorithms should be integrated in a database system (Ali & Abdelhadi, 2022). The failure algorithm steps may be, for example, an onboard monitoring system, then the condition indicators should be defined, identify, and refine the failure data, then find the failure modes and deterioration and finally develop the algorithms for each failure mode to predict remaining life, Figure 6 (Ali & Abdelhadi, 2022).

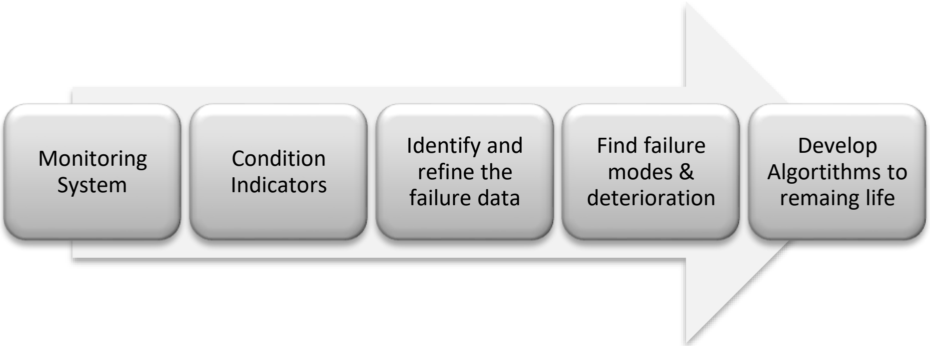


Figure 6 - Failure algorithm steps

Source: adapted from Ali & Abdelhadi (2022)

Advantages of CMB may be (Dong et al., 2019):

- The equipment state can be continuously monitored;
- Prevents some equipment unexpected anomalies;
- Maintenance is more predictable;
- Extend the equipment functionality knowing eventual consequences;
- Plan the maintenance.

Some disadvantages of CBM can be (Sakib & Wuest, 2018):

- Initial investment is higher;
- The benefits are only patent further in time;
- Bad maintenance schedule if data is not trustworthy.

Nowadays, for condition based maintenance is being considering not only the data from equipment but also the data of "multi-component multi-sensor systems, in light of global optimization functions and the analysis of humans and machine interactions in a progressively more digitalized era" (Quatrini et al., 2020).

In CBM many non-destructive tests may be applied. In this scope we can consider the visual observations (e.g.: visual exam, dimension control, borescope), the electromagnetic tests (e.g.: "Eddy Current" tests, magnetic particles tests, magnetic fields anomalies, electric field anomaly, magnetic resonance), penetrating radiation tests (e.g.: X-ray, gamma-ray, neutron radiography), dye penetrate, fluid analysis, ultrasonic, thermography exams and vibration measure and analysis. Only observation, data treatment, vibration and thermography will be used in this investigation (Dwivedi et al., 2018; Nepomuceno, 1985).

2.2.1. Vibration measurement and analysing

The mechanical equipment during the continuous technological development is becoming more complex (Xu et al., 2018).

Vibration measures have been being a base for rotating equipment health diagnosis. rotating machine has a natural vibration frequency, if a disturbance in its functioning occurs, its health can be expressed by its vibration frequency signature measured by sensors (Ghazali & Rahiman, 2021).

As a non-destructive technique measuring and analysing vibration can allow preventive intervention and knowing the rotating equipment state. The main advantages of this technique are anomaly detection without disassembly and stop the equipment, early anomaly detection, diagnosis the anomaly cause, and global maintenance long-term costs reduction (Villarroel, 2019).

The vibration sensors positioning can be permanent or temporary, measure with fixed or portable equipment’s, and the measures should be taken periodically as defined by the fabricant or by the equipment maintenance responsible (Lampreia, 2013).

In vibration collected data, we can analyse the frequency, or for an overall and immediate result observe the Root Mean Square (RMS) results, which allow the anomaly detection. The RMS can be calculated by (Zainal, 2020; Lampreia, 2013):

$$x_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{i=N} x_i^2} \quad (1)$$

Analysing frequencies

For anomaly causes the detailed frequency Spectre should be analysed. But before detail the abnormal frequencies the equipment characteristics frequencies should be referred.

The rotating equipment frequencies spectres characteristics are a product of its components and rotation. A rotating shaft will generate a characteristic frequency at its velocity rotation, Figure 7 (Institute, 2005).

"A vibration FFT (Fast Fourier Transform) spectrum is an incredibly useful tool for machinery vibration analysis. If a machinery problem exists, FFT spectra provide information to help determine the source and cause of the problem and, with trending, how long until the problem becomes critical" (Mais, 2002).

The abnormal characteristic frequencies can be misalignment, unbalance, mechanical looseness, bent shaft, rolling element bearing defects, gears, blades and vanes causes and electrical problems (Mais, 2002). On the present research only the RMS values will be used, for more details about type of probable anomaly it should be consulted other bibliography, for example Mais (2002), Campanie (2019) and Lampreia (2013).

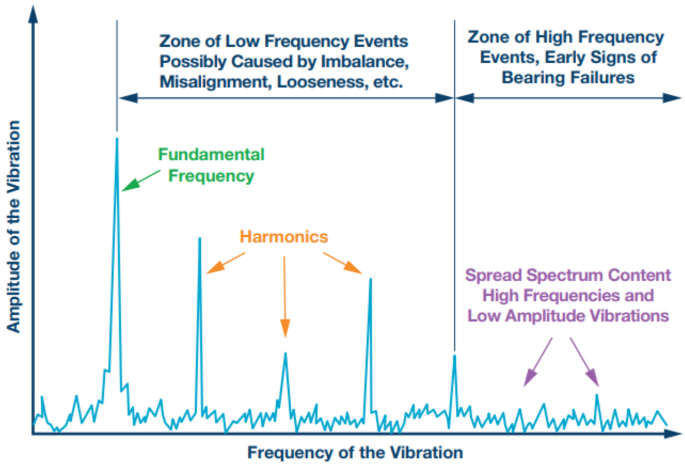


Figure 7 - Typical spectre signatures

Source: Campagnie (2019) & Institute (2005)

Vibration analysis is a complex technique in equipment anomaly detection and diagnosis, but for reasons of study limitation and because of the data dynamic intended to use in this investigation, this is the development decided to present.

Usually in the organization where the study was made the vibrations are collected offline, and the collected data are treated *à posteriori*, represent an exception the gas turbine propulsion systems. The decision to maintenance intervention is made with complementary non-destructive tests, but no computer algorithm is applied to data, only human sense and vibration normative.

To contribute for the decision-making in the model that will be define in this investigation, vibration measures will be used to feed the database.

Because on this investigation only RMS values will be considered, only if vibration is, or not in normal level will be considered.

2.2.2. Condition monitoring based in thermodynamic Parameters

For another data, in this investigation was considered oil pressure and temperature which both were included in the database.

For condition monitoring in complex systems various variables like bearing temperature, pressure of various fluids, vibration and others may be used to support equipment state (Long et al., 2020).

To predict the failure type, control charts may be applied in various parameters like noise, vibration and temperature (Shbool & Alanazi, 2023).

Condition based maintenance support on temperature may be a system for monitoring Wind Turbines, considering a data-driven modelling (Baboli, 2021).

Gearbox temperature monitoring may be an approach for detecting a possible failure, it can be “an alternative to vibrational or acoustic health monitoring” (Touret et al., 2018).

Thermodynamic parameters with or not statistical treatment has been used to control the functioning of equipment´s for guarantee it does the work it is design for, but also to maintain a good performance and for maintaining its good state.

2.2.3. Thermography measurement and analyse

Thermography is a condition based maintenance technique used to analyse the temperature distribution on equipment’s and electrical box, etc. Considering standards normative, if an abnormal temperature is detected probably an anomaly exists (Gazzar & Hashim, 2018).

This is a technique that if allied to other non-destructive condition analysis techniques, like measuring and analysing vibrations, can enhance the performance of predictive maintenance (Gazzar & Hashim, 2018).

Thermography has advantages in the detection of possible causes of failures such as overheating, overload, high energy consumption, failure of thermal insulation that can be representative of misalignment on an electro pump (electrical pump) that represents higher temperature in coupling, high temperature in an electrical box may represented by unscrewed screws blocked heat exchangers, low insulation resistance in electric motors, Current/voltage imbalance between phases or other (Aroeira, 2019).

There are two ways for measuring temperature, the quantitative and the qualitative. For one, the temperature of the objects is taken, the other the temperature are measured in an object hotspot and then is compared with other temperature of the objects in the same conditions (Taib et al., 2012). Some limits considered for equipment's are represented in Table 1.

Table 1 - Standard of thermography inspection

Standard of Thermography Inspection					
Max. Temp.\Differential Temp.	**<5ºC**	**5ºC-10ºC**	**11ºC-20ºC**	**21ºC-40ºC**	**>40ºC**
<75ºC	**Normal**	**Low**	**Medium**	**High**	**Critical**
75ºC-100ºC	**Information of overloading**	**Medium**	**High**	**Critical**	**Critical**
>100ºC	**Information of high overloading**	**Critical**	**Critical**	**Critical**	**Critical**

Source: adapted from Paiva et al. (2019) & Maulana et al. (2014)

These limits can be different for each kind of equipment. With the infrared thermography besides the systems temperatures, we can observe which are the higher temperature region and eventual discriminate the cause (Bagavathiappan et al., 2013). At Figure 8 image we can see an example of an electrical terminal under abnormal functioning, the Sp2 under normal conditions and the Sp1 with abnormal temperature, for reasons of safety it must be corrected immediately, with terminal grip. The encircle region may represent improper coupling (Marinha_f, 2021).

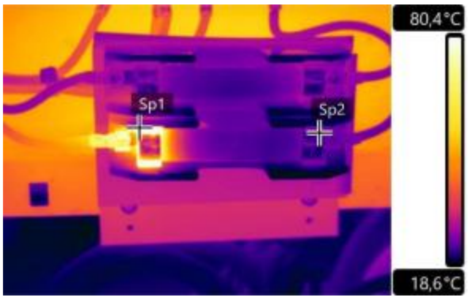


Figure 8 - Standard on thermography

Source: Marinha_f (2021)

2.2.3.1. Principal component in thermography

Using the Principal Component Thermography (PCT) inspired in the statistical Principal Component Analysis (PCA) may be a tool for identified "specific patterns in data sets and analysing data sets in a way which enables depicting similarities and differences of specific patterns occurring in data using statistical modes acquired by decomposing data to singular values" (Milovanovic et al., 2020) considering that the data are various equipment thermography's.

If it is present for analysing a sequence of images, for applying PCT to a thermogram sequence the 3D matrix must be converted to 2D matrix, and each thermogram in the sequence are represented by a Nu.Nv dimensional vector **X**, Equation 2 (Milovanovic et al., 2020):

$$\boldsymbol{X} = [\boldsymbol{x_1}, \boldsymbol{x_2}, \dots, \boldsymbol{x_{N_u \cdot N_v}}] \qquad (2)$$

On Equation 2 "the x_i are the individual pixels of the thermogram arranged one behind the other thus forming a 1D vector" (Milovanovic et al., 2020).

For all other thermograms, N_t, generates a 2D matrix, where each row is one thermogram from the sequence (Milovanovic et al., 2020). In the matrix the columns are the N*t* vectors of individual thermograms (Milovanovic et al., 2020). The resulting matrix are a "raster-like matrix (Milovanovic et al., 2020).

Considering the collected data for the 2D matrix, for normalise data, there are the necessity of mean calculus that then will be subtracted to the initial data (Milovanovic et al., 2020).

The covariance of the normalise data are, Equation 3 (Milovanovic et al., 2020):

$$Cov = \frac{1}{N_t} X X^T \qquad (3)$$

The X matrix integrates the data normalization, and the covariance matrix has $N_u.N_v x N_u.N_v$ dimension (Milovanovic et al., 2020).

The issues with PCT are the data computation "of diagonal matrix and eigenvalues of the 2D raster matrix" (Milovanovic et al., 2020).

The procedure for singular value decomposition (SVD) has the same procedure as in the previous Equations, but the computation is less (Milovanovic et al., 2020).

2.2.3.2. Neural network in thermography

Deep learning may be used in thermography data collection analyses and learning images resulting in new techniques of image treatment (Ramesh, 2017).

A Deep Neural Network (DNN) is built using an artificial neural network (ANN), designed to replicate the structure and function of the human brain. It's made of interconnected nodes (or "neurons") that work together and often link with other types of networks, Figure 9 (Song & Chen, 2022).

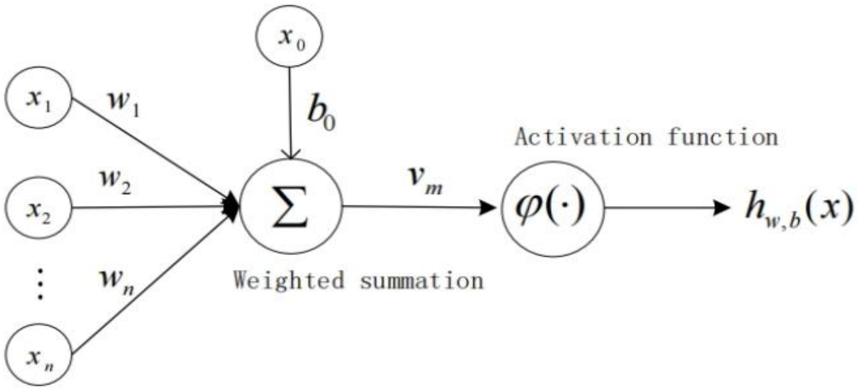


Figure 9 - Neuron structure diagram
Source: adapted from Song & Chen (2022)

At Figure 9 the connection between each received X_i signals is an input signal, the letter x_i multiplied by the weight w_i is traduced as a stimulus for the neuron (Song & Chen, 2022). The neuron structure result on the weighted sum of input signal x_i on the neuron´s synapse, and on the input weighted sum v_m (w_i and b), Equation 4 (Song & Chen, 2022).

$$V_m = \sum_{i=1}^{n} w_i x_i + b_0 \tag{4}$$

This is a proposed method for monitoring and analyse equipment's performance with thermography. Because the lack of registering thermography's on the equipment's understudy, it will not be full developed on this research and will not be included on the calculations with real data. For more information about neural networks the references in the thesis related to this subject, or others, must be consulted.

2.2.4. Condition monitoring based in text

The equipment condition monitoring based on text can use historical data. This method may use data that already exists to determine, or to complement equipment state (Boettcher, 2022). An algorithm that recognizes similarities between data and puts them in a database may be appliable but also programming in a simple language on Python that may be possible.

There are studies using questionnaires to draw up for personnel involved in the maintenance of naval air assets, which were then treated with Bayesian methods to reduce air accidents that statistically in 80% of cases occur due to human error, not only in the conduct of the system but also due to problems related to maintenance (DOD, 2021).

"Naval Aviation Squadron Risk Analysis Predictive Bayesian Network Modelling Using Maintenance Climate Assessment Survey Results" (Robinson, 2014).

Bayesian statistics may be applied in the mapping of automobile engines to control pollutant emissions and operating performance with a view to monitoring combustion and consequently reducing damage due to the probable correction of combustion anomalies in good time (Ward et al., 2002).

Bayesian algorithms are statistical methods that use a theorem to enhance the probability of a hypothesis as more available evidence. Due to the Baye´s theorem performance, to agile uncertainty and allow predictions based on historical data, it is applied in various areas, such as machine learning, statistics, spam filtering, medical diagnostics, pattern recognition, recommendation systems, artificial intelligence (Bernardo & Smith, 2000). For example, in spam filtering, a Bayesian algorithm can classify emails as spam or not spam based on keywords and characteristics of previous emails (Gelman et al., 2013).

$$P(H|E) = P(E|H) * P(H) / P(E) \qquad (5)$$

Bayes' theorem establishes a relationship between the probability of an event and the probability of another related event. It can be expressed in the Equation 5, where P(H|E) is the probability of hypothesis H being true given event E. P(E|H) is the probability of event E occurring given that H is true. P(H) is the initial probability of the hypothesis. And P(E) is the probability of event E occur (Gelman et al., 2013).

Although Bayesian algorithms are recommended by the author, also for reasons of study limitation, it will not be full developed, to complement information the references, in the thesis, and others related to this subject must be consulted for further studies.

2.3. Maintenance management in military environment & others

The factors that influence decisions about maintenance on warships was examined considering the future perspectives of the need to reduce costs and difficulties in scheduling maintenance given the availability of shipyards (Blanton, 1997). A qualitative analysis about life cycle status of surface ships was made in United Kingdom Royal Navy (RN) due to some changes that occurred in the RN (Ford et al., 2015). To reduce investment in the military, the workforce was reduced, and consequently the life cycle and maintenance of ships were affected. Therefore, there was a need for readjustments in maintenance procedures considering the application of risk prediction and analysis methodologies. At an interview with an admiral, Commander of Regional Maintenance for the United States of America (US Navy), he mentioned that maintenance on US Navy surface ships was being modernized considering that it was intended to be implemented a fault prediction system (Lee, 2020). US Navy specialists believe that more companies should be involved in repairing US Navy ships, and that industry and shipyards should rethink military ship construction and maintenance strategies (Eckstein, 2020).

The ship future maintenance strategies should be integrated and planned when project and construction is made, if it is so, maybe the process of future maintenance intervention will be agile and adaptive (Eckstein, 2020).

It was presented by Cullum et al. (2018) a scheme that proposes three steps to carry out a maintenance plan on ships that involve: “Risk Assessment-Condition Monitoring and Machine Learning”, “Maintenance Scheduling-Decision Theory” and “Quantify Availability and Overall Maintenance Cost”. These steps imply periodic condition monitoring of ship systems, which allow updating risk analysis implicit in the action of maintenance and updating the maintenance planning. It was proposed a system that uses the computerized maintenance management system (CMMS) for application in military ships, considering ships in the process of modernization with the implementation of automation and sensors, and the construction of new mean (Dragos et al., 2020). With this system, it is intended to reduce the occurrence of anomalies and increase the availability of equipment by starting to implement maintenance based on the condition and consequently based on data, to the detriment of the systematic preventive maintenance implemented until then.

Also, Drago et al. (2020) propose the application of a CMMS, in which they refer to the need to perform several actions before its implementation, which includes the planning and preparation of software where control attributes must be included and the process for obtaining the Dice. The Portuguese Navy has implemented a data collection and processing system since the 1980s (Marinha_a, 1984), computerized in the 1990s, with software that would come to be called SICALN, first in an MS-DOS environment, and later in an ORACLE environment (available on various operating systems, and via network services). The current maintenance system provides for the requisition of work within the various stages of intervention in the Navy (1st stage, 2nd stage, and 3rd stage), has introduced equipment manuals and the maintenance management system for each class of ships based on in publications such as (Marinha_c, 1998), also integrating the logistics supply chain of spare parts. However, contrary to the initial objectives of the development of the so-called Data Collection and Treatment System (SRTD), there is no systematic statistical treatment of the collected data, which are available for consultation. The Maintenance Cycles of Naval Units and Helicopters (Marinha_b, 1997) are also defined by the Ship Technical Direction of the Navy, in accordance with the technical framework and logistical and financial conjecture, which periodically lead to an update.

Ships must have a record of anomalies to prevent the occurrence of similar damage. In this way, it is also possible to measure the performance of the implemented maintenance and make proposals for improvement in case of need (Alhouli, 2011). Recent research within the scope of CINAV, Escola Naval, shows that certain statistical methodologies can effectively contribute to the implementation of conditional maintenance. This is the case of control charts for univariate and multivariate data (Lampreia et al., 2018), and of multivariate methods of multivariate data analysis, such as Biplots (Vairinhos et al., 2018).

In 2015, two maintenance strategies were presented in the US Navy: one to prioritize maintenance, assuming that not all maintenance can be performed according to the various factors involved, and the second strategy was that maintenance not performed should be reallocated also according to future prioritization. To implement these strategies, decision trees were used. In general, present a concern with the naval maintenance industry, where the Fragility and Criticality (FaC) methodology was used to study the probability of any maintenance capacity being discontinued or not be possible in the shipping industry that ships from the United States of America may have to resort to (Button et al., 2015; Martin et al., 2017).

The maintenance optimization intervals are believed that in the condition monitoring the criteria of maintenance need evaluation should be adapted, for example, in the flight hours of a helicopter should be discriminated against the time it flies over the sea in a saline environment and the time it flies over land. It also suggested the use of the condition based maintenance in substitution of the maintenance based in functioning time (Tinga at al., 2020).

Reliability Centered Maintenance (RCM) arose with the need to optimize passenger air resources, not only to reduce costs, but also to reduce accidents. Nowlan and Heap (1978) refer that RCM carefully follows the answer to some questions: “How does the failure occur?”, “What are its consequences?”, and “What are the benefits of preventive maintenance?". And for answering the last question, it was found that some preventive maintenance that is not guided by condition assessment through non-destructive testing (NDT) does not necessarily lead to improvements in equipment condition, and in some cases may even be a cause of anomalies. To address this limitation, a dynamic latent variable model was proposed for dynamic failure detection, enabling the identification of deviations from normal operating conditions at each stage of the process (Li et al., 2011).

A dynamic latent variable model has been developed, with it was possible to reduce the percentage of uncertainty during the monitoring of an industrial process, reducing detection failures without increasing the number of false alarms Dong and Qin (2020). Latent dynamic variable regression model may be used for data modelling and for monitoring chosen variables (Qin & Zhu, 2017; Zhai & Ye, 2018). A study to calculate the reliability of products in which failure modes are induced to cause their degradation. In this way, it is intended to model and consequently predict possible anomalies in the future.

Multivariate control charts based on principal component analysis (PCA) may be used for variables and quality attributes of a given system, process, or equipment (Ahsan et al., 2018). The efficiency of this type of multivariate chart in monitoring process changes is shown. In this case, it is applied to fault records of a machine where 16 variables and three attributes are considered. The author believed that the continuity of this study can translate how mixing variables and attributes will affect monitoring systems, not only in industry, but also in monitoring human health and in cybersecurity systems.

Latent variable models, latent space models and latent class models may also be used to perform the statistical modelling of dynamic data networks (Kim et al., 2018). These models aim to extract information about the use of networks, whether social statistical information, or to understand how networks work and how to improve them. In the scientific community in general, new forms of data processing are continually being developed, not only numerical data, but also text related to maintenance activities or systems management. In this way, it is demonstrated that this is a current issue and still in development of more and better data management and processing methodologies.

Current Ship´s Maintenance Project (CSMP) has the purpose of "provide unit and activity maintenance managers with a consolidated list of deferred maintenance to identify the material condition of the ship" (DOD, 2021). The USA Navy had developed a Maintenance and Material Management (3-M) program that it is "primarily managed via the CSMP. If its application is correct, it demonstrates the ship condition or its activity.

This brief literature review demonstrates that the international naval military industry is in readjustment to the current situation (strategic, personnel, material and financial conjecture) which demonstrates the military's commitment to continuous improvement and the use of advanced equipment monitoring techniques, as well as the use of data processing methodology to know the state of the means and to support decision-making.

2.4. Maintenance in Portuguese Navy surface ships

In Portuguese Navy, Maintenance is defined as the technical and administrative actions to keep an equipment or system with its initials specifications performance. The Navy, through its technical organ, periodically define the various maintenance stage of the ships, adapting the life cycle accordingly the material specifications, the material state preview, and the logistic system considering the spare parts, manpower and the availability of the shipyard maintenance enterprise (Marinha_b, 1997; Oliveira, 2020).

The basis of Portuguese Navy Maintenance it is called the Maintenance Management System (SGM). The implemented system exists to ensure the availability of all assets and materials, it also defines the procedures, the manpower and it is a maintenance registration system. To accomplish this aims three requisites are necessary: "obtaining acceptable degrees of material reliability; obtaining high coefficients of means availability; achieving the lowest maintenance costs" (Marinha_b, 1997).

In Portuguese Navy it is considered two types of maintenance the preventive and the corrective. The preventive maintenance can be systematic or conditioned. And the corrective maintenance can be current, eventual, urgent or very urgent, Figure 10. This concept it is similar but different from EN13306 which has less divisions in the corrective maintenance (EN, 2021).

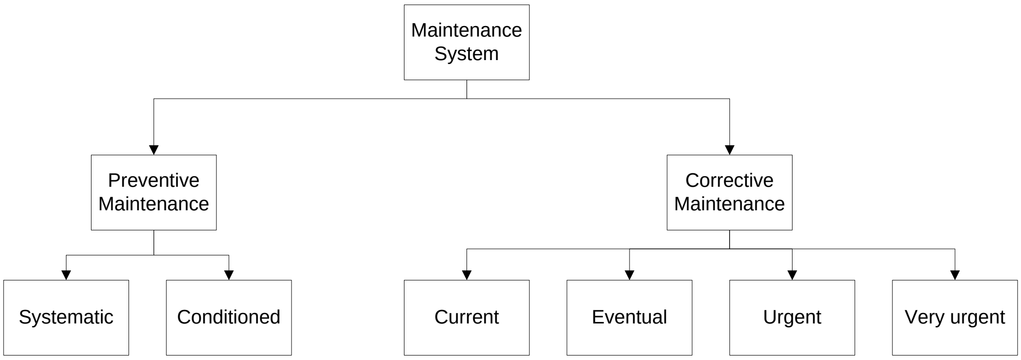


Figure 10 - Portuguese Navy maintenance plan
Source: adapted from Lampreia et al. (2021)

Despite the implemented system, there are difficulties in the organization to carry out maintenance processes, essentially due to the lack of specialized human resources and the continuous budget deficit resulting from the successive economic crises that Portugal went through (Marques, 2020; Oliveira, 2020). In these situations, the maintenance process must continually adapt to assigned missions (Marques, 2020; Oliveira, 2020).

The SGM is part of the Navy's Logistics System and has two subsystems: the Data Collection and Processing System (SRTD) and the Planned Maintenance System (SMP). The SMP has various types of information, such as planning, requirements, associated with preventive maintenance, and the SRTD includes all information regarding corrective maintenance and information about all maintenance that has already been performed.

The SGM is based on four major pillars that, in turn, are interrelated, and they are: execution, information, control and planning (Marques, 2020). Maintenance in the Navy is complex but crucial for the good performance of ships, hence the importance of managing maintenance on equipment and systems.

2.4.1. Portuguese Navy planned maintenance system

Maintenance in the Portuguese Navy has three stages. The ship's crew carries out the first stage. The second stage is carried out by a shore based technical support workshop hierarchically under the Naval Command (CN – *Comando Naval*, which has the ships Operational Command). The third stage is under the responsibility of the Ship Technical Direction (DN-*Direção de Navios*), that determines what work should be done, and if it will be carried out by the navy shipyard (Arsenal do Alfeite SA (AA)) or another company.

The current maintenance plan of the Portuguese Navy, as in international and national normative and even some organizations, is divided into two large groups: preventive maintenance and corrective maintenance, as can be seen in the diagram shown on Figure 10. Despite the maintenance plans of specific ships, the Navy follows as a guide the National and International regulation in its means, aiming to comply with them and to minimize the risk of eventual damage.

The Portuguese Navy Maintenance Management System (SGM - Sistema de Gestão da Manutenção) is part of the Portuguese Navy logistic system (Marinha_a, 1984). This maintenance system is divided in two subsystems, the subsystem where the maintenance data management system implemented on surface ships is called Data Collection and Treatment System (in Portuguese: "*Sistema de Recolha e Tratamento de Dados*" (SRTD)) and the Planned Maintenance System (SMP – *Sistema de Manutenção Planeada*) subsystem which with equipment respective cards describes all the maintenance procedures, the tools, the components, and specialized persons needed for each procedure. SMP even specifies "registering cards" for equipment and system condition monitoring (Marinha_a, 1984).

The Portuguese Navy Helicopters and Submarines have other maintenance management systems. It originates some problems, because the data it is not integrated and for a higher level of decision making process, maintenance data, manpower, spare parts and financial data cannot be observed continuously for a better decision. A single global system should be used considering the particularity of each system. In this research, the focus will be only on surface ships.

Thus, the SRTD is the maintenance database where the Portuguese Navy have the data from the SMP and data which represents documents usually filled by the primary users (members of the ship garrison). The SRTD will be developed in detail on Chapter 3.

2.4.2 Planned maintenance for the ship under study

The maintenance cycle for the ship under study in this document is present on Figure 11.

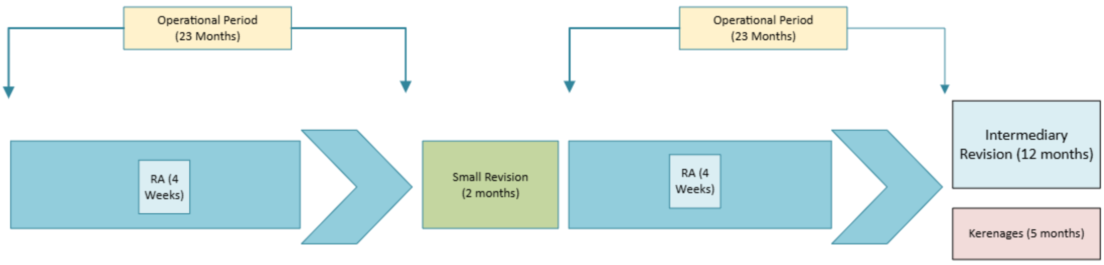


Figure 11 - Maintenance cycle for the ship understudy
Scource: Marinha_f (2020)

The maintenance cycle for these warships is 260 weeks (60 months/5 years) counting from the date of completion of the last major overhaul or intermediate overhaul and the end of the following intermediate overhaul (Marinha_f, 2020).

In Table 2, it can be observed the dedication time for each phase the ship state, the maintenance cycle (CMa) has 260 weeks, the time for an extended (big) revision (GR) is from 78 to 104 weeks, time for intermediary revisions (RI) are 52 weeks, time for small revisions are 10 weeks (PR), for kerenages/docking(Q) are made in simultaneous of intermediary revisions during 22 weeks and usually begins 1 week and a half from the begin of RI. On the operational period is counselled to do two periods of assisted revision, considered the second stage of maintenance (it will be detailed on 3.4 of the present document), for this time it is estimated 8 weeks.

Table 2 - Ship revision

	Week	Months	%
Time for assisted revisions (RA) (note: %=RA/PO)	8	1,8	3,1
Time for small revisions (PR)	10	2	3,8
Time for intermediary revisions (RI)	52	12	20
Time for Extended (Big) Revisions (GR)	78-104	18-24	30-40
Time for operational periods (PO)	198	46	76
Kerenages (Q)	22	5	8,5
Operation Availability for cycle	190	44	73,1
Maintenance cycle	260	60	100

Source: Marinha_f (2020)

These are the main guidelines for the ship maintenance, there are outside orders, and extraordinary missions, place on the curve of the bathtub where the equipment/ship is located that can change the planned maintenance or maintenance cycle. For that contingency that changes it is used the condition monitoring system, although not used, yet an integrated algorithm or Artificial Intelligence system to support the decision.

2.5. Intelligent and dynamic maintenance

Dynamic maintenance is a new flexible, data-driven approach to maintaining complex systems such as warships; this means that the priorities of system maintenance would change with time according to how often they degrade and due also by environmental and operational conditions. Many such tools are leveraged to maximize operational availability and minimize downtime, using predictive algorithms (Kaiser & Gebraeel, 2009) or a failure mode, effects, and criticality analysis approach (FMECA), where this information may be used for spare purchase optimization.

Dynamic maintenance models continuously analyse data streams to estimate the probabilistic failure rates and cascade them through condition-based or predictive management approach - this is more efficient compared with traditional time-infinite policies for repairs (Diamond & Marfatia, 2002; Ben-Daya et al., 2009).

Data from various sources, considering data from sensors and from registered events, may be used to find correlations between data sources, and earlier get knowledge potential failures of equipment’s or systems. This data management for getting responses about the equipment performance may be a basis for a dynamic maintenance concept (Li et al., 2020).

2.5.1. Maintenance management with data driven - dynamic concept

This research will be centred in the developed of a system to support the decision of doing or not maintenance and the level of risk the responsible of the operations are willing to run. The developed system will lead to a dynamic maintenance concept.

“Dynamic maintenance includes the operations (e.g., deploy, undeployed, and so forth) to large scale service components in the runtime. The dynamicity of maintenance means that the maintenance will not affect the execution of existing components and promise the downtime as little as possible. Normally the maintaining requests are delivered by the administrators and provisioning modules" (Global, 2022).

A multi-attribute model (MAM) can be used to determine the maintenance opportunity, defining Maintenance Time Window (MTW) system to enhance the cost benefice effect in the maintenance activities (Xia et al., 2012).

A dynamic maintenance can be “based on a simple usage registration procedure” (Tinda at al., 2019). In one case study, to considerate the critical components, had followed various procedures: "determine the critical (sub)systems", "define the functional usage profiles for the system", "quantify the relation between the usage profiles and the degradation rates" and "monitor the usage and optimize the maintenance intervals" (Tinda at al., 2019). In their study they had defined the critical components by analysing the costs generated by some systems operators and the inherent loss of performance of the systems. They also, in a third case study, considered the environment influence in systems degradation.

An algorithm has been developed by Wu et al. (2021) that uses the high average-utility itemset mining (HAUIM) to pré-deletion process in dynamic process, this procedure enhances the database performance along the time.

A Poisson process may be used "to model the data shock arrival process" in a repairable system. The Monte Carlo simulation was used along the time the system will degrade, and the equipment's and systems reliability will decrease (Yousefi et al., 2020).

A dynamic maintenance system that considers historical data, the system production performance and at a chosen time is obtained the "minimal expected total cost per unit time" was developed by Chen (2011).

An interesting study about the areas of decision-making algorithms, was made by Bousdekis et al. (2019), they refer that most algorithms consider that maintenance is made correctly, not previewing different maintenance degrees. In their investigation it was considered various maintenance steps/levels (Bousdekis et al., 2019).

During the development of a maintenance optimization model Mahar et al. (2022) did "a modification to the dynamic predictive maintenance policy of Van Horenbeek and Pentelon…", which consisted in the inclusion maintenance human error on the original algorithm (Mahar et al., 2022). For that they considered the optimization on four phases: the stochastic simulation phase, the individual optimization phase, the actions grouping optimization phase and finally the implementation phase (Mahar et al., 2022).

Other methods had been applied for support decisions in maintenance area to reduce costs, such has neuro-fuzzy systems to treat data Condition Based Maintenance (Kothamasu & Huang, 2007; Vafaei et al., 2019). But according to some authors (Ierace & Cavalieri, 2008) as some negative points for example the connections and the weight in evaluations depends on not from collected data and applied algorithms but from human decision about the weights values and about what is chosen to made the decision, that is, it depends on the common sense and experience of those who develop the Fuzzy system, so the results can be easily manipulated.

In the present investigation the decision process is made also in FMECA analysis which the quality depends on the present investigator, but also from data collected from continuous condition monitoring.

2.5.2. Risk analysis in maintenance

The risk management uses continuously policies that are used to structure the risk itself (ISO, 2018), Figure 12.

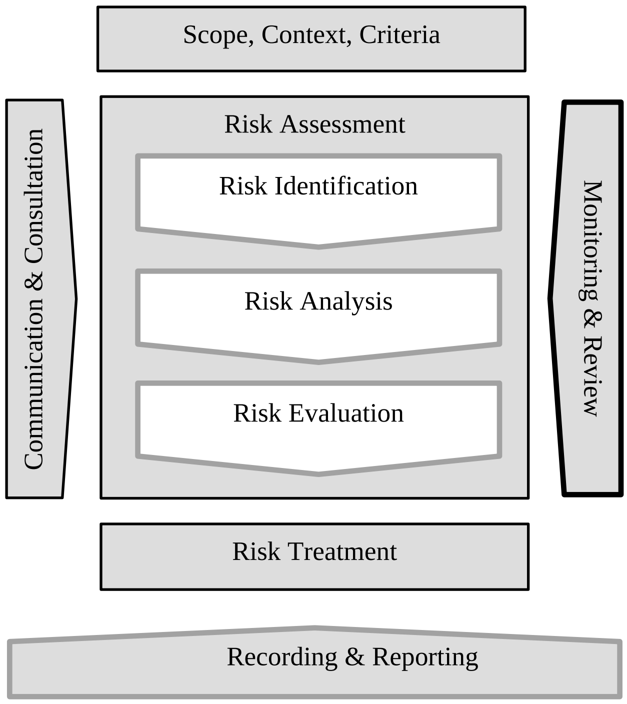


Figure 12 - The process of risk management
Source: adapted from ISO (2018)

Although it was not used a methodology like Fuzzy-RBM, it may be applied in equipment's monitoring using a methodology based on maintenance risk analysis to define the best maintenance procedures in air compressors from a Portuguese Navy ship (Mestre, 2021).

Also, Néri (2010), had applied a methodology based in fail tree analysis (FTA) to study the reliability and optimize the maintenance management in a class of frigates from the Portuguese Navy (Néri, 2010). This methodology may be used as a risk management in a maintenance priorities definition.

Risk management in maintenance is a tool for risk analysis in systems or equipment's. Risk management differs from the FMECA because the first one monitors the risk and the other the failure mode.

2.5.3. Failure mode, effects and critically analysis

A maintenance monitoring management system can be based on a Failure Mode and Effects Analysis (FMEA) methodology. This methodology and FMECA can be a good methodology hypothesis to be applied in an intelligent dynamic maintenance concept on ship maintenance management.

Today organizations are more focused in risk management, so decisions are based on data to enhance confidence and the probability of a good decision (Alvand at al., 2021). For risk assessment various methodologies may be used. And in the maintenance area Failure Mode and Effect Analysis and Failure Mode, Effects and Critically Analysis (FMECA) may be one of the applicable methodologies (Alvand at al., 2021).

FMEA is a methodology that allows analysing possible failures and what their occurrence could cause. FMEA and FMECA may be used as a phase one in maintenance strategy (Sielaff, 2022).

Application of the FMEA Method in Improving the Quality Management of Emergency Complete Blood Count Testing (Lv et al., 2023).

A "expanded FMEA approach for time dependent failure probability" was developed by Sielaff (2022). He had defined, based on the experience of the workers from a workshop in the occurrences of anomalies in certain equipment, some probabilities of failure without equipment maintenance (Sielaff, 2022).

FMECA is a systematic and structured approach used to identify analyse and evaluate potential failure modes within s system or process and the associated effects on the systems performance and criticality (Nadjafi et al., 2023).

FMECA is an extension of Failure Mode and Effects Analysis (FMEA) where criticality analysis is included.

A FMECA system should be dynamic and iterative because its preliminary purpose is to identify critical failure considering eventual occurrences in equipment's or systems

(DOD, 1980). Given the factors that can influence the equipment performance, the level of criticality and the type of occurrences may be variable in time (DOD, 1980).

When projecting or acquiring a new system, FMECA should be a structuring tool for its life cycle (DOD, 1980).

A Fuzzy system integrated with FMECA may be used as an artificial intelligence technique to perform a risk study in a ship propulsion system (Ahmed et al., 2022).

In this investigation it is believed that applying FMECA methodology reinforced with condition monitoring data, because it will increase the knowledge of risk and will support preventing failure during ship operation.

It will be developed to be used in a decision support model in a concept of dynamic maintenance, based on data from a dynamic list.

2.5.3.1. Procedures for implementing FMECA

When developing FMECA there are two inherent actions: the first one is creating FMEA and the second is performing criticality analysis.

A FMECA methodology can help identifying potential risks of failure in equipment and systems, allowing future project enhancement (Nadjafi et al., 2023).

FMECA can be used to determinate the interval of maintenance of a warship radar. They used reliability and cost benefit ratio (CBR) to obtain 2nd time interval replacement of critical components (Suharjo et al., 2019).

FMECA may be applied to support risk management in maintenance management (Khan et al., 2023).

A FMECA application may consider the next 8 steps that were adapted from Khan et al. (2023):

Step 1. Identification of failure modes considering the system, sub-system, spare part, and if applied auxiliary equipment that supports the system (considering the cause, and the conditions at it occurs);

Step 2. Transfer Information from the FMEA to the FMECA

Step 3. Classify the failure effects by severity (change to FMECA severity consequences of the failure mode);

Step 4. Perform criticality calculations;

Step 5. Rank failure mode criticality and determine highest risk items.

Step 6. Analyse results based on statistic techniques or on expert evaluation. Failure modes are assessed considering the likelihood of the occurrence and the severity;

Step 7. Take prioritization and mitigation actions and document the remaining risk with rationale (a software system or by the sense of engineers the failure modes are prioritized to mitigation strategies be implemented, where design changes on the system can be included);

Step 8. Follow-up on corrective action implementation/effectiveness.

A modified FMECA implementation procedure may include different severity hazards, like hazards on persons, on machinery and introduce the structural complexity on detection and the costs of detection, Figure 13 (Tian et al., 2024).

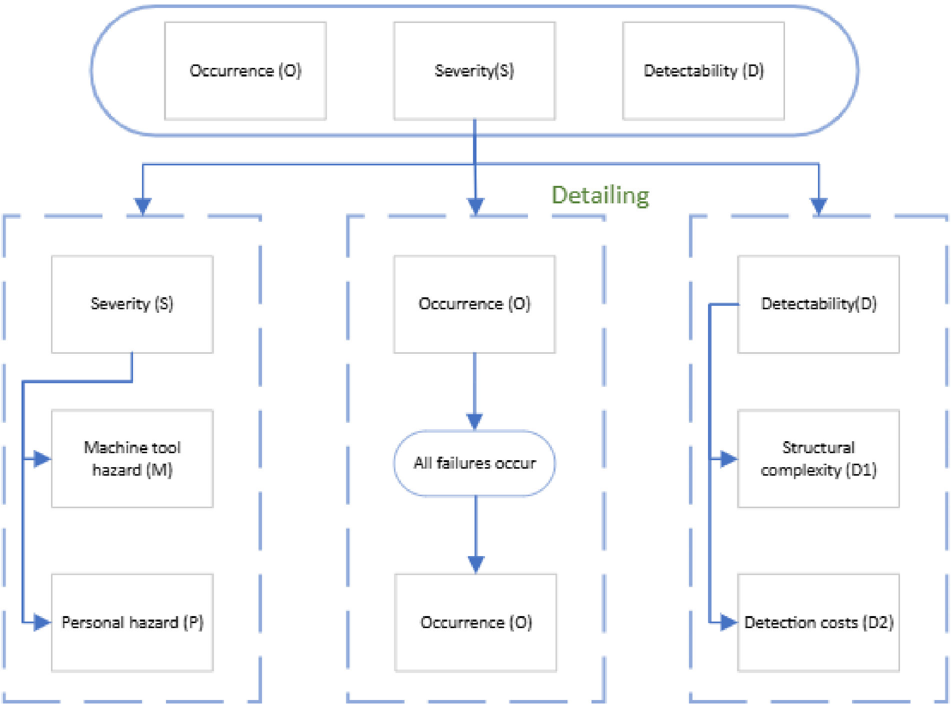


Figure 13 - Optimization indicators for risk factors
Source: adapted from Tian et al. (2024)

Example of works developed with FMEA/FMECA may be seen in Table 3.

Table 3 - Example of research and applications with FMEA/FMECA

Authors and Year	Title	Contribution
DOD (1980)	Procedures for Performing a Failure Mode, Effects and Criticality Analysis	Define the procedure of FMEA and FMECA referred as a structuring technique for those responsible for decision making in military equipment´s in USA
Reliability Analysis Center (1993)	Failure Mode, Effects and Criticality Analysis	A profound study about FMEA and FMECA
Kacprzynski & Byington (2001)	Enhanced FMECA: Integrating Health Management Deign and Traditional Failure Analysis	It is presented a concept of FMECA++ where are included methods to enhance Failure mode analysis, equipment health management and maintainability.
DA (2006)	Failure Modes, Effects and Criticality Analysis for Command, Control, Communications, Computer, Intelligence, Surveillance, And Reconnaissance (C4ISR) Facilities	It is manual to guide Army facilities managers through FMECA process, to exposed how it can be applied to command and control, and other military related systems.
Chen et al. (2012)	Status of FMECA Research and Engineering Application	It shows that FMECA Standards “follow the latest developments” and adapt to new realities, because the original risk calculus does not contemplate all the variable in a system.
Onofrio et al. (2015)	Failure Mode, Effects and Criticality Analysis for medical devices: Does standardization foster improvements in the practice?	State of art of risk assessment methods and the impact of risk assessment techniques on the medical devices. It was found a gap between the users of medical devices and the theoretical that development risk assessment methodologies.
ABS (2015)	Guidance Notes On: Failure Mode and Effects Analysis (FMEA) for Classification	American Bureau of Shipping required clients to develop and submit FMEA´s as part of Classification requirements for select systems”. It is believed that if FMEA´s is well design and adapted to systems on ships along lifecycle it will reduce “failures, downtimes and incidents”.
Sarr et al. (2017)	Analysis of failure Modes Effect and Criticality Analysis: A Stand-Alone Photovoltaic System	A FMECA methodology is performed on a photovoltaic system to increase reliability reduce eventual failures.
Mohamed et al. (2017)	Detecting Failure Modes, Effects and Criticality Analysis of LEO Spacecraft Solar Array System	“Reliability issue of a array of LEO spacecraft was analysed with FMECA” for ensure delivering power without any failures in its lifecycle.
Rajamanickam (2018)	Analysis And Implementation of FMECA Methodology - Vacuum Machine	“The FMECA methodology is applied to the vacuum equipment in order to identify its potential failure modes and to evaluate the effects that these failures may have on the foundry machine.”
Tajung et al. (2019)	Risk Management Analysis Using FMECA and ANP Methods in the Supply Chain of Wooden Toy Industry	it was used FMECA to risk assessment and it prioritization, minimizing losses and enhance equipment’s performance in a wooden toy industry.
Stamatis (2019)	Risk management using failure mode and effect analysis	Gives a perspective of techniques using FMEA in risk analysis.
Suharjo et al. (2019)	Failure Mode effect and Criticality Analysis for Determination Time Interval Replacement of Critical Components in Warships Radar	FMECA is used to determine potential failure modes in a radar system of a warship, and to define the “time interval replacement of Critical components”.
Siswantoro et al. (2020)	Failure Mode and Effect Criticality Analysis Fuzzy to Evaluate Critical Level on Main Engine Supporting System	“To determine the priority of maintenance on the equipment, the risk priority level method is used” using FMECA in main engine supporting system.

Gallikova et al. (2020)	FMECA analysis of thermal deburring machine EXTRUDE HONE TEM P-350	It's a study that "investigates FMECA analysis and its potential use in improving the reliability and maintenance of the thermal deburring machine in a manufacturing company located in Slovakia".
Ruixin et al. (2021)	Failure criticality evaluation of ship propeller shaft system based on Fuzzy FMECA method	A Fuzzy-FMECA method was applied to take on account the limited maintenance conditions on a ship shaft propeller contributing to enhance the propeller shaft design and the maintenance work.
Wang et al. (2021)	An Integrated Approach-Based FMECA for Risk Assessment: Application to Offshore Wind Turbine Pitch System	They used Z-numbers to uncertainty information studying the failure modes dependency using experts' evaluations for it.
Ghani (2021)	Integration of FMECA and Statistical Analysis for Predictive Maintenance	The author applied a FMECA "to determine which bearing in the production line is most prone to failure".
Fata et al. (2022)	Improved FMECA for effective risk management decision making by failure modes classification under uncertainty	A Tri method is proposed a failure mode classification in risk categories, in which was used FMECA experts to output consensus results
Ofanson et al. (2022)	Failure mode effects and criticality analysis using fuzzy logic for ship dynamic positioning (DP) systems	They predicted FMECA in a dynamic positioning using fuzzy logic.
Correia, J. (2022)	FMECA Applied to Air-Cooled Chillers	It was used RAMS methodology (Reliability, Availability, Maintainability and Safety) with FMECA is used to identified failure modes, causes, effects and criticality analysis in a air-cooled chillers.
Carvalho et al. (2022)	A Functional FMECA Approach for the Assessment of Critical Infrastructure Resilience	It was designing a FMECA to assess risk on critical infrastructure considering cyber-physical systems (CPS).
Eikasrawy et al. (2024)	Maintenance optimization based on modified FMECA: a case study applied to a spinning factory	FMECA method is applied to enhance maintenance and life cycle of two spinning machines in a factory.
Tian et al. (2024)	A novel FMECA method for CNC machine tools based on D-GRA and data envelopment analysis	It proposed a new FMECA approach considering various subdivisions of the detectability and a subdivision on severity into machine hazard and personal hazard.

The references in Table 3 include recent and old references to show that the FMEA and FMECA systems are not recent, but they are fundamental in an equipment maintenance system, its application and evolution have been continuous and may even evolute in future.

2.5.3.2. Variables in critical analysis

The variables in FMECA calculus are (Stamatis, 2019):

N	−	The number of components that are redundant;
M	−	The required number of components necessary;
Beta (β)	−	The failure effect probability, which is used to quantify the described failure effect for each failure mode shown in FMECA;
Alpha (α)	−	The probability that the given part or item will fail in the identified mode (all alphas for all items, means it value is 1). Or the probability of the occurrence of the failure mode (failure mode ratio);
Failure rate (λ_p)	−	The number of failures per unit of time, usually expressed in failures per million hours;
λ_m	−	The modal failure rate.

The "modal failure rate is the fraction of the item´s total failure rate based on the probability of occurrence of that failure mode", Equation 6 (Stamatis, 2019).

$$\lambda_m = \alpha\lambda_p \tag{6}$$

In the present study, probability of occurrence for single node will not be evaluated. For full development of the modified FMECA (FMECA-H-CM), on the Equation will be integrated various condition monitoring parameter and the threat environment. The FMECA objective is the calculation of Risk Priority Numbers (RPNs), and to begin development of this, the three risk factors are used severity (S), occurrence probability (O) and the detection (D), and the product of the three represents the RPN Equation nr 7 (Wang et al., 2022).

$$RPN_{DM}= S*O*D \tag{7}$$

A usual matrix for FMECA is presented on Figure 14 (ABS, 2015). It represents the likelihood of the occurrence of an event and the consequence for the personnel, community, environmentally and facility, present with colour to enhance the risk level state.

Frequent: Incident is likely to occur at this facility within the next 5 years.	4	LIKELIHOOD			HIGH	RISK
Occasional: Incident is likely to occur at this facility within the next 15 years	3					
Seldom: Incident has occurred at a similar facility and may occur at this facility within the next 30 years	2			MEDIUM	RISK	
Unlikely: Given current practices and procedures, incident is not likely to occur at this facility	1		LOW	RISK		
Personnel/Community/Environmental/ Facility			CONSEQUENCE			
			1	2	3	4
			Incidental	Minor	Serious	Major

Figure 14 - Usual matrix for FMECA
Source: ABS (2015)

2.6. Chapter maintenance elations

In this chapter it was presented the maintenance state of the art focused on the perspective of the condition-based maintenance, maintenance based on risk considering the parameters and the methods that may support it to be included on FMEA and FMECA methodologies developed in Chapter 4.

On future studies for text treatment was recommended the use of Bayesian methods. But to frame the present research a simple detection of selected words and counting will be used.

It also was presented the maintenance organization on the Portuguese Navy surface warships and the methodology FMECA and the variables on critical analysis that will be the inspiration of the methodology developed on this research.

3. Data and databases

3.1. Chapter introduction

Trusting in the "Human algorithm" on maintenance management, or if it may be said: "Human good sense" may be a problem, because even with a good sense, person can't see the unseen, hear the unheard, not even predict the future of a machine if they had no data or don´t used data with decision algorithms.

Nowadays data it is part of every engineering activity, which as conducted to a Big Data concept. If it is used well, it can lead to a safer equipment handling and operation reducing life cycle costs.

This Chapter will integrate an introduction to dynamic databases including cybersecurity databases, presenting a state of art of data management in maintenance, and data management in Navy Ships.

3.2. Dynamic databases

In early 2000 years Dynamic Database-Driven value was discussed by Davis & Robbins (2003). They exposed that the use of database-driven web sites can be the response for continuous change in electronic resources, where the information is available, and which can be fed with other websites with databases and other sources.

"Flexible conservative re-clustering is the key in determining a clustering algorithm's ability to adapt to changes in access pattern" (He & Darmont, 2005). Dynamic databases through various statistic methods can be the key for database metamorphosis adapting to new data, substituting unrevealing data, highlighting the relevant results (He & Darmont, 2005).

One issue in clustering data is to define an algorithm that represent various types of data of the same object universe, sometimes it must be manually adjusted, and the challenge may be find a flexible autonomous algorithm (He et al., 2018).

Big Data may have three characteristics: volume, velocity, and variety (Zerhari et al., 2015). Various techniques have been suggested for treating and clustering data considering simple machine clustering and multimachine clustering, but the simplest conclusion is the need of the cluster algorithms improvement "…by reducing, their complexity in terms of time and memory" (Zerhari et al., 2015).

A Fuzzy Delphi-AHP-TOPSIS framework was used by to eventual identify obstacles of the application of Big Data methodology in maritime environment. For that, they defined the linguistic terms and attributed the Fuzzy numbers to graphically and with a matrix representation, compare the success factors calculating the success vector, and then the obstacles level is compared with it (Zhang & Lam, 2019).

A machine learning algorithm trained on dynamic data can be applied on Fuel Oil prediction consumption used a trained algorithm applying historical data and validated it using test data and 10 different test samples but always using the same amount of data (Ahlgren et al., 2019). They had optimized the model using the AutoML-library Tree Pipeline Optimization Tool (TPOT).

"Recently, with the intention of remote ship monitoring for better services for ship costumers, vessel builders started to adopt new sensor technology by installing different sensors for different components on board…" and "…builder companies realized that the collected sensor data could also help improve vessels 'maintenance and future design". With an integrated system on board, they expect to have "… analytics results to support vessels operations; analytics results to support diagnosis of vessels, prediction for maintenance needs, and allocation of maintenance facilities and resources…" (Wang et al., 2015).

Machine Learning is a result of three fields interaction: computer science, engineering and statistic (Divya et al., 2018). They also refer that "Algorithms that simplify the function to a known form are called parametric machine learning algorithms" (Divya et al., 2018). And the "Algorithms that do not make strong assumptions about the form of mapping function are called nonparametric machine learning algorithms" (Divya et al., 2018).

In parametric algorithms at first, it is selected "a form for the function" and in second, it is learned "the coefficients for the function from the training data" (Divya et al., 2018).

With the amounts and the various origins of data produced by sensors on board ships the data must be treated with new and adaptive algorithms" (Athmaja et al., 2017). New types of data treatment arise with new concepts like machine learning.

"Machine learning is an interdisciplinary research area which combines ideas from several branches of science, namely, artificial intelligence, statistics, information theory, mathematics, etc" (Athmaja et al., 2017).

"The prime focus of machine learning research is on the development of fast and efficient learning algorithms which can make predictions on data" (Athmaja et al., 2017).

Mathematical algorithms for support decision-making in Big Data environment should be developed in an “accountable algorithmic culture”, because although the data protection, the results of the applied algorithms should also be protected. If not, it may be subjected to misapplication. In an algorithm, not also its quality and performance should be checked but also the results and the access to it (Vedder & Naudts, 2017).

It is believed that categorizing framework may allow the algorithm choice for a decision process by hiding useless information (Ajin & Kumar, 2016).

“Since the synchronization and communication constraints of the available hardware naturally dictates the choice of the algorithms, we expect that new approximation tools will continue to be discovered that ideally adapt convex algorithms to the heterogeneity of computational platforms” (Cevher et al., 2014).

In medicine Big Data area, sometimes there are occult algorithm flaws in tendency prediction that can lead to false positive or false negatives, it is both negatives’ results (Cahan et al., 2019). These may also occur in machine condition monitoring approach, where a not cautioned result may lead to unnecessary maintenance intervention, or a maintenance absence that conduce to a catastrophic anomaly.

To make data useful, many statistics methodologies may be found in applied in various subjects as a pillar of modern decision world.

Reinforcement learning works like in games or metaverse systems (decision support systems). Deep learning happens when there are more than two levels of decision.

Reinforcement requires a large amount of data for the system to be able to carry out learning. Big Data systems must be stripped of the data that allow them to feed Data Science.

The first data steps go through data collection, then data storage and processing (Cluster, for example), thirdly through Data Analysis (Neural Networks, Control Charts), and finally the results.

The pre-processing of data, as the brain already does, is to remove from the data the information that is not necessary, or to remove what is necessary.

Limit text analysis to previously chosen keywords, anticipate interventions. Correlate the interventions with the readings of the equipment.

So, the steps necessary to define on maintenance process decision based on the criteria that will be exposed on Chapter 4 and then include the human algorithm (considering other expertise’s responses to be integrated on FMECA, where the mean between responses were used) for a decision process full implemented on Chapter 6. Usually on Portuguese Navy the maintenance managers are engineers and specialist graded on sergeant and sailor. It is believed that FMECA maintenance concept is possible on a dynamic maintenance methodology, where existing data can be continuously obtained, validated and enhanced the results giving an online equipment risk state and maintenance priorities and options.

3.2.1. Databases, data processing and management

To have useful data, in a Big Data Organization, it should be organized in a well-distributed scheme, and the processing system we use is the data flow we need to extract information to decision making support system.

A study of a multilevel grid file (MLGF) was made to enhance the performance of "estimation of multidimensional file structure that gracefully adapts to nonuniform and correlated distributions" (Whang et al., 1993). This was one of the beginnings of dynamic databases, but the data was on queries, along the time and with more data, it becomes more difficult to data dynamic relations between it.

A few years ago, graphs were analysed in an offline manner, nowadays to support decisive decisions all the data must be online (Robinson, 2014). Graph databases can be the key for a creation of an "agile software" (Robinson et al., 2015). To correspond to this software aims various factors are important to coexist: performance, flexibility, and agility.

A graph database can maintain a database performance even when it starts to have amounts of data by the possibility of having various information queries are represented in a graph small zone. If we have data, but don´t quite understand yet, flexibility should be a constant in database, a graph representation can be the response to find data connectivity, connections and relations, the result of graph analysis can support a decision-making algorithm based on the information. The use of graph database has "lack the kind of schema-oriented data governance mechanism" (Robinson et al., 2015), this characteristic creates a space for agility a multivariate and multidimensional database needed to traduce useful information (Robinson et al., 2015).

Robinson et al. (2015) presented the key´s to define a database in most of the times. The first thing they refer is that the nodes are used for things and the relationships to the structure (Robinson et al., 2015). They considered that the nodes represent the data that can be marked and grouped. The use of relationships can demonstrate the connection between the data and creates a framework, the direction of the relationship can help to understand the framework, the node properties can represent the data attributes, and the relationship properties can express the characteristics of relationship (Robinson et al., 2015).

Usually, in relational databases if the information increases the quality behaviour changes, but with a graph database its state trends to remain (Patil et al., 2014). This data storage can mean a change in data arrangement in Big Data databases.

Late database´s research doesn´t treat the graph database in a dynamic way, which leads to a more computer processing time. They considered that the use of graphs on data complex structures modelling can simplify the process (Patil et al., 2018).

A time-based dynamic synchronization (TDS), applied to databases, that only actualizes when some limits are exceeded, this system avoid eventual inaccessible software during the actualization (Qu & Jiang, 2018). They detailed that when there are changes in data sources this information is also updating by synchronization. For the decision system procedure, they use the Markov Decision Process (MDP).

Big Data can give the maintenance managers equipment condition monitoring but collecting data can´t only be data storage. Data storage should obey to a methodology to give the correct information so maintenance managers can decide about the maintenance priorities.

A data mining technique that uses geometric transformation and a privacy model that guarantees the obtained information is different from the original data mining concept (Haoxiang & Smys, 2021). They also use a matrix to represent perturbed data that represents various factors.

There are models using Big Data Analytics approach applied to ship collision risk analysis using data collected from AIS-system and now-cast data (Zhang et al, 2021). This study involved various parameters for example. from a certain area of globe: season, current speed, wind speed, etc; they used clusters analysis to study the risk with good results.

“Big Data covers information from various sources i.e. sensors. There are many difficulties associated with capturing, sorting, analysing and managing data”. Ships data sources and user functionality after analysis has demonstrated its utility, Figure 15, Zaman et al. (2017) believe on a future of data-driven maritime where data analytics enhances the operational planning of the ship augmenting its performance in sectors like voyage planning, operational predictability, vessel safety a security, condition monitoring, predictive maintenance system, etc.

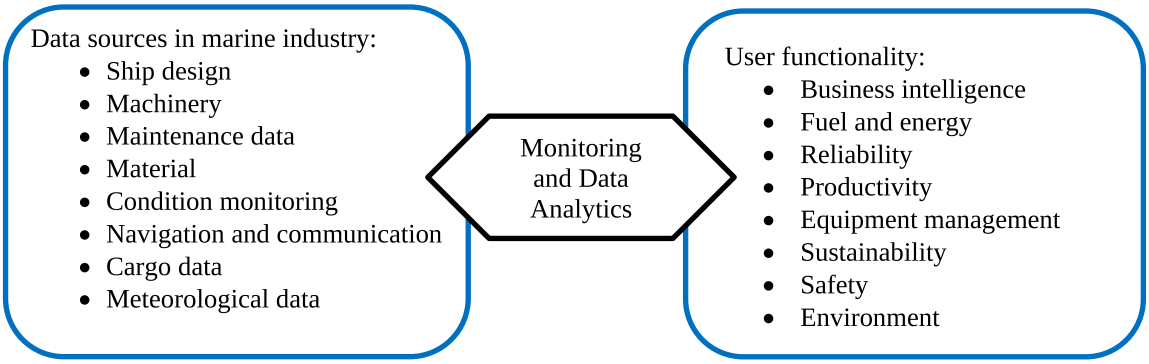


Figure 15 - "Ship data sources and user functionality after analysis"
Source: adapted from Zaman et al. (2017)

There are some developments in machine learning systems that allow the autonomous ship intelligently manoeuvring accordingly the obstacles in the area, it was developed a simulator for machine-learning evaluation in autonomous ships that can be improved considering a dynamic context (Hupponen, 2020).

There are some researches that have interesting comparisons between different schedulers in Hadoop[1], and it was found for online cluster´s, if the owners provide the deadline, the Deadline Constraint scheduler must be applied and the job time scheduling accomplished (Gautam et al., 2015). In the customized MapReduce optimization techniques, it was exposed that one application of Hadoop can be "Relational Operations in Query Processing for data projections join etc", and its advantages are: "Keeps the original MapReduce interface; Does not modify Hadoop framework; Improves query runtimes without using Structured Query Language (SQL) interface and local Database Management System (DBMS)" (Gautam et al., 2015). In addition, the Disadvantages: "It Gives better performance but less fault tolerant and vice-versa" (Gautam et al., 2015). The same authors also presented different algorithms for different job scheduling, and they provided "the classification of Hadoop schedulers based on different parameters such as time, priority, resources etc" (Gautam et al., 2015). They also "discusses about how various resource monitoring tools or frameworks help in achieving better result in Hadoop cluster" (Gautam et al., 2015).

[1] "Hadoop is an open-source distributed processing framework that manages data processing and storage for Big Data applications in scalable clusters of computer servers" (Stedman & Rosencrance, 2019).

“Data Parallel Systems are crucial to the success of Big Data” (Xu et al., 2015). In a system like Google File System (GFS) and MapReduce, clustering is autonomous, where each node store and treat data. It is called “data locality” which have the advantage of moving, not data, but results of processing data and “protect local private data” (Xu et al., 2015).

Data-efficient algorithms are a challenge in Big Data, to resolve some Artificial intelligence (AI) issues. Find the ideal algorithm for a certain amount of data and only use the necessary data in learn-data and not all, are an aim of data scientists (Adabi, 2021). Finding the suitable, flexible and agile algorithms are now in some enterprise’s agenda, to accomplish it data-learners should be inherently improved (Adabi, 2021).

“The performance metrics also include the data source validation check and the comparative analysis of the algorithm with the base technique, which are the effectiveness indicators of the assumption and results made in the algorithm “ (Gupta et al., 2016).

3.2.2. Cybersecurity and Blockchain in maintenance database

“A blockchain is a digital ledger made up of linked entries, referred to as blocks, that, depending on the application, store some form of data” (Green et al., 2020).

“To decentralize the technology, copies of a blockchain are shared and stored on all computers in a common network rather than on a central server alone” (Green et al., 2020).

In a considered decentralized system like blockchain, an information modification by a user in a certain computer must actualize the information in a whole network, in these systems there in no centralized authority (Green et al., 2020).

Blockchain technology (BT) was proposed by Petkovic et al. (2019) “to enable secure communication and secure data storage exchange between Marine Autonomous Surface Ships and shore control system”.

Implementing blockchain in ships data allow a network with connections to users, ships, and shore control center; the users must be certified by a certification authority, and who access the network must continuously verified their access. This point of view decreases the cyber threats to the systems, Figure 16 (Petkovic et al., 2019).

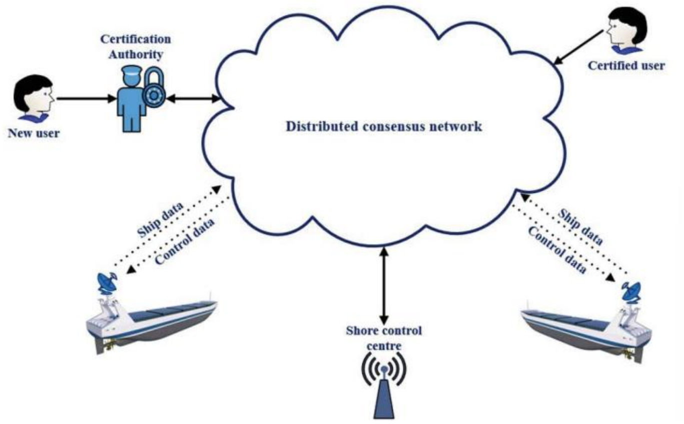


Figure 16 - Network with cybersecurity concerns
Source: Petkovic et al. (2019)

The blockchain in past has been considerable an unbreakable security system, but know has been being hacked, but mostly concerning to public blockchain network (Orcutt, 2019; Waldman, 2022).

“Blockchain is a pre-existing cryptography technology expressed in a new concept of application with a chief benefit of ensuring that war fighters maintain high confidence in the authenticity and security of the data they get from DOD[2] networks” (Alcazar, 2017).

“Chinese military publications have consistently proclaimed that blockchain technology will provide people´s Liberal Army (PLA) with an edge in intelligence, weapons lifecycle, personnel management, and information warfare” (Logan & Lebryk, 2021). The PLA is viewed like it can contribute for “data integrity through military supply chains” (Logan & Lebryk, 2021).

In blockchain applied to financial matters there are multiple stages of validation on the network, these stages are represented by nodes Figure 17 (Angin, 2020). Although malfunction occurred in the network usual the system maintains its operationality (Angin, 2020).

[2] DOD – Department of Defense

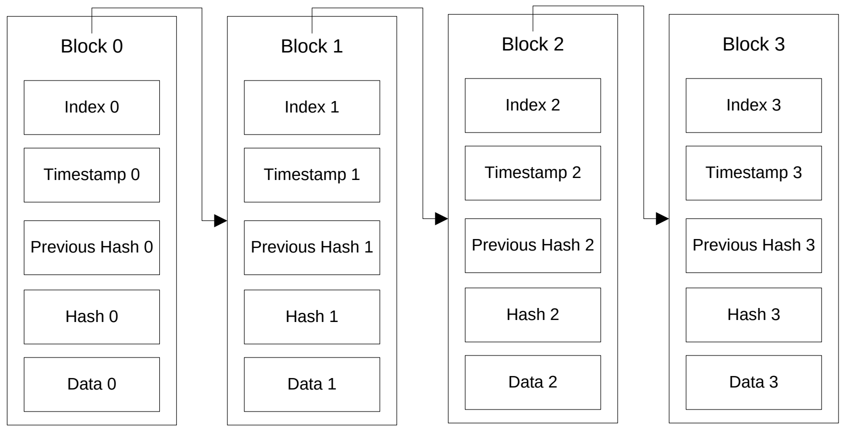


Figure 17 - Blockchain structure
Source: adapted from Angin (2020)

Blockchain concept might be implemented in various areas in the Aerospace and Defense (Ahmad et al., 2021). A study of these areas ("Battlefield operations management", "Logistics and supply chain management", "Autonomous Swarm Drones management" and "Border protection") show that it might create a trusted network environment because the registering of military material and personnel are secured and certified (Ahmad et al., 2021).

There are some "critical factors in determining when blockchain technology might apply to military intelligence processes" (McAbee et al., 2019). The considered factors are: "process involves collaboration" and "the collaboration is interrelated or sequential", or "there is uncertainty related to trust between participants", or "the current architecture is vulnerable due to centralization and redundant copies,…", or "there are problems related to traceability/transparency", or "decentralization is congruent with applicable command philosophy and regulation" (McAbee et al., 2019).

"Blockchain technology presents a new chapter of capabilities for cyber, operations, and even acquisitions" (Korsak & Fuqua, 2021).

To implement a blockchain concept in DOD it must be considered "four main parts: the blockchain ledger, the smart contracts repository, the document repository, and the component distribution history" (Woodfield, 2019).

For United States of America (USA), China and Russia militaries it is determinant the implementation of blockchain for the network security and military logistics (Lilly & Lilly, 2021). In Table 4 we can observe that the most common cases to the three cases are: anti-hacking, intrusion detection, network and data redundancy, encrypted communications client, supply chain management (Lilly & Lilly, 2021). On military logistics is one of the areas that can be applied on maintenance with blockchain conceptualization.

Table 4 - Possible Blockchain in USA, China and Russia

Warefare Focus	Specific Use Case	USA	China	Russia
Civil–Military Integration	• Smart contract management. • Civilian supply chain auditing. • Critical defence infrastructure monitoring.	x x 	x 	 x
Command and Control (C2)	• Anti-hacking, intrusion detection. • Battle orders management. • Network and data redundancy. • Digital order-of-battle verification	x x 	x x x x	x x x
Communications (C4ISR)	• Encrypted communications client. • Credentialled identity management	x x	x 	x
Operations	• Drone swarms, micro-UAV management. • Airborne ISR platforms.	 x	x 	x
Military Intelligence	• Handler and source/informant tool. • Confidential payment platform.		x x	 x
Military Logistics	• Supply chain management (inventory). • Quality assurance. • Additive manufacturing/3D printing.	x x x	x x x	x
Psychological Operations	• Decentralised propaganda channels.		x	
Training	• Professional military education. • Officer and NCO career tracking.		x x	
Terrorism and Counterterrorism (CT)	• CT tracking, targeting and disruption. • CT sanctions, finance enforcement.	x x		

Source: adapted from Lilly & Lilly (2021)

The categories of blockchain databases can be public blockchains, consortium blockchain and fully private blockchain (Buterin, 2015).

A private blockchain applicable in a maintenance system, with accreditation levels, with nodes corresponding to identified users may be a decentralized system with the same structure of original blockchains (Mohril, 2021). The system may use a node where various users intervene, like the maintenance occurred in a workshop, a workshop authority and maintenance contractors' validation; in this system if the intervention is approved, we will have a chain of actions, if note an alarm should be present and cybersecurity must be checked (Mohril, 2021). As data in military environment is usual confidential the blockchain technology seems to be applicable, since it still to be a more secure systems than other concepts (Mohril, 2021).

Usually, the Military Command has centralized information, so in case of a hack event, in wartime or in peacetime, confidential information may be vulnerable being available or even loss of information (Zhu et al., 2020). If a blockchain database is implemented some risks, like access and uncertified information share, may be mitigated, by having data layers or network layers that will enhance data reliability and credibility (Zhu et al., 2020).

3.2.3. Database management in maintenance

When building a maintenance database from an equipment or system the next information is needed: the equipment/system configuration, data from its project or functioning parameters, and eventual accidents and its consequences (Duarte et al., 2013).

In the subject of maintenance management, there are validated models comparing real intervention data and prediction models outputs (Bastos, 2014). The maintenance database attributes the data had been breakdown id, machine part, machine component, reason of the breakdown, action made in maintenance and the record date. For the monitoring database, other attributes were chosen record id, record date, value of the monitored indicator, lower limit warning, critical lower limit warning, upper limit warning and critical upper limit alert (Bastos, 2014).

There are also high complexities of Big Data and the necessity to process data with a methodology that should check the data utility; to accomplish this aim the manners that matters are (Muniswamaiah et al., 2019):

- Data transmission;
- Data acquisition and storage;
- Data curation;
- Scalability;
- Elasticity;
- Availability;
- Data integrity;
- Security and Privacy;
- Heterogeneity; Data Governance and Compliance;
- Data uploading;
- Data recovery;
- Data visualization.

To build a database capable of delivery credible data, the systems must have supervision, because the data quality it is important for a correct machine learning based on applicable algorithms (Sarver, 2021).

In industry environment an unsupervised machine learning was developed for pre-processing an analysis in predictive maintenance, for these it was used the K-means clustering that grouped data which has not been labelled, but accordingly its characteristics it can be clustered to better understand the results (Bekar, 2020). As the database is filled with data, the centroids of the clusters are readjusted, as well as the relationship between them, when there is no change in the centroid, the iterations stop.

A framework representing data from various sources that include data from equipment's sensors, data from an event log, with registry of failures, and maintenance actions, and data from the equipment manufacturer may be organized to supply useful information (Schmidt et al., 2012). Those authors also defined a mode for information Fusion in Maintenance, that can be seen on Figure 18 (Schmidt et al., 2012).

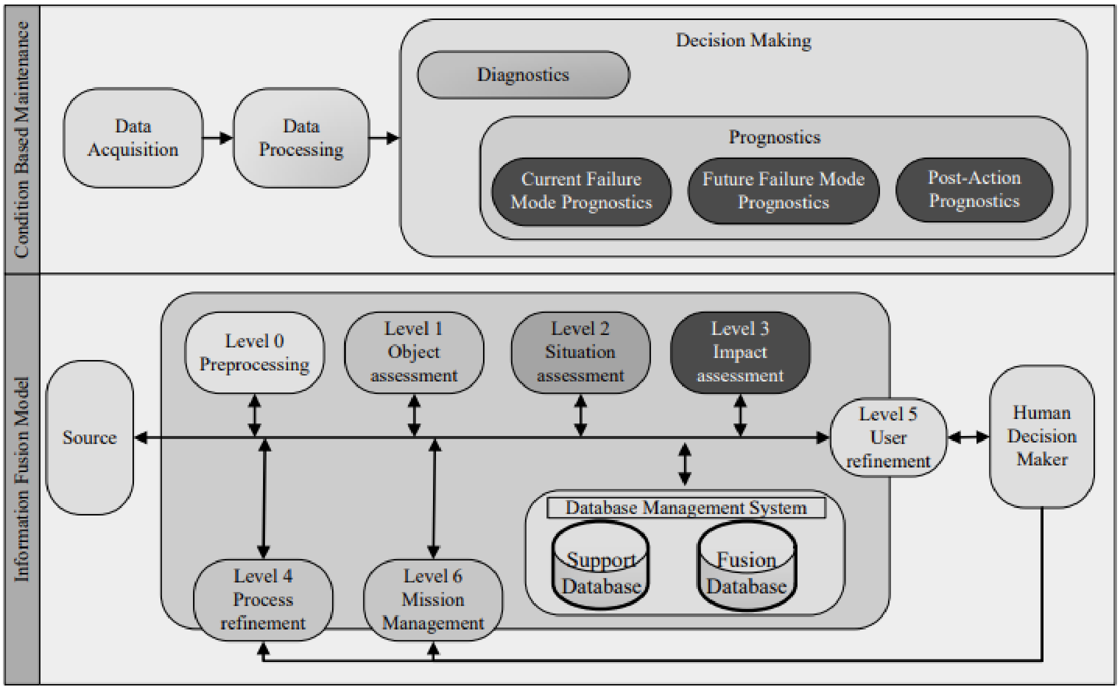


Figure 18 - Modes for information fusion in maintenance
Source: Schmidt et al. (2012)

Four types of machine learning may be considered: supervised learning, unsupervised learning, semi-supervised learning and reinforcement learning (Mohammed et al., 2016). The selected data and algorithms and its quality are the base for a fulfilment of an implemented machine learning program in an organization (Sarker, 2021). In addition, for investigators and consultants certify the developed machine learning system, the algorithms should be tested and trained on-job, using online data (Sarker, 2021).

In industries with systems and equipment’s operating and with production deadlines it is vital to define a maintenance plan and base it in data, basing the maintenance in the condition, and it should occur online (Burhanuddin et al., 2015).

Considering that maintenance has its cost, it is essential the management between the maintenance need of, the cost and the safety on material and human involved. To increase efficiency on maintenance the interventions should be clustered based on the time and the opportunity (Agergaard et al., 2022).

3.2.4. Data management in ships

Collecting and processing data in ships contributes to a better understanding and performance of the ships (Jovic et al., 2019). These systems are today’s reality but still have challenges in the horizon, sometimes data are not adequate for the implemented database, and cyber security risk can originate a system failure, bad functioning, and operation.

The use of collected data by AIS systems combined with other ship´s and port´s registers information can contribute for a more reliable conclusions and development of preventing risk accidents systems (Kongsvik et al., 2017).

Munim et al. (2020) who had written about AI (Artificial Intelligence) in ships refer as an example of AI in maintenance the work of Coraddu et al. (2016). A “unsupervised machine learning methods“ had been studied by Coraddu et al. (2019), considering the continuous monitoring of equipment’s functioning condition, observing and registering thermodynamic parameters and others, pointing these works for future studies in maintenance area.

“Establishment of a “Data Driven Culture” within a shipping company can clearly improve the current business model and at the same time promote sustainability” (Dakaklis et al., 2021).

The development of machine learning in ships it is imminent, and already ongoing, but there are futures risk that should be taken in account (Krestchmann, 2020). Considering Big Data, it is a reality in ships it is important to define indicators that allow the continuous knowledge of the imminent risk considering the maritime operations, but also the ship equipment’s and system performance.

Although applied to different kind of data, Feng et al. (2022) refer that maritime target data processing can process a limited size of AIS (Automation Identification

System) data, so they proposed for future research the appliance of Big Data Algorithm and cloud computing architecture to enhance the data processing.

"Big Data is the name given to the large volume of data – both structured and unstructured – that is generated in our personal and professional lives" (Trelleborg, 2018). It also refers that the study of the data from Maritime Industry can reveal some hidden information. How the collected data is structured, and the applied analytics can eventually allow to show eventual standards by clustering data and other graphic patterns. The document also enunciates that Maritime Industry have a slower adoption of the Big Data concept comparing with other industries, and only a few maritime companies apply the concept.

When analysing data, the analyst should make sure of the data quality, for its various methods can be applied. A ship performance monitoring system was defined by Bui & Perera (2021), in their study they present two data anomaly detectors, to test data quality, Figure 19. One detector considers minimum and maximum values and the other, considering its application after the digital modelling uses the singular vectors based.

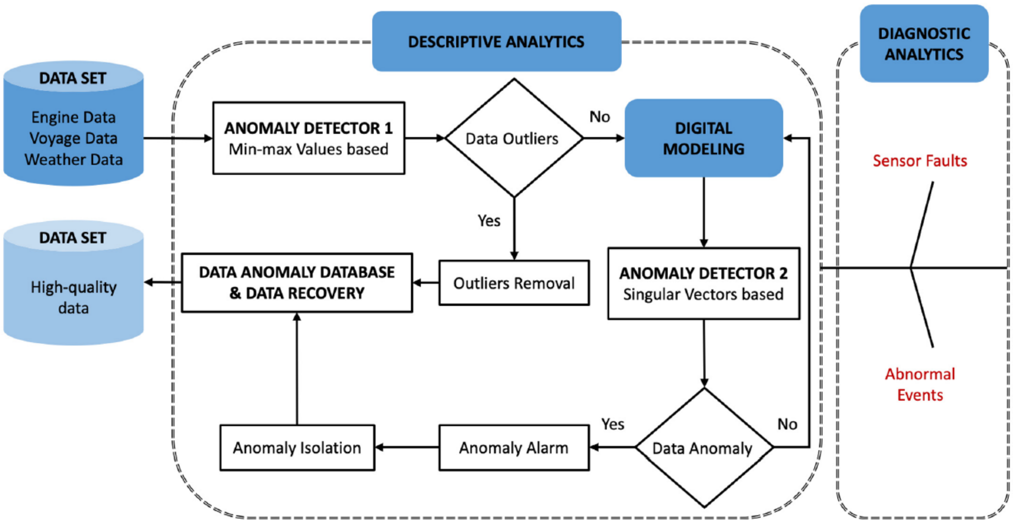


Figure 19 - Descriptive analytics
Source: Bui & Perera (2021)

Big Data face problems like data quality and the excessive quantity; they refer the advantages of the systems by eventually optimizing the "logistic network design and the energy efficiency. Along with cost reduction and environmental benefits, safety at sea can be also improved (Mirovic et al., 2018). Anomaly detection makes it possible to identify issues in real time so that they can be resolved as soon as possible" (Mirovic et al., 2018).

Nowadays ships are complex systems that generate large amounts of data. Onboard sensors and data acquisition systems are responsible for data collecting and processing, this data may be treated on board, in port or the owner's facilities (Perera & Mo, 2016). Ships may be collecting data and transmitting it by satellite for a data receiver responsible for transferring data to the system, that using mathematical algorithms making data useful, enhancing the energy efficiency, and the equipment's condition knowledge and consequently improve its reliability by reducing anomalies and help to plan the next maintenance intervention, Figure 20 (Perera & Mo, 2016).

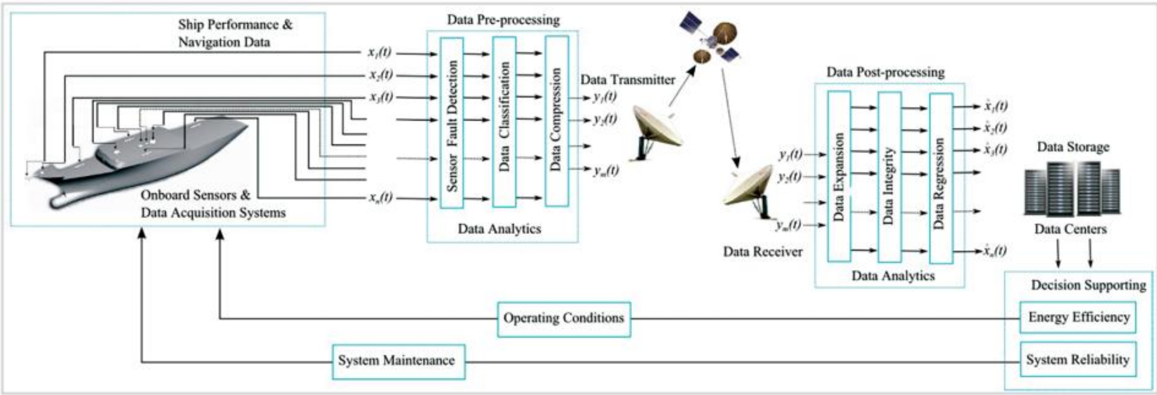


Figure 20 - Ship performance and navigation information
Source: Perera & Mo (2016)

Applying a risk evaluation matrix may be a useful tool to test the maintenance database security. And if this information system concept is maintained in time, with continuous online data feed, its knowledge will probably mitigate cyber-risk in maintenance database preventing unauthorize access and eventual damage (Lampreia et al., 2022).

3.3. Data and databases on Navy military ship equipment´s

In Portuguese Navy surface ships, there are various maintenance dynamic lists but not integrated or related with each other, Figure 21. For example, there are the various lists produced by the SRTD, the working lists where after evaluation represent decisions of the engineers after investigation of the need for maintenance, the lists of work produced by the shipyard, MMHS messages related to some anomalies, list of spare parts request in the Navy logistic system to the Supplier Direction, and other equipment historical lists produced on board and other Navy organisms.

As referred in Chapter 2, and although some occurred cyber-attacks, blockchain seems to be the most secure data structure to be applied in the data arrangement it is proposed in this thesis.

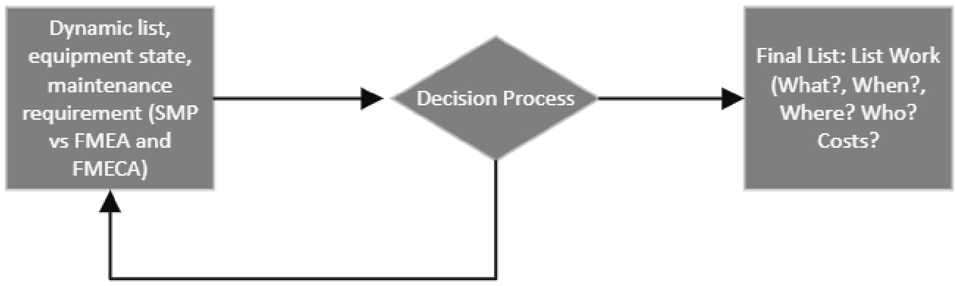


Figure 21 - Macro data supply

This study will be limited to processing data from SPM with FMEA and FMECA application, condition monitoring (e.g.: vibrations and thermodynamic parameters registration), threat state provided by the dynamic lists and software language, defining the procedures and methodology for data treatment (the decision process) and then the final decision support considering risk, priorities and maintenance options.

Nowadays the existing software that support information of the SRTD can´t directly and clearly support decision making to CN, SM, EMA and Supply Direction (DA – Direção de Abastecimento) organisms, which can lead to dispend more time to data analysis and to extract it value by the maintenance managers.

In Navy ships, when maintenance needs occur, the ship reports or requests the maintenance event at SICALN (an ORACLE language software, which represents the Navy Logistic Integrated System software for maintenance). A ship report of a maintenance corresponds to a 1st stage maintenance. The administrative command of the ships, ENS, which is responsible for processing the request from the ship may forward it to the 2nd stage workshop or sending it to the 3rd stage that is to DN to assess the work carried out by the shipyard. Parallel to this process the need of spare part is emitted to the logistic department.

For the third stage, the *Arsenal do Alfeite* SA (AA), it is the shipyard that, by law, Portuguese Navy must request the ship third stage maintenance, unless it does not have the capacity to execute. The shipyard receives the maintenance needs from the DN, but it has it owns database.

The SRTD is processed by the SICALN, the system is fed by the Integrated Logistic System (SLI - *Sistema Logístico Integrado*). The logistic information it is in SLI, and it is connected to DN, the organism responsible for software management. The SLI is also connected to Armed General Staff (EMA - *Estado Maior da Armada*), other Material Superintendence (SM - *Superintendência do Material*) organs and the CN. These organisms should have the maintenance information available and statistically treated to support decisions, but this type of systems is not implemented.

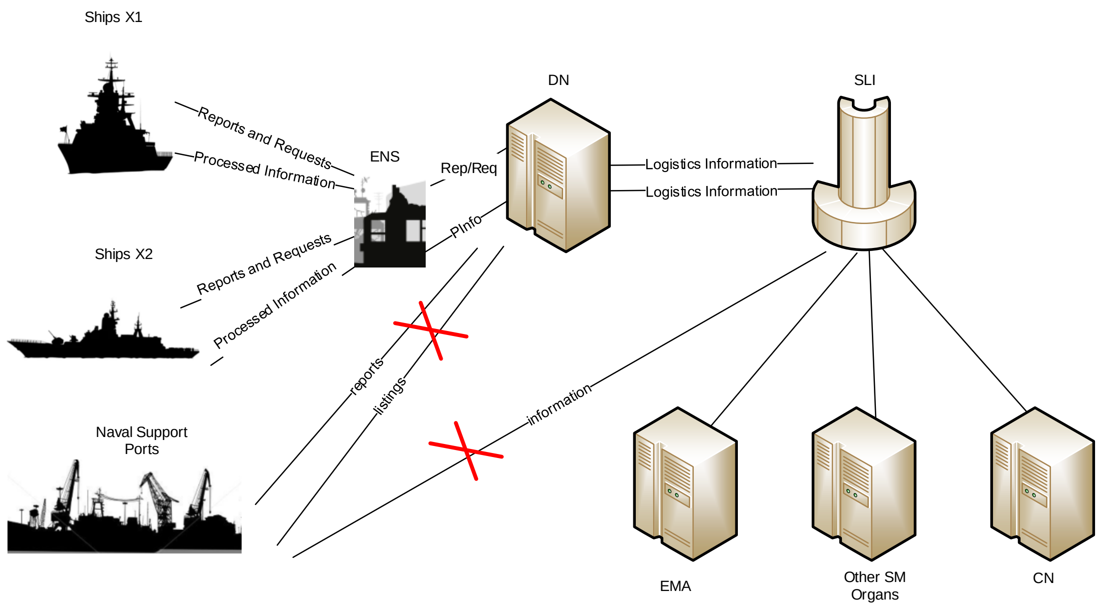


Figure 22 - Modified SRTD model
Source: adapted from Marinha_a (1984)
(EMA: Armed General Staff; CN: Naval Command; ENS: Surface Ship Squadron; DN: Ship Technical Directorate; SM: Materials Superintendency; SLI: Integrated Logistics System; Rep: Reports; Req: Request; PInfo: Processed information)

Figure 22 is an adaption of an image present on Marinha_a (1984), it was made some modifications to try to correspond to actual organization and connections. The connections between ships and the ENS and ENS and DN mean ships correspond to processed information or requests in three types of registering data models. These models are DSM58, DSM59 and DSM60 forms, more detailed on Subchapter 3.4.2 and Subchapter 3.4.3.

Allying the SRTD information with a dynamic database related to algorithm future development, may allow the users and managers to obtain the systems and equipment real state, serving as a base of decision-making.

There is a study where a system for predicting the demand for spare parts, was developed, it was verified that, according to the records in SICALN, there were possibly of unrecorded maintenances and others poorly registered, in terms of the type and stage of maintenance, which caused some constraints pursuing that research (Passinhas, 2013).

3.4. Portuguese Navy data collection and processing system

3.4.1. Navy data collection and treatment system

As referred before, some documents that are part of the SRTD are the: DSM58, DSM59 and DSM60. The requests and reports about interventions can be found in the DSM58 documents, but not with algorithms applied to treat data. Because of it, it was decided to include it on the research. DSM59 is the document where the equipment functioning hours, marine gasoil and oil consumption, and time operative limitations (Limop) and inoperative (Inop) are registered (Anexo B). The DSM60 is also an important document because it refers to spare parts request to the ship Supply Direction (DA) from Portuguese Navy.

The database scheme taken for ship flux maintenance data on the SRTD are represented on Figure 23. At this scheme can be observed how the information of text that will be analysed flows through a ship maintenance object, intervention and its description.

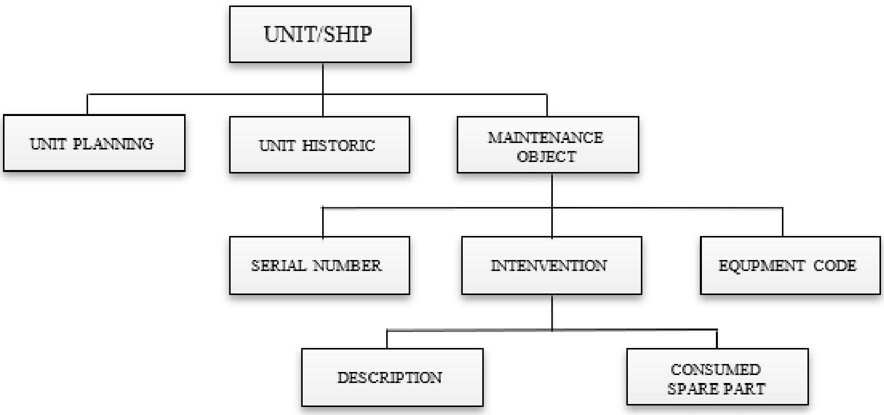


Figure 23 - Database scheme - maintenance data from Ship Technical Direction

On the present research, one of the study objects are the registering maintenance of a ship, considering the selected ship equipment or system and its work description on

DSM58. On Figure 24 it can be observed how the actions are taken through maintenance manifestation of need and its execution.

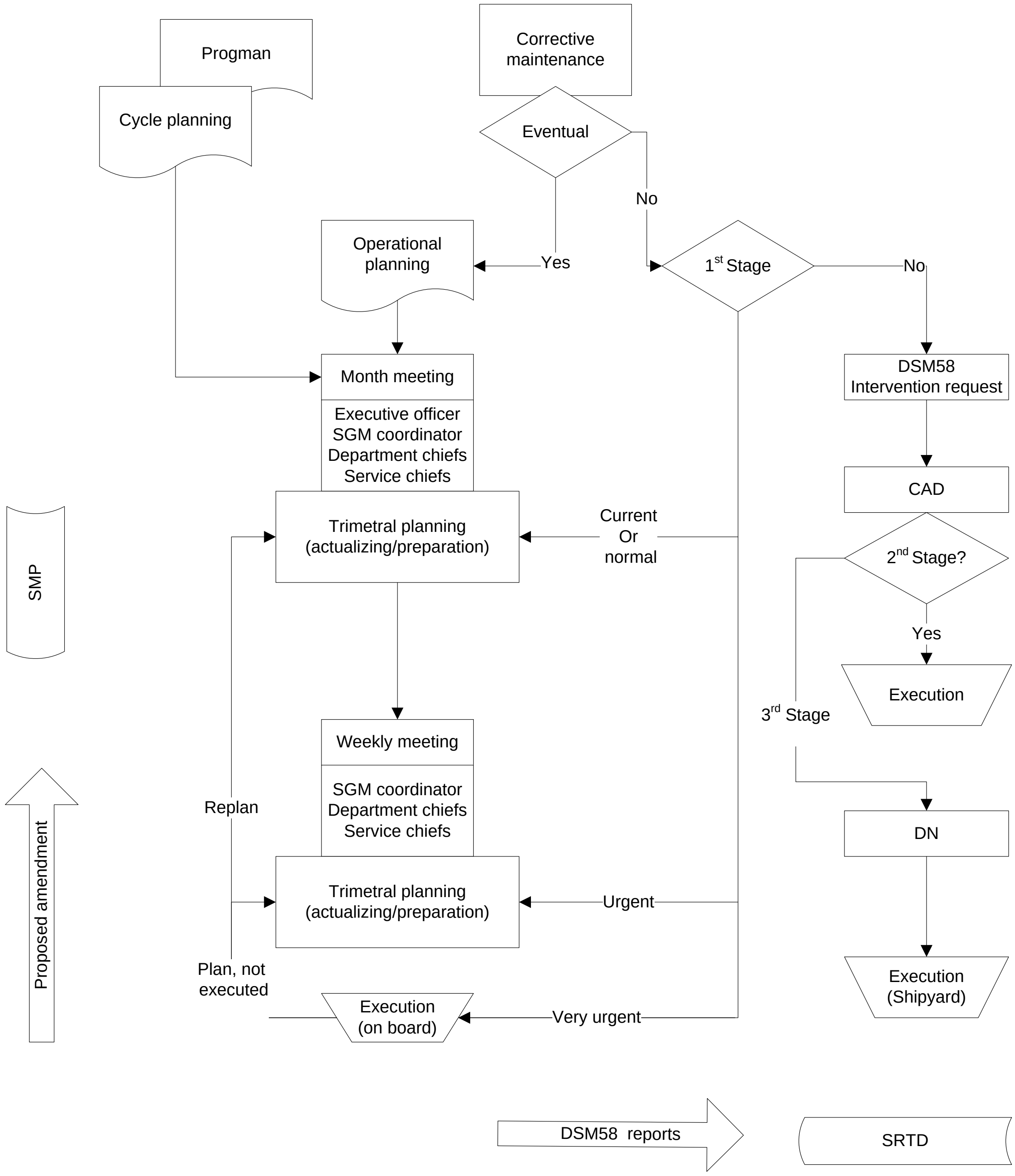


Figure 24 - Maintenance management system execution – actions
(Progman: maintenance progman; SGM: maintenance management system; CAD: administrative command; DN: ship technical directorate; SRTD: - Data Collection and Treatment System)
Source: adapted from Marinha_c (1998)

Also based in the SMP, there is institutionalized the PLAMANCURT (Maintenance Plan of Short Duration) and the PLAMANLONG (Maintenance Plan of Long Duration) defined by the Ship Technical Direction. This plan previews the ships mid-term revisions, minor revisions and general revisions which before it begins a shipyard intervene list should be built by the ship and reviewed by the Surface Ship Squadron (ENS – *Esquadrilha de Navios de Superfície*) and the Ship Technical Direction.

Regarding the types of maintenance used in the Organization, it is important to refer the problem of deciding which are the most appropriate type of it, for each case, considering the economic and personnel limitations. In this way, the SGM must find a balance between what needs to be done and the resources available.

To the present specific research, the intervention document from Navy SRTD that can feed in an online feeding database are the DSM58, DSM59, DSM60. For motives of data assessment and to limit the investigation only the DSM58 from the SRTD will be used. Other documents like SMP and equipment data and condition data analysis will be also used.

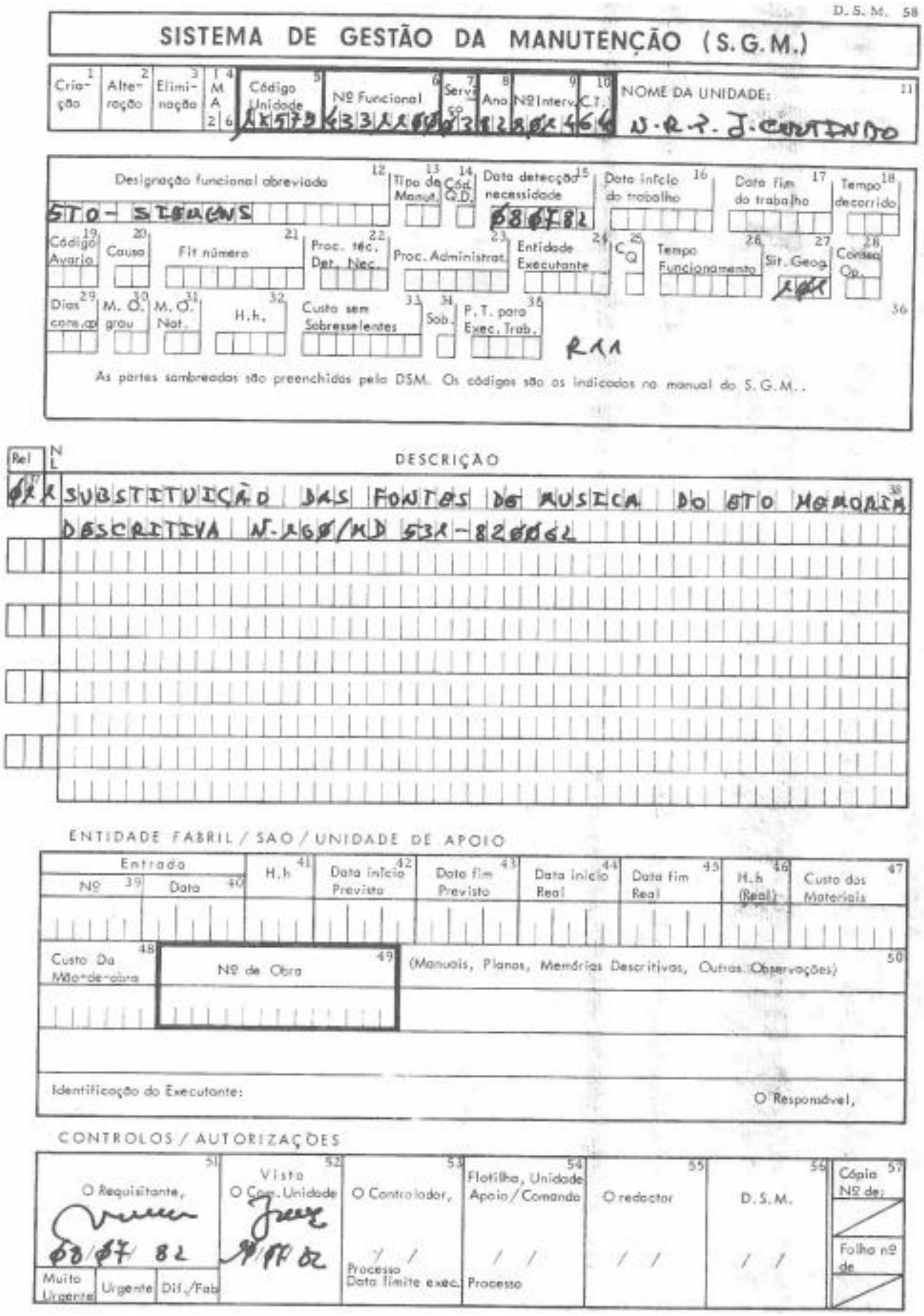
In the case of SMP there is the Planned Maintenance Cards (CARM) where the types of maintenance to each equipment are exposed, on the respective FIT´s the maintenance is explained step by step and are enunciated who are the specialist's area who execute it, the tools, and spare parts to request and use.

Although it will not feed the database, DSM59 and DSM60 from SRTD and neither the FIT´s, LIM´s document, some CARM´s with the generic maintenance activities from the selected equipment´s was used to elaborate the FMEA.

3.4.2. DSM58 document

The data from DSM58 document´s will be specified and treated. For example, with the ship identify number, the equipment functional number, the description will be analysed, options like a ship code number, equipment functional number, action description should be available to organize data that will be integrated on a decision support system.

An example of a DSM58 document is presented on Fig. 25.



D. S. M. 58

SISTEMA DE GESTÃO DA MANUTENÇÃO (S.G.M.)

1 Cria-ção | 2 Alte-ração | 3 Elimi-nação | 4 M A 26 | 5 Código Unidade | 6 Nº Funcional | 7 Serv. | 8 Ano | 9 Nº Interv. | 10 C.T. | 11 NOME DA UNIDADE: N.R.P. J. COUTINHO

12 Designação funcional abreviada: STO - SIEMENS | 13 Tipo de Manut. | 14 Cód. Q.D. | 15 Data detecção necessidade: 08 07 82 | 16 Data início do trabalho | 17 Data fim do trabalho | 18 Tempo decorrido

19 Código Avaria | 20 Causa | 21 Fit número | 22 Proc. téc. Det. Nec. | 23 Proc. Administrat. | 24 Entidade Executante | 25 C Q | 26 Tempo Funcionamento | 27 Sit. Geog. | 28 Condiç. Op.

29 Dias corr. | 30 M. O. grau | 31 M. O. Nat. | 32 H.h. | 33 Custo sem Sobresselentes | 34 Sob. | 35 P. T. para Exec. Trab. | 36 RAA

As partes sombreadas são preenchidas pelo DSM. Os códigos são os indicados no manual do S. G. M..

Rel | NL | DESCRIÇÃO

SUBSTITUIÇÃO DAS FONTES DE MUSICA DO STO MEMORIA

DESCRITIVA N.160/MD 531-820061

ENTIDADE FABRIL / SAO / UNIDADE DE APOIO

Entrada: 39 Nº | 40 Data | 41 H.h | 42 Data início Prevista | 43 Data fim Prevista | 44 Data início Real | 45 Data fim Real | 46 H.h (Real) | 47 Custo dos Materiais

48 Custo Da Mão-de-obra | 49 Nº de Obra | 50 (Manuais, Planos, Memórias Descritivas, Outras Observações)

Identificação do Executante: | O Responsável,

CONTROLOS / AUTORIZAÇÕES

51 O Requisitante, 08/07/82 | Muito Urgente | Urgente | Dif./Fab | 52 Visto O Com. Unidade | 53 O Controlador, / / Processo Data limite exec. | 54 Flotilha, Unidade Apoio / Comando / / Processo | 55 O redactor / / | 56 D. S. M. / / | 57 Cópia Nº de: Folha nº de

Figure 25 - DSM58 document

Source: Marinha_a, (1984)

The data from DSM58 document on excel software provided by the organization, extracted from SICALN, has the follow information in the presented order: The File Name (Non correspondent field name, because one filled DSM58 generates a file, where then the need information for treatment are extracted), the Year (Field 8), Unit Code (UC)

(Field 5), Intervention Number (Field 9), Intervention Description (ID) (Field 37), Necessity Data (DatN) (Field 15), Estado, Functional Number (FuN) (Field 6), Functional Description (Description of Field 6), Ship Service (Field 7), Anomaly Cause Code (Field 19), Description of Anomaly Code (Correspondent to Field 19), When Discovery Code (Field 14), Geographic Position When Discovery (Field 27), Description of Geographic Position When Discovery (Description of Field 27), Technical Process Open (Field), Transaction Code (Field 10), Description of Transaction Code (Description of Field 10), Maintenance Type (TM) (Field 13), Description of Maintenance Type (Description of Field 13), Technical Execution Process (Field 22), Execution Geographic Situation Code, Description of Execution Geographic Situation, Execution Start Date (Field 16), Execution Finish Date (Field 17), Graduation Code (Field 30), Speciality Code (Field 31), Description of Speciality Code (Description of Field 31), Man/Hour (Field 32), Executing Entity (Field 24), Operational Consequence Code (Field 28), Description of Operational Consequence (Description of Field 28), Situation State Code, Description of Situation State, Days in the State (Field 29), Quality Control Code and Description of Quality Control (Marinha_a, 1984).

The chosen fields for be used in database for the condition monitoring are UC, TM, FuN, ID, and DatN, because the ship need to be identified to analyse the risk of one specific equipment, the Functional number to identified the equipment, because it was found some errors on the fill of the Maintenance Type, this field will be maintained, the description field is the confirmation of what was actually made or are needed, and finally the Date, if some other studies like reliability are needed in future

UC code identifies the ship, and in the present study represent only one ship class and can be: 282, 283 and 284.

The functional number (FuN) used on DSM58 document has seven positions considering the classification levels Table 5:

Table 5 - FuN characters

Level Name	Level	Nr of Positions
System	5	1
Subsystem	4	1
Spare part	3	1
Sub-spare part	2	1
Group	1	1
Sub-group	0	2

The general FuN for the main equipment’s understudy, diesel propulsion engine (MD), is present in Table 6.

Table 6 - Equipment´s understudy

Functional Number	Selected Equipment
2331100	Mot PP EB
2331200	Mot PP BB

The equipment’s understudy has the same functional number in the other ships, in the DSM58 only the UC is different.

In Table 7, it is observed other equipment’s related to the propulsion diesel engine.

Table 7 - Equipment’s directly related to the engine propulsion

Functional Number	Selected Equipment
2411100	Starboard (SB) Gear Box
2411200	Portside (PS) Gear Box
2431100	SB Propeller Shaft
2431200	PS Propeller Shaft
2441100	SB Bearing Shaft
2441200	PS Bearing Shaft
2451100	SB Control Pitch Propeller (CPP)
2451200	PS Control Pitch Propeller
2613110	Marine Gasoil Purifier nr 1
2613120	Marine Gasoil Purifier nr 2
2643111	Oil Purifier
5515311	Low-Pressure Air Compressor nr 1
5515321	Low-Pressure Air Compressor nr 2

From Table 7 and for reasons of the existent data and study limiting it was chosen three equipment´s from the selected equipment’s of the Portuguese Navy Class of Ships understudy, the marine gasoil purifier nr 2, the oil purifier and the low-pressure air compressor nr 2, all these three equipment´s are in the propulsion diesel engine´s room. Other related equipment´s in this study were considered like demo, or operational. These equipment’s are related to propulsion diesel engines and were used to prove the dynamic maintenance theory to related equipment’s when the decision to intervention in the diesel propulsion engine is made.

The case study of this investigation will be mainly developed around the diesel engine propulsion and the three related selected equipment’s.

For Maintenance type the options in Portuguese Navy surface ships are 1ststage, 2ndstage and 3rdstage.

On the document DSM58, the field 13, the Maintenance Type, can be:

- 11 for a preventive systematic maintenance of 1st stage (*Manutenção Preventiva Sistemática 1° Escalão*);
- 12 for a preventive condition maintenance of 1st stage (*Manutenção Preventiva por Avaliação 1° Escalão*);
- 13 for a corrective maintenance of 1st stage (*Manutenção Corretiva 1° Escalão*);
- 21 for a preventive systematic maintenance of 2nd stage (*Manutenção Preventiva Sistemática 2° Escalão*);
- 22 for a preventive condition maintenance of 2nd stage (*Manutenção Preventiva por Avaliação 2° Escalão*);
- 23 for a corrective maintenance of 2nd stage (*Manutenção Corretiva 2° Escalão*);
- 31 for a preventive systematic maintenance of 3rd stage (*Manutenção Preventiva Sistemática 3° Escalão*);
- 32 for a preventive condition maintenance of 3rd stage (*Manutenção Preventiva por Avaliação 3° Escalão*);
- 33 for a corrective maintenance of 3rd stage (*Manutenção Corretiva 3° Escalão*)
- 42 for a change proposal in a system or equipment (*Alterações*);
- 99 for maintenance or manufacturer action not applicable directly to a specific system or equipment.

On Figure 26 it can be observed that the corrective maintenance of third stage is the one with more occurrences on SRTD database, and then corrective maintenance of 1st stage. The type of maintenance 99 has a significative occurrence, but in detailed data it was found some errors on registering data, where sometimes the type of data didn´t correspond to the type of maintenance.

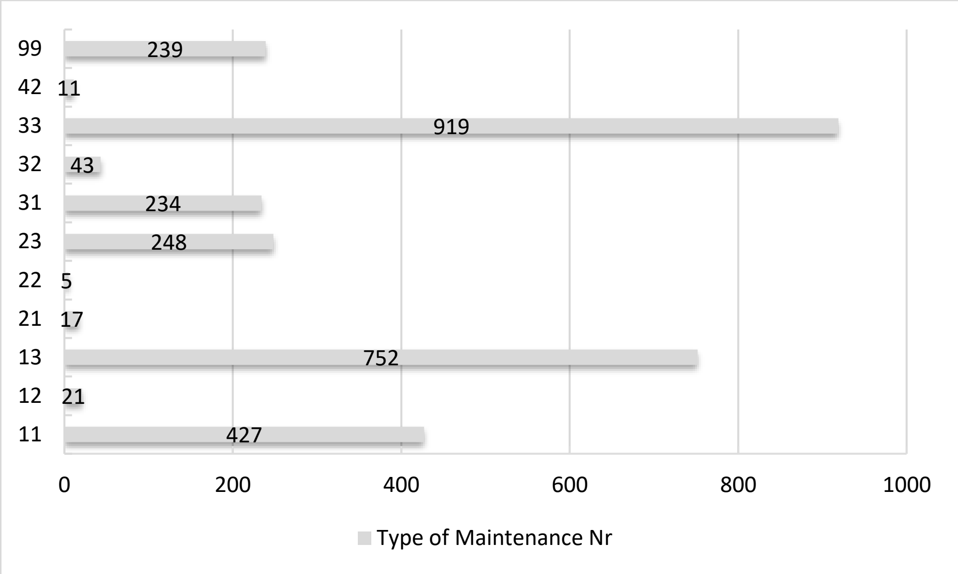


Figure 26 - Type of maintenance registered on SRTD for ship nr 3

Other documents were considered the condition monitoring sensors measures and analysis that are foreseen SMP and others not, like results of vibration and thermography measure and analysis, parameters like oil pressure and temperature. Other documents on the SRTD may also be data from Shipyard maintenance ship work list that was originally requested from the Ship Technical Direction.

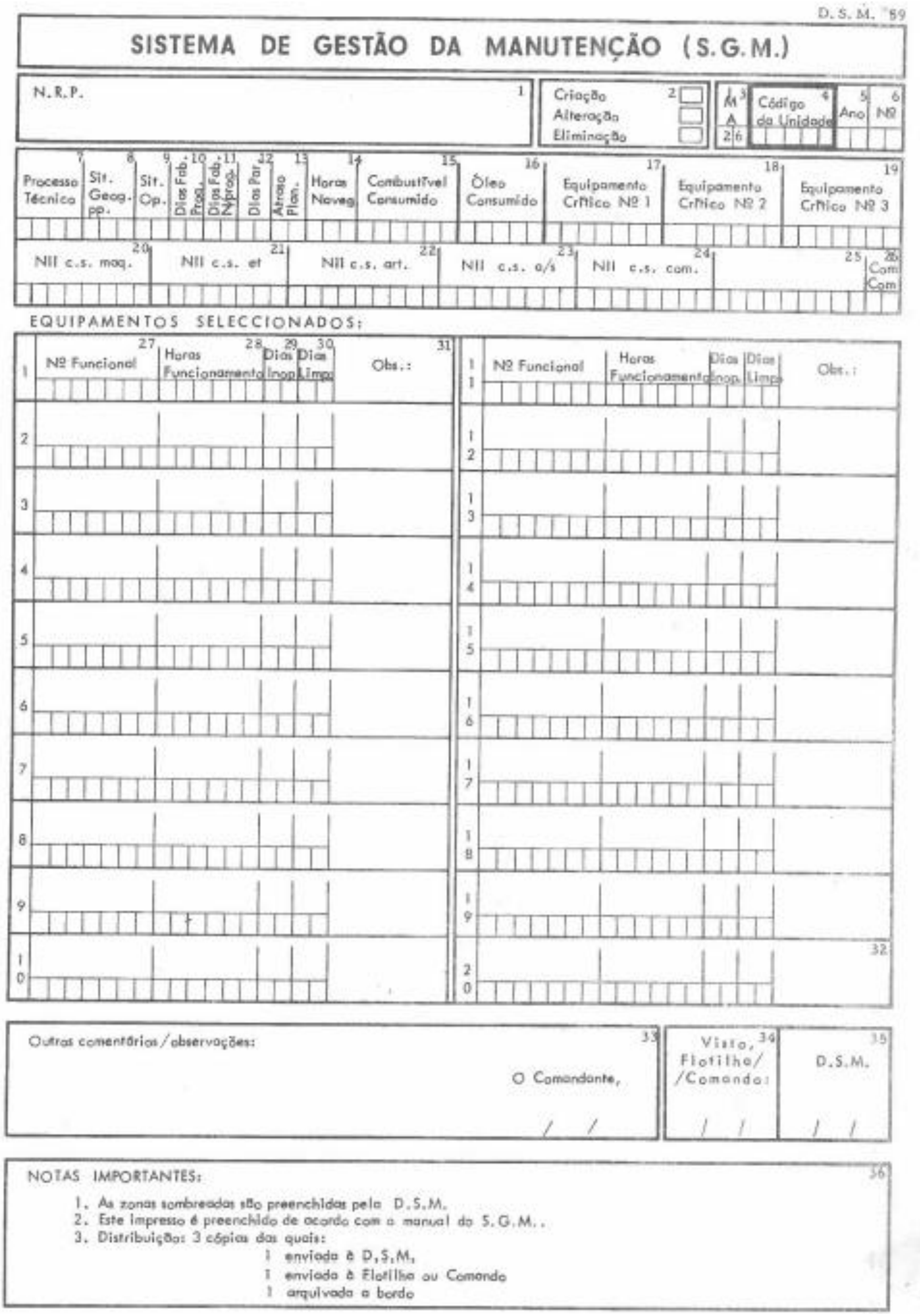
3.4.3. DSM59 and DSM60 document´s

The fields of the document that collected the equipment’s time function and inoperability periods (DSM59) that in further studies may contribute are Unit Code, Functional number, Total Functioning Hour (TFH), State of the equipment (SoE), Date (D), present in Table 8 (Marinha_a, 1999).

Table 8 - Selected data from DSM59

UC	FuN	TFH	SoE	D
…	…	…	…	…

On Figure 27 are presented the DSM59 document where the equipment operating hours from selected equipment´s are introduced (Marinha_a, 1984):



D. S. M. 59

SISTEMA DE GESTÃO DA MANUTENÇÃO (S.G.M.)

N.R.P. 1

Criação / Alteração / Eliminação 2

M / A 3 | Código da Unidade 4 | Ano 5 | Nº 6

Processo Técnico 7 | Sit. Geog. pp. 8 | Sit. Op. 9 | Dias Fab. Prog. 10 | Dias Fab. N/prog. 11 | Dias Par. 12 | Atraso Plan. 13 | Horas Naveg 14 | Combustível Consumido 15 | Óleo Consumido 16 | Equipamento Crítico Nº 1 17 | Equipamento Crítico Nº 2 18 | Equipamento Crítico Nº 3 19

NII c.s. maq. 20 | NII c.s. el 21 | NII c.s. art. 22 | NII c.s. o/s 23 | NII c.s. com. 24 | 25 | Com Com 26

EQUIPAMENTOS SELECCIONADOS:

Nº Funcional 27 | Horas Funcionamento 28 | Dias Inop. 29 | Dias Limp. 30 | Obs.: 31

1–20 | 32

Outros comentários/observações: 33

O Comandante,

/ /

Visto, Flotilha/ /Comando: 34

/ /

D.S.M. 35

/ /

NOTAS IMPORTANTES: 36

1. As zonas sombreadas são preenchidas pela D.S.M.
2. Este impresso é preenchido de acordo com o manual do S.G.M..
3. Distribuição: 3 cópias das quais:
   1 enviada à D.S.M.
   1 enviada à Flotilha ou Comando
   1 arquivada a bordo

Figure 27 - DSM59 document

Source: Marinha_a, (1984)

The chosen selected equipment's from DSM59 of ship class understudy (Marinha_a, 1984), are the ones on bold format in Table 9.

Table 9 - Selected equipment´s and its functional numbers

Functional Number	Selected Equipment	Functional Number	Selected Equipment
2331100	**Diesel Propulsion Engine SB (1)**	3112110	Generator 1
2331200	**Diesel Propulsion Engine PS (2)**	3112210	Generator 2
2341100	Gas Turbine SB	3112310	Generator 3
2341200	Gas Turbine PS	3112410	Generator 4
2411100	Gear Box SB	5515311	Compressor Ar BP 1
2411200	Gear Box PS	**5515321**	**Compressor Ar BP 2**
2431100	Shaft Line SB	5515111	Compressor Ar AP 1
2431200	Shaft Line PS	5515121	Compressor Ar AP 2
2441100	Shaft Bearing SB	5611110	Steering Gear
2441200	Shaft Bearing PS	5651101	Stabilizer EB
2451100	Variable Pitch Propeller SB	5651201	Stabilizer BB
2451200	Variable Pitch Propeller PS	5311110	Water Generator – Vaporizador Destilador
2613110	Marine Gasoil Purifier 1	5312110	Water Generator – Inverse Osmosis
2613120	**Marine Gasoil Purifier 2**	5932110	Oil Waters Separator
2643111	**Oil Purifier**	5931210	Wastewater Treatment Plant

The DSM60 document which represents spare parts requests, that could also in the future be part of decision system database are present on Figure 28 (Marinha_a, 1984):


7530-NI-013-0311
CONTROLO DE CONSUMO DE SOBRESSALENTES
D. S. M. 60 - ALT. 1
SISTEMA DE GESTÃO DA MANUTENÇÃO (S. G. M.)

NOME DA UNIDADE 1 | Cód. Unidade 2 | N.º Funcional 3 | Serv. 4 | Ano 5 | N.º Interv. 6 | Codigo de Equipamento 7

NNA / N.º Abastecimento 8 | N.º da Parte (Fabr.) 9 | 10 | Outra Identificação 11

NOME DO SOBRESSELENTE 12

N.º Série do Equipamento 13 | Nome do Fabricante 14 | Cod. Fabr. 15 | N.º Req. S. Téc. 16 | Prioridade 17 (R | U | MU)

Data Req. 19 | Exist. 20 | Quant. 21

Tabela de Armamento 22 | Lista Sobres. 23 | 24 | Localização 25 | Datac. 26 | Ficha 27 | Unidade Fornec. 28 | Data 1.º Aviam. 29 | Orig. 30 | Quant. 31

O Chefe Serv. Técnico 32 | O Chefe Serv. Abast. 33 | Satisfeito (Serv. Abastec.) 34 | Recebido (Serv. Técnico) 35 | Registado (Serv. Abastec.) 36 | Data 2.º Aviam. 37 | Orig. 38 | Quant. 39

Custo Unitário 40
1.º Fornec.
2.º Fornec. 41

OBSERVAÇÕES: Preencher os campos referidos, de acordo com o seguinte: 42

3 — Ver a lista dos números funcionais; 10 — Código de outra identificação (ver no manual SRTD); Desenho, Manual, figura, número de marinha origem, etc.; 16 — n.º dentro do Serviço Técnico, em cada ano; 22 — Vide na Tabela de Armamento; 23 — só na falta de TA; 24 — Inclui amostra : — S-SIM, N-NÃO; A preencher pelo Serviço Técnico; 17, 18, 19, 21, 32, 35 a preencher pelo SAB; 15, 20, 22, 23, 24, 25 a 31, 33 e 34, 36 a 41, 44 e 46.

Visto D. S. M. 43 | Requisição à DA N.º 44 Data

ATENÇÃO:
Este impresso só deve ser usado em unidades em que se aplica o Sistema de Manutenção. Serve para levantar sobressalentes do paiol e relatar o consumo de sobresselentes com outras origens.

Registado 45 | Quant. Requisitada à DA 46

AUTOCO/56 (2A6) 210 x 248 - Bl. c/ 5 x 40fls.

Figure 28 - DSM60 document

Source: Marinha_a, (1984)

3.5. Chapter elations

On Subchapter 3.1 it was exposed some concepts about databases, data processing and its management, considering dynamic databases which are the one it will be proposed to be implemented in a dynamic maintenance system. The cybersecurity and blockchain were brief introduced in the investigation, because the research needed to better understand the importance of secure maintenance information, and what were the measures of security should be taken if in the future a system like this will be running online in a navy ship.

Then on Subchapter 3.2 it is exposed some state of art of maintenance management, and in 3.2.1.1 the data management in ships.

On Subchapter 3.3 is presented the way maintenance data management is made in Portuguese Navy ships, focusing in the SRTD.

On 3.4 were present some of the maintenance databases that are managed on surface ships, and then the Data collection and processing system (SRTD).

And on 3.5 where the DSM58 document is presented and detailed.

4. Methodologies and methods on dynamic maintenance

4.1. Chapter introduction

When the author proposed this research to give a novelty scientific contribution, the major idea were implementing a dynamic maintenance system integrating the possible existing data related to selected equipment´s; SMP data, the SRTD data (including DSM58, DSM59, DSM60), database of existing spare parts in DA or other ships, data from condition monitoring (Vibration, Thermodynamic and physics parameters, thermography), reliability continuous study and the availability of electromechanical workshops and/or shipyards to pursue a maintenance if it is needed.

The referred data will be the basis for Dynamic Maintenance Database building considering its feeding, processing and results. Figure 29 integrates all the information of the original research idea, presented on the first paragraph of this chapter.

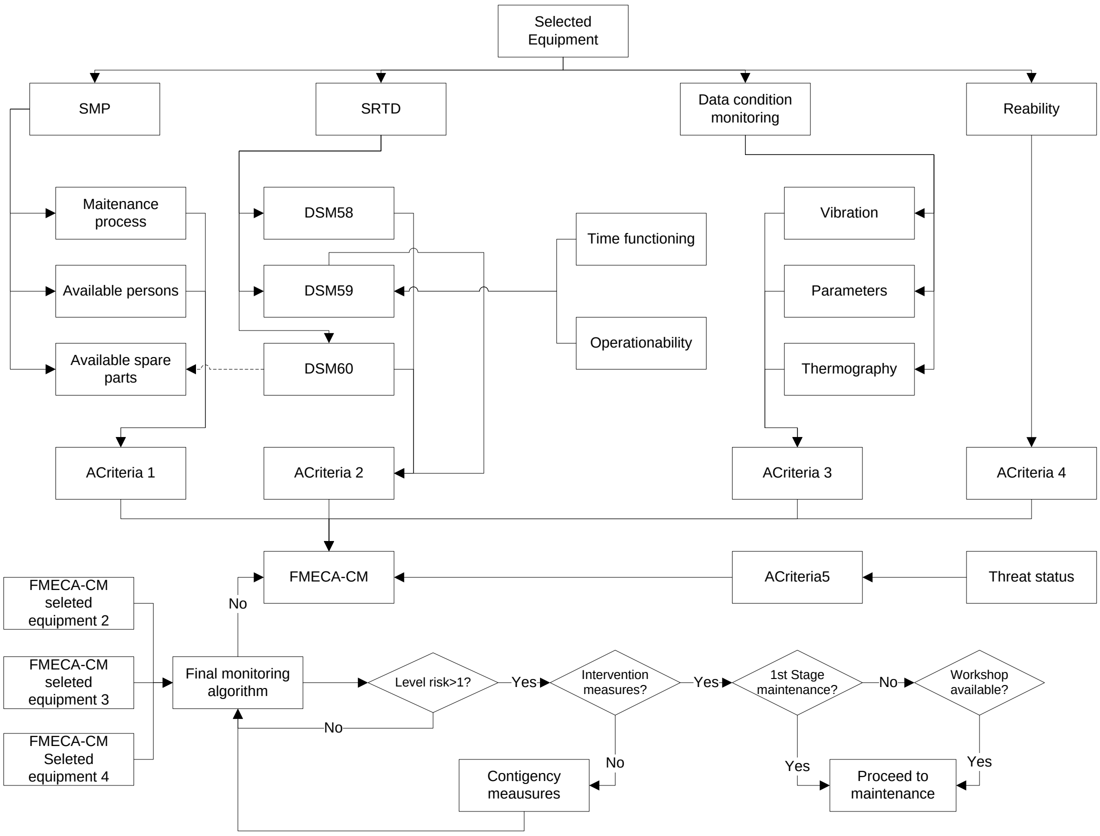


Figure 29 - General dynamic maintenance diagram

The present research was limited to SMP, DSM58 intervention reports and the available condition monitoring data and threat.

Although the author limited the study, it still is possible to integrate all data from a maintenance triangle (e.g.: material, personnel, collected data and operations environment). That information, empirically, are always used by the maintenance managers and operations persons, even without a mathematical algorithm implemented decision-making process, Figure 30. That information may support the knowledge of equipment degradation level defining operation limits, so ships can maintain navigation and accomplish attributed missions. The use of the four types of information, material, personal, collected data and operations environment, will be reserved for future studies.

Figure 30 – Maintenance triangle

To assume a certain level of risk, the decider must decide if the risk is worthy, for example, there is a difference between a routine mission, training mission, save and rescue mission and a National Security matters mission.

At the presented state of art, it may be found various methodologies for data treatment in maintenance that can be integrated in FMECA-CM. For reasons of limiting this study it was chosen to use the expedite methods that allow the various considered variables to be integrated in a unique decision system considering a rapid screening of the actual state of complex systems on the study selected from a warship. It is believed that the methodology that will be present will facilitate the results visualization by the systems and equipment's managers. In the present research the equipment's risk will be accessed by applying a modified FMECA, a FMECA-CM, where selected condition monitoring parameters, and the menace/threat environment in a context of dynamic maintenance will be integrated for a trustworthy maintenance decision making system.

For example, the expedite methods for engine vibrations, and oil Thermodynamic control will be the Modified Q Charts. For thermography of engine systems will be suggested neural network (for limiting study, not full developed and not considered in the final calculus), and for text detection on DSM58 expedite ways of software detection of words related to corrective maintenance.

4.2. Data from condition monitoring methodologies

In the present chapter the four chosen condition monitoring parameters categorization that will be exposed are: vibration, from the thermography images, from the pressure and temperature parameters, and from text from DSM58 document. One other parameter will be the threat environment.

The objective is to select the data to be keep and how to be organized and be used for the decision process based on a model.

4.2.1. Modified Q control charts in data processing

Now it must be defined how the condition monitoring - vibrations (CMV) and the condition monitoring - parameters (CMP) will be controlled.

On the last years, some developments have been present for statistical control charts application, besides its previous applications on control process stability. Control charts have been applied even to diseases surveillance (Hamm et al., 2022), monitor airplane accidents (Alevizakos et al., 2021), but also the equipment functioning performance (Rasay et al., 2018; Lampreia et al., 2018).

It had been shown that modified control charts (Lampreia et al., 2018) may be applied in equipment´s condition monitoring. Because the data collected from the ship was limited and exposed to various power regimes when working it was chosen to use the modified short run control charts (or modified Q Control Charts).

In the present investigation the chosen control charts will only be used to check tendency in the vibration and thermodynamics parameters and will to integrate a system called FMECA-CM.

Short run control charts were used in this study because data are not abundant and we will be dealing with data from equipment that undergoes continuous power variations, a ship's diesel propulsion engine. The fact that there is little data does not allow the mean and standard deviation of the records to be calculated with a high degree of confidence.

In the application of modified Q charts the data are considered independent, with normal distribution, a mean of zero and a unitary variance of $Q \sim N(0;1)$ (Lampreia, 2013; Pereira & Requeijo, 2012).

The Modified Q Chart (QM) was adapted to be applicable to equipment´s, Equation 8. The variable X is also transformed into the variable Q. The characteristic Q, considering the instant r will be (Lampreia, 2013):

$$Q_r(X_r) = \Phi^{-1}\left(G_{r-2}\left(\sqrt{\frac{r-1}{r}}\left(\frac{X_r - (T_L)_{r-1}}{S_{r-1}}\right)\right)\right) \qquad r = 4,5,\ldots \qquad (8)$$

In Q charts there is only one phase, the control chart being represented by to r. This type of card will allow monitoring of the equipment status from (Lampreia, 2013). The difference to the original Quenseberry charts is that the value of is replaced by that represents the limit defined by the manufacturer or by a standard, as applicable to the monitored equipment (Lampreia, 2013). At time r the mean and variance are:

$$\overline{X}_r = \frac{1}{r}\sum_{j=1}^{r} X_j \qquad (9) \qquad \text{and} \qquad S_r^2 = \frac{1}{r-1}\sum_{j=1}^{r}\left(X_j - \overline{X}_r\right)^2 \qquad (10)$$

In this Equations (9) and (10), X_r are the observation in instant *r* and $(T_L)_{r-1}$ are the vibration limit $(T_L)_r = (T_L)_N - 3\sigma_{r-1}$, $(T_L)_N$ is the limit defined by the manufacturer, S_{r-1} are the observation standard deviation $(r-1)$, $\Phi^{-1}(\cdot)$ is the inverse functioning of Normal Distribution and $G_\nu(\cdot)$is the function *T-student* with ν freedom degree (Pereira & Requeijo, 2012).

As the Q variables has Normal distribution, the charts limits, considering de detection of maximum values, are:

$$CL_Q = 0 \qquad (11)$$

$$AL = 2.5 \qquad (12)$$

$$UCL_Q = 3 \qquad (13)$$

Where CL (Equation 11) is the center line, AL (Equation 12) is the alert level and UCL (Equation 13) is the upper control level.

To diagnose the condition of the equipment, the analysis of the QM charts will not be carried out as in the original charts, so the limits defined for the machine under study will be considered and rules for action will be created.

Although the define rules for interventions, the charts limits should be adapted according to equipment age and performance, and even by the users and fabricants demands.

For more the detailed about the control charts and modified control charts Pereira & Requeijo (2012) and Lampreia (2013) should be respectively consulted.

4.2.1.1. Vibration categorization

For vibration values in this investigation, it was chosen to apply the modified control charts Q to measure and analyse vibration in the engine. This will represent a methodology for Vibration RMS Values treatment (Lampreia et al., 2018). At Table 10 the categorization of vibration to be included as a parameter in FMECA-CM are present.

Table 10 - Categorization of vibration

Value Attribution	Vibration (CMV)	Rules for Vibration Modified Q Charts
1	Low level	Less than 3 consecutive observations above AL
2	Low medium level (below alert level)	3 to 5 consecutive observations between AL and UCL
3	Average level (on the alert level)	More than 5 consecutive observations between AL and UCL
4	Medium high level (between alert level and alarm level)	5 consecutive observations above UCL
5	High level	More than 6 consecutive observations above UCL

In terms of integration in the risk matrix, it was considered only 5 levels, where it is considered level 1 (green) all the vibration parameters below the control limit, level 2 and 3 (yellow) the vibration between the alert level and the upper control level, and level 4 and 5 (red) the vibration above de upper control limit considering the individual observation control charts.

4.2.1.2. Temperature and pressure categorization

On the condition monitoring based on functioning parameters many parameters may be considered: like temperature and pressure from fluid, like freshwater, sea water, air compressor, marine gasoil and lubricant oil. For reasons of limitation, but also of importance for the chosen equipment, diesel engine propulsion was elected the lubricant oil temperature, the data from existing sensors and because it will be directly related to oil pressure (basis perfect gases Equation, PV=RT).

If one of this parameters, pressure or temperature, is above the limit level the value considered and to enter in FMECA-CM should be above the first value attribution these parameters. The oil temperature and pressure criteria are present in Table 11.

Table 11 - Oil temperature and pressure criteria

Value Attribution	Operating Parameters (Temperatures or Pressures) (CMP)	Rules for Temperature Modified Q Charts
1	Low level	Less than 3 consecutive observations above AL
2	Low medium level	3 to 5 consecutive observations between AL and UCL
3	Medium level	More than 5 consecutive observations between AL and UCL
4	High medium level	5 consecutive observations above UCL
5	High level	More than 6 consecutive observations above UCL

Where for level 1 it is considered a low level (green), then 2 low medium level (yellow) and 3 medium level (yellow) and nr 4 high medium level (red) and 5 high level (red). To define the levels, it was used the results of observing data with the support of Modified Q control charts.

4.2.2. Thermography categorization

Since Neural Networks have been applied on data treatment and filter, for example on medicine for interpretating images from breast cancer (Koay et al., 2004), it probably may be used in future work to threat thermal images acquired with thermal imaging camera. It is believed that, for eventual complementary performance diagnosis of diesel propulsion engines data neural networks may be used, and accordingly its results it can be framed in the categories to be integrated in FMECA-CM.

For reason of study limitation, and because there is no historical thermography data, it will only be defined the categories that can be included in FMECA-CM if in future thermal images will be acquired. In terms of FMECA-CM final calculus it was considered neutral.

The categorization was made accordingly the results of temperature that are associated to the colours of thermal images. It was considered 5 levels, level 1 (green) (no difference from the normal values), level 2 and 3 (yellow) (respectively 1º-4ºC difference from normal and 4º-15ºC difference from normal), and level 4 and 5 (red) (respectively difference 15ºC and maintains and difference >15ºC from normal).

The thermography categorization levels are presented in Table 12.

Table 12 - Thermography categorization

Value Attribution	CM Thermography (CMT)	Actions
1	Low level (no difference)	Equipment within normal parameters
2	Low medium level (1º - 4ºC difference from normal)	Possible deficiency; equipment under observation
3	Average level (4º - 15ºC difference from normal)	Probable deficiency; repair when possible
4	Medium high level (difference 15ºC and maintains)	Maintain surveillance until corrective measures are taken
5	High level (difference >15ºC from normal)	Large discrepancy, fix immediately

Because the lack of data this condition monitoring parameter will not be included in the final calculation of the FMECA-CM. The proposed methodology including data from thermography is appliable due to the integrative criteria definition, even after applied other methods like neural network, although it still needs the final validation with more collected data.

Figure 31 - Thermography on a Portuguese navy ship
Source: Marinha_e (2021)

By the analysis of Figure 31, the methodology analysis and validation were made to the Starboard (SB) Propulsion Panel. The representatives of Condition monitoring Cabinet from the Ship Technical Direction, had concluded that the terminals should be tightening, because the level were in level 4 of the categories in Table 12.

4.2.3. Text recognizing categorization

For the text recognizing and categorization, it should be selected the characters or words we want to detect and list.

In the present investigation it will be considered the characters or text from DSM58 fields. And the information flux from maintenance databases will be unit choice, the maintenance object (equipment or system), the intervention and its description, Figure 32.

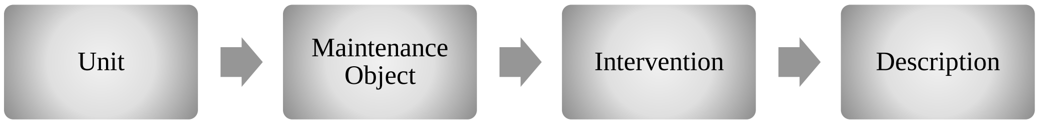


Figure 32 - Information flux or direction in text analysis

The chosen fields to integrate the database with DSM58 information are five: Unit Code (UC), Functional Number (FuN) (first three digits), Maintenance Type (MT), Intervention Description (ID) and Necessity Date (DatN). Why choose this fields? Because the ship need to be identified to analyse the risk of one specific equipment, the Functional number to identified the equipment, because it was found some errors on the fill of the Maintenance Type, this field will be maintained, the description field is the confirmation of what was actually made or are needed, and finally the Date, if some other studies like reliability are needed in future (Marinha_a, 1984).

The Unit Code (field nr 5) is where ship is selected, then the first three digits of the FuN (field nr 6) for diesel engines, the maintenance type (field nr 13), description field (field nr 38) and the necessity date (Field 15) of maintenance.

For field 6 the first three digits are chosen, for example 233 for propulsion diesel engines, because it takes in to account the system itself and all directly related subsystems, and the information can be processed to define the equipment state.

Referring to the observation of data from the DSM58´s, sometimes it was found that the field: “maintenance type” doesn´t match with the description of the work itself. For example, sometimes the user put the maintenance has been preventive, but it was corrective. So, one preoccupation is continuous maintenance literacy in the software’s maintenance and alert users for the importance of a correct the fields filling. So, field 13 Maintenance Type, has a contradiction, this is a field not necessary, or the only one necessary, but it is a desirable information of confirmation and proves if the code was attributed correctly. It will fill the table with fourth column of results.

The selected words in field 38 are in Portuguese because is the official language of SRTD – SICALN. The words for the word counting in field 38, considering the equipment’s understudy (diesel propulsion engine, seawater an air filters from diesel engines propulsion, air compressor, diesel purifier and oil purifier) are suggested to be:

- “correctiva” ou “corretiva” (corrective);
- “reparar”, “reparação”ou “reparado” (repair, repairing);
- “substituir”, “substituição” ou “substituido” ou “substituida” (substitute, substituing);
- “limpar”, “limpeza”, “limpo” (clean).

On field 15 (Data necessity) is where it is checked if the DSM58 information fits in time with other databases related to the condition of the equipment.

In case of the related equipment´s, the FuN will be full searched in the DSM58 document, because they are specified with more characters. This search in the present research will be done for the selected equipment’s on the “house of diesel engine propulsion systems”: “2613120” for marine gasoil nr 2, “2643111” for the oil purifier and “5515321” for the Low-Pressure Air Compressor.

Why only consider corrective maintenance? Because on the risk analysis the planned maintenance was already included in the FMEA, and physical changes or other events to the systems if not related to an anomaly are also rejected on the present investigation for reasons of study limitation.

The result table/database design with the compile information about DSM58 are presented in Table 13, where ON is the order number of interventions, and the others are like descripted in 3.4.2 of this thesis.

Table 13 - Selected data from DSM58

ON	UC	FuN	MT	ID	DatN
…	…	…	…	…	…

The recognizing text to support determination of the equipment state can also be extended to other document like the military communication systems, MMHS (Military Messaging Handling Systems, NATO Terms), where can exist information about equipment state, and others like spare parts requisitions, DSM59 which refers functioning hours and the state of selected equipment’s, official documents (e.g., offices and notes), and other used databases. For the present study only the DSM58 text will be considered.

For reasons of limitation it was chosen a simple method, creation of a simple software language for counting the occurrences of words and distribute the results (attributed values) according to text occurrence categorization, presented in Table 14.

Table 14 - Text occurrences categorization

Value Attribution	Text Detection about engine and corrective maintenance
1	No occurrences in the last 5 years
2	Occurred once in the last 5 years
3	Occurred between 2 and 5 times in the last 5 years
4	Occurred 5 to 10 times in the last 5 years
5	Occurred more than 10 times in the last 5 years

Like in vibrations and temperature the level 1 was considered a green level, then 2 and 3 the yellow level and nr 4 and 5 the red levels. To define the levels, it was used the results of observing data with the support of Modified Q control charts.

4.2.4. Threat situation

In the Portuguese Navy there is a threat categorization on land units and on ships. For classified information only general information of organization will be exposed and the publications will not be referred, and then the author categorization of threat levels is independent of military information. This categorization will only be used to demonstrate that in a dynamic maintenance database from a military ship, but maybe also to civilians, it is possible to integrate in the FMECA-CM the threat information.

The threat analysis can be included on FMECA-CM considering two perspectives: One is that the can functioning till its limits, even without performing preventive or conditional maintenance, and other that consider that maintenance should really be performed so ship maintained high operation performance.

The last terms are the one considered in the present study, but the most important concept about this model is that the decision maker has always the information about the ship state and its equipment limits.

4.2.4.1. Threat assessment

The threat is an important parameter because instable environment may have negative impact of infrastructure. There are some studies in this area that refer the importance of infrastructure and give an example of economic infrastructure and Military Infrastructure, Table 15 (Krzykowski, 2018).

Table 15 - Strategic infrastructures

Economic and social infrastructure	Military infrastructure
State Defense management posts	Armed forces command posts;
Government administration facilities crucial for State Defense;	State air defence system components;
Communications and telecommunication systems components regarding state management;	Integrated recon system components;
Material reserve bases and stockpiles;	Telecommunication, and postal system components used by the armed forces;
Food maintenance and processing facilities;	Special-purpose military structures;
Important facilities and devices: transport, hydro-technical, power;	Facilities and devices of military naval bases, road sections of strategic importance, military aero-bases, manufacturing military technology workshops.
Work, equipment manufacturing facilities and materials for defence purposes;	-
Important facilities and public devices	-
Banks and taxes facilities	-

Source: adapted from Krzykowski (2018)

To define a categorization considering threat risks on military installations, in the case of Navy ships, the author considered three steps of risk: possible occurrences, effects and its mitigations:

First phase: possible occurrences

a. Causes of Communication loss (e.g., loss of signal, hacking, or interference in communication systems);
b. Logistical interruptions (e.g., blockages or destruction of supply lines of essential materials);
c. Cyberattacks (e.g., intrusions into digital systems causing malfunctions like malware, phishing, hacking,);
d. Physical damage to a ship and its equipment (e.g., caused by missile, explosions).

Second phase: effects of those failures on systems and operations

a. Communication disruptions can lead to lack of coordination, operational errors, loss of control over important assets;

b. Logistical disruptions can cause operations to stop due to lack of spare parts or materials;
c. Cyberattacks can disable control systems, leak sensitive information, or cause operational systems to malfunction;
d. Physical damage can result in loss of critical equipment, risk to human life, interruptions of essential operations (e.g., MMHS system).

Third phase: mitigations and corrective actions for threats

a. Physical protection measures: Strengthen infrastructure, eventually build bunkers, install defense systems;
b. On Cybersecurity it should be improved firewalls, use encryption, implement intrusion detection systems, database with blockchain structure;
c. On logistics management it can be created stocks, develop supply alternatives (like using addictive manufacture), logistics planning for war scenarios;
d. Contingency plans: Establish rapid response and recovery plans for different types of failures.

4.2.4.2. Threat categorization

With reason of study limitation and simplification with a considered good level loyalty to reality, and considering the previous assessment to threat its effects and possible ways of mitigation it, the possible threats were integrated in FMECA-CM.

It was made no difference between whether the ship was at shore or at sea, the categorization was made thinking that: if the equipment is immediately needed if it is available and what is level of performance.

At Table 16, like in the previous categorization for other parameters, and after conducting various simulation on information and attributed values, it was considered five level attribution, considered an integrated threat level (threat level, threat status (TS) or threat situation), enunciating the cause in the fourth column and the correction action to specifically this parameter to be integrated in the action to take when the risk is high (column five).

Table 16 - Threat situation categorization

Value Attribution	Threat Status	Threat Occurrence	Cause	Corrective Actions
1	No threat	Without Threat	Peace Environment	Surveillance systems in the 5 types of affect/failure modes
2	Slight threat	Only Threat and Bluff	Reinforce investment in security systems	Reinforcement of surveillance systems in the 5 types of affect/failure modes
3	Medium threat	Cyber Attack	Malware, network invasion	Implementing intrusion detection systems
4	High medium threat	Communications and logistic interruption	Systems hacking	Improve cybersecurity, use redundancies
5	Imminent threat	Physical damage from bombing/Explosion	Air attack	Strengthen structures, install anti-aircraft defenses

It was considered that, the threat state affects the selected equipment's in similar ways, so, once defined it is the same for all maintenance procedures for all equipment's.

4.3. FMEA on ship equipment

To access equipment state considering the SMP and applying a Failure Mode Effects and Analysis it was made a critical analysis, considering a FMECA approach.

To implement a FMEA first the equipment should be selected, then its maintenance activity plan should be consulted (First column), and for each maintenance task it should be made a failure mode effects and its analysis considering the next: potential failure mode (second column), the failure cause (third column), failure effect (fourth column) and how to detect it (fifth column), Table 17.

Table 17 - Example of a table for FMEA

Maintenance Activity (SMP)	Potential Failure Mode	Failure Cause	Failure Effect	How detect/detection
…	…	…	…	…

4.4. FMECA-H-CM methodology in ship equipment

Using the same FMEA for assessment the equipment state considering the SMP and integrating data from equipment's condition monitoring, a FMECA-CM was developed to be included in the decision to do, or not to do the maintenance procedure and to know the risk level if not do it.

FMECA assessments are made considering an equipment or system, its function, failure mode, cause, effect, the way of detection, the equipment Severity, probability, criticality and recommended actions. In the present thesis it was added the condition control data to enhance the FMECA performance and Threat environment to integrate military concept on it.

During the critic evaluation to attribute the weight of criteria on the various variables, including the level of risk, were observed the results of FMECA-CM according to the author evaluation, and other observers. For the condition control data, it was also analysed through real data and with simulated data, considering the aggravation of anomalies, so the FMECA-H-CM could support decision and maintenance prioritization with most realistic results.

From the general methodology presented on Figure 29, only SMP, SRTD and condition monitoring data will be used. And from SMP only the maintenance process, of the DSM58 document of SRTD and from condition monitoring data the vibration and thermodynamic parameters.

For the proposed methodology it was considered various steps:

Step 1 - Choice of the equipment's to implement FMECA-CM;
Step 2 - Apply a FMEA immediately follow by a Critically Analysis;
Step 3 - Validate the responses of the investigate the FMECA calculus should be done by other experts, and to that it is called humanize the responses, FMECA-H-CM;
Step 4 - Chose the control condition parameters to be integrated in FMECA-H-CM;
Step 5 - Define the limits for intervention;
Step 6 - Validate the limits, performing some tests and simulations;
Step 7 - Analysis of results should be done to appreciate FMECA-CM performance; If the performance is not good it should return to step nr 2, if the performance is good, it continuous to step nr 8.
Step 8 - Define the dependency of maintenance between equipment's and do some simulations;
Step 9 - The performance of the FMECA-H-CM that integrate various equipment´s are analysed, if the performance it is bad it returns to step 8, if it is good it passes to step nr 10.
Step 10 - The connection and dependency of equipment's are fixed.
Step 11 - Define others equipment´s parameters for condition monitoring should be defined;
Step 12 - The FMECA-CM are operationalized for a continuous and online monitoring;
Step 13 - Threat level is integrated n FMECA-H-CM;
Step 14 - Are the results reliable? If yes continue to step nr 17, if not return to step nr 8;
Step 15 - The risk level is above 1? If yes continue to step nr 17 and evaluate if some measures are possible, if not proceed to step nr 16 where it is checked if all the condition monitoring data are below criteria nr 3.

Step 16 - Is the condition monitoring data under control? If CM are not in control, we should proceed to step 17, if it is under control proceed to step nr 20;
Step 17 - Applying maintenance measures are possible considering spare parts and degree of readiness? If yes evaluate if there's time till next mission and shipyard availability (step nr 18), if not evaluate if the equipment can still function or if not, the ship may accomplish the mission (step nr 19);
Step 18 - Time and shipyard available for maintenance? If yes, it proceeds to step nr 21, if not procced to step nr 22;
Step 19 - Check if, although a degraded state or equipment inoperative, the ship still and ship accomplish its mission? If yes procced to step nr 23, and if not procced to nr 24;
Step 20 - Online continuous monitoring;
Step 21 - Define planned maintenance measures;
Step 22 - Define contingency/Maintenance Measures;
Step 23 - Online continuous monitoring. Not evasive maintenance. Prepare for emergency;
Step 24 - Preparing for maintenance or hibernate system.

On Figure 33 it can be seen specifically the FMECA-H-CM methodology with the various Steps, when data is integrated.

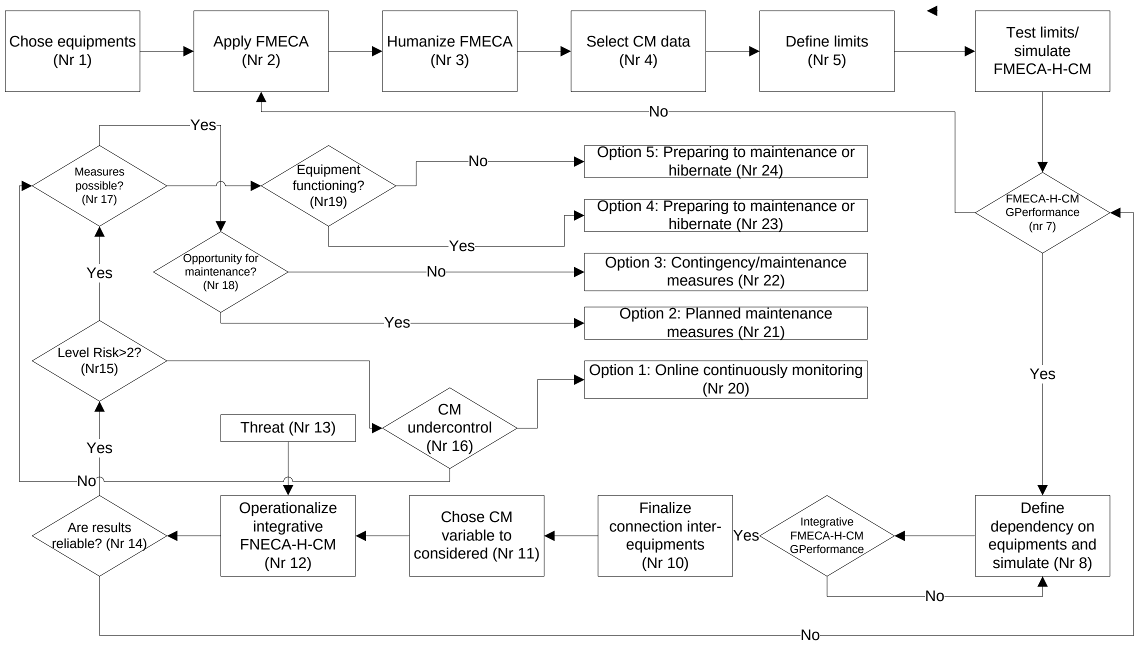


Figure 33 - FMECA-H-CM methodology

(CM: condition monitoring; GPerformance: good performance)

In Table 18 can be observed 5 options according to the results of the calculated risk and the defined, methodology.

Table 18 - Action option given the level of risk

Options	Actions	Previous correspondence on methodology	Risk level
Option 1	Good equipment performance, do online monitoring with normal periodicity (Step nr 21 of FMECA-CM);	Step nr 16 if yes	Nc
Option 2	Just do the planned maintenance when its possible (limiting the wait time), material and personal and financial resources, considering eventual maintenance to others equipment's, if shipyard available (in material and personnel resources) (Step nr 18 of FMECA-CM);	Step nr nr 18 if yes	Lc
Option 3	Define minimal maintenance (contingency) so the ships can fulfil the mission, considering eventual maintenance to others equipment's, always considering when, where, who and how the maintenance will be accomplished. Reinforce online monitoring (Step nr 18 of FMECA-CM);	Step nr nr 18 if no	Sc
Option 4	Only not evasive actions, take full risk, ship navigating. Reinforce online monitoring. Prepare for emergency (Step nr 22 of FMECA-CM);	Step nr nr 19 if yes	C
Option 5	Don´t take any action, ship considered inoperative, prepare for maintenance or hibernate (Step nr 17 of FMECA-CM, for the equipment's that working);	Step nr nr 19 if no	Vc

If option 1 and option 2 are taken the follow-up to the corrective action should be taken.

If option 3 is taken the engines and systems should have reinforced surveillance and possible condition monitoring measures to not compromise human life and the platform integrity.

In the evaluation of the author, it was considered the follow "premise": maintenance of the first stage/level can be always accomplished (e.g., oil and marine gasoil filters change, oil change, observations check without dismount, etc), except some exceptions.

The sub-methodology actions, FMECA, or more detailed FMECA are: transfer information from the FMEA to the FMECA; classified the failure effects by severity, occurrence and detection; perform criticality calculations; rank failure mode criticality and determine equipment and/or it´s items are on risk; made the FMECA available to experts to validate the FMECA results; and periodically revise the FMECA basis, the methodology can be observed on Figure 34.

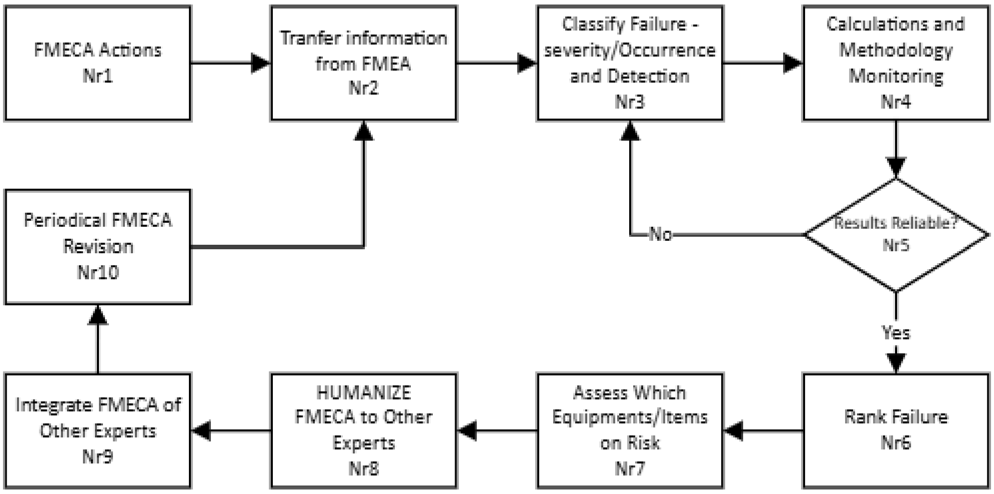


Figure 34 - FMECA detailed procedure

On Figure 34, on the Step 6 when ranking failure mode, it will be included the condition monitoring data with origins in vibration measure, temperature from oil lubricant, and text from DSM58 document of SRTD Portuguese surface ships.

On the FMECA analysis the same principle for calculation of the Risk Priority Numbers (RPNs), it was considered various severities, but it was inserted the mean of the five considered. Then will be integrated with the Condition monitoring data and the threat environment. So, it will be used severity mean (S_m), occurrence probability in FMECA (O) and the detection (D), and the product of the three, represents the RPN from the Dynamic Maintenance (RPN_{DM}), Equation 14.

$$RPN_{DM}= S_m*O*D \qquad (14)$$

Where S_m on Equation 15 is:

$$S_m=(S_S*S_A*S_E*S_P*S_O)/5 \qquad (15)$$

To integrate condition monitoring (CM) on the generic FMECA-H-CM, like on the methodology on Figure 33 and Step 6 of Figure 34 it is used temperature, pressure, vibration, thermography, elected text presented on documents registration, DSM58 and other information which are may also be categorized and integrated considering the product of this data.

When developing the calculus equation, it was tested Equation 16 and Equation 17, but the results of first one was too high and the second to low. It was also tested Equation

18, but the values were still too high and then to define the risk level the jumps between values assigned by the categorization were very large and unbalanced.

$$\text{FMECA-CM}_a = Sm*O*D*[(CMV+CMT+CMP+CMTex)/4]*T \qquad (16)$$

$$\text{FMECA-CM}_b = LN[Sm*O*D* [(CMV+CMT+CMP+CMTex)/4]*T] \qquad (17)$$

$$\text{FMECA-CM}_c = Sm*O*D* LN[(CMV+CMT+CMP+CMTex]*T \qquad (18)$$

Where:

CMV	– Control of vibration
CMT	– Control of thermography
CMP	– Control of Parameters (e.g., temperature or pressure)
CMTex	– Control of number of occurrences of previous selected words.
T	– Threat

After some simulation it was chosen Equation 19. The FMECA-CM integrated the RPN_{DM} and the CM information scales using the logarithm neperian bases to contain the results scalability, Equation 19 are proposed for diesel engines, where naturally T parameter are included. Although for the present study of diesel propulsion engines and considering the existing data, the CMT it will not be included, because there are not available data, so Equation 20 will be used for diesel propulsion engines.

$$\text{FMECA-CM} = Sm*O*D* LN [(CMV+CMT+CMP+CMTex)/4*T] \qquad (19)$$

$$\text{FMECA-CM} = Sm*O*D* LN [(CMV+CMP+CMTex)/3*T] \qquad (20)$$

For other equipment (marine air filters and sea water engine sub-systems, low pressure air compressor, diesel purifier and oil purifier) the calculation of FMECA-CM is made using Equation 21, because there are no registering of vibration thermography and thermodynamic parameters data for those equipment´s.

$$\text{FMECA-CM}_O = Sm*O*D* LN [(CMTex)*T] \qquad (21)$$

In Table 19 it can be observed the defined severity criteria considering the various severities.

Table 19 - FMECA-CM severity criteria

Value Attribution	Security Severity	Environment Severity (S_E)	Equipment Severity (S_{Equ})	Severity on People (S_P)	Operational Severity (S_O)
0,1	Without impact	Without impact	Without impact	Without impact	Without impact
1	Low impact	Low impact	Low impact	Low impact	Low impact
2	Medium impact	Impact medium severity	Equipment working without security systems	Health impact	Severe impact
3	Severe impact	Severe impact	Equipment operating in general degraded mode	Impact on health with absence from the service	Limop ship
4	Inoperational ship	Impact on the interior of the ship	Inoperative equipment with redundancy	Permanent health damage	Limop ship at risk of imminent failure
5	Impact in the ship platform safety	Aggravated internal and external impact	Ship INOP_Equipment inoperative without redundancy	Risk to life	Dead Ship

In Table 20 the severity criteria and the correspondence occurrence.

Table 20 - Severity criteria and consequence correspondence

Severity - Value	Occurrence	Occurrence - Value
0,1	None	0,1
1	Incidental	1
2	Minor	2
3	Medium high	3
4	Serious	4
5	Major	5

In Table 21 the criteria of occurrence and detection.

Table 21 -FMECA-CM criteria for occurrence and detection

Value Attribution	Occurrence (O)	Detection (D)
0,1	Occurred more than 10 years ago	Easy detection
1	It occurred between 5 and 10 years ago	Detection difficulty medium low
2	Occurred less than 5 years ago	Medium difficulty detection
3	Occurred less than 1 year ago	Detection difficulty medium high
4	Occurred less than 6 months ago	Extremely high difficulty detection
5	Permanent	Not detectable (until something goes wrong

The risk levels or significance for the selected equipment's for study, its linguistic term, a succinct description, classification considering the obtained FMECA-H-CM corresponding to a risk level and respective prioritization are present in Table 22. Table 19 was defined to be applied to the diesel propulsion engine system and to the other selected equipment. These levels were determined after various simulations that allow to decide the reasonable limits of each critic levels.

Table 22 - FMECA-H-CM risk levels and prioritization

Linguistic term (Risk level)	Abbreviation	Description	Classification	Risk Level	Priority
Not critical	Nc	Risk is totally controlled	[0, 19]	1	5
Less critical	Lc	Risk is controlled	[20, 49]	2	4
Semicritical	Sc	There is a preoccupation about the equipment and system state	[50, 159]	3	3
Critical	C	There are some preoccupations about the critic equipment/system situation	[160, 250]	4	2
Very critical	Vc	The equipment/system are in a very critical situation	[251, 402.36]	5	1

Considering the Equation 19, Equation 20 and Equation 21, because it was decided to use the mean of data from condition monitoring, the classification limits for risk level stays the same.

The results of applying FMEA and FMECA-H-CM are presented in 6.3.1, 6.3.2 and more detailed and complete on a link constant on the end of point a.1 of Annex A and on Appendix C.

For the implementation of FMECA-H-CM, it was considered that both diesel propulsion systems are the unique propulsion systems of the ship. The resume of FMECA-H-CM methodology is present on Figure 33; the detailed original methodology is present on Figure 29.

The proposed risk matrix for the FMECA-H-CM is presented on Figure 35, crossing only information of risk and severity a coloured result is given, green corresponds to a lower risk, yellow to medium and red to a higher risk.

Very critical: The equipment/system are in a very critical situation	5	LIKELIHOOD				HIGH	RISK	
Critical: There are some preoccupations about the critic equipment/system situation	4							
Semicritical: There is a preoccupation about the equipment	3				MEDIUM	RISK		
Less critical: Risk is controlled	2							
Not critical: Risk is totally controlled	1			LOW	RISK			
Security/Environmental/Equipment/Personnel/Operation			SEVERITY					
			0,1	1	2	3	4	5
			None	Incidental	Minor	Medium high	Serious	Major

Figure 35 - Risk matrix for FMECA-CM

This matrix allows easily interpretation of the risk state to take eventually some immediately measures. If the risk is higher and the severity on security, environment, equipment, personnel and operation is predicted to be high. Although this coloured code it will not be used on priorities definition and options of maintenance.

To demonstrate that the FMECA-H-CM methodology can be integrated on a support decision software, it was used Python language supported by the Google Colab Platform, both available for free in the world web sites platforms.

4.5. SWOT analysis of the proposed methodology

After the study of eventual application of the FMEA, FMECA and the creation of FMECA-CM, the author decided to analyse its applicability in the context of the present investigation, for that it was chosen the SWOT analysis of the basis FMECA and FMECA-CM. This analysis is exposed in Table 23.

Table 23 - Swot analysis for classical FMECA methodology

SWOT	Positive Factors	Negative Factors
Internal Factors	**Strengths** • It defines the possibles failures of an equipment. • Systematic fault identification allows detailed analysis of failure modes, their effects and criticality. • Data-driven decision making helps prioritize maintenance and improvement actions. • Versatile application. It is used in various industries such as defense, aerospace, automotive and energy. In present case it is applied to various electromechanical equipment´s.	**Weaknesses** • It´s quality depends on the experience of persons. • Time-consuming and resource-intensive process. It requires detailed analysis and technical expertise. • Subjectivity in risk assessment. The criticality assignment can be influenced by the experience of the assessors. • Difficulty in modelling complex systems. For dynamic systems, it may not capture all failure interactions.
External Factors	**Opportunities** • Avoid failures. • Define a maintenance plan. • Reduces maintenance costs in short time. • Integration with data analytics and AI – Machine Learning can improve prediction and automation of analysis. • Use in predictive maintenance. Historical data and IoT sensors can feed online failure analysis. • Can be applied to various types of equipment´s.	**Threats** • Workers doesn´t use the defined strategy in case of failure. • Competition with other methodologies – Methods such as FRACAS (Failure Reporting, Analysis, and Corrective Action System). • Rapid technological evolution. New systems may require hybrid or different methodologies for criticality analysis. • Cost of implementation: small ships may have difficulty implementing FMECA due to limited resources.

The analysis of FMECA-CM is presented in Table 24. Observing the SWOT analysis and comparing the use of traditional FMECA or FMECA-H-CM it is considered that there are similar advantages between FMECA and FMECA-H-CM like systematic risk and eventual fault analysis, but FMECA-H-CM is more accurate. Also, FMECA could be more accurate if lack of data and FMECA-H-CM algorithm should be flexible, because existing data from the considered variables may change.

Table 24 - Swot analysis for FMECA-CM methodology

SWOT	Positive Factors	Negative Factors
Internal Factors	**Strengths** • Allow define the priority of maintenance of an equipment or its component. • Optimized maintenance, with reliability increasing if did it during product developing. (Quality-One, 2023; Quality-One, 2023). • Early knowledge of failure modes. • It uses various mathematical methods, integrating various condition monitoring data. • Data triage and continuous results. • Before an alert level is reached, we can see the data evolution. • Storage on relevant data, reducing costs on storage data. Bayesian rapid detection of patterns.	**Weaknesses** • It depends on the experience of the people that define the equipment or system criticality. • Time consumed during the FMECA implementation. • False alerts. • Various variables if not and density. Lack of data, induce bad interpretation, if the variables to include not well chosen.
External Factors	**Opportunities** • Helps support maintenance priorities. • Reduces maintenance costs in time vs lean operation and manufacturing (Quality-One, 2023; Quality-One, 2023). • Increased reliability (Quality-One, 2023; Quality-One, 2023). Bayesian early detection of data groups performance.	**Threats** • Workers doesn´t consult the normative applied to equipment´s and the results of a maintenance systems based on FMECA. • Cyberattack to database. Sensor lecture errors.

Considering that for the propulsion system and the auxiliary equipment´s (e.g., air compressors, oil and Marine gasoil purifier) not all data from condition monitoring can be used the parameters to enter the Equation of FMECA-H-CM calculus should be flexibles. Before the calculus variables to include should be chosen, to not induce errors of data interpretation because the eventual lack of data of some condition monitoring parameters (e.g., thermography, registered oil temperatures and pressure). Both methodologies may be appliable to the equipment data for the present research but is believed that FMECA-H-CM will be more accurate.

4.6. Chapter methodologies elations

This chapter reflects main steps for accomplish the present research by giving a methodology that can support data-driven decisions. To achieve this, various data from equipment´s were first be understood, then, using selected methods and algorithms, the system was built to predict outcomes of eventually anomalies on equipment´s. Based on this, we determine appropriate maintenance actions by analysing the equipment´s performance.

This developed dynamic maintenance system will work like a data supply chain, where various linked database will be filled, considering the SMP database, the elected condition monitoring data integrated in FMECA and the threat environment, followed by the actions due to the results.

On Subchapter 4.2.1, 4.2.2, 4.2.3 and 4.2.4 for the level of each of new considered parameters of FMECA, it was considered levels with colours. Its concept was not applied on the case study but should be included on a user-friendly software of further developed methodology or eventual new contribution for the present research.

5. Navy ship equipment´s and data selection

5.1. Chapter introduction

For reason of research limitation and considering the existent data the main equipment understudy it is a diesel propulsion engine (main engine/propulsion engine) from a selected frigate that will be called ship nr 3, and to test the dynamic maintenance concept it was used the seawater filters and air filters system from main engine, low pressure air compressor´s (nr 2), marine gasoil purifier (nr 2) and oil lubricant purifier.

The condition monitoring on FMECA-CM with parameters CMV, CMP and CMText was only considered for the main engines because the lack of registered information for others equipment's. Also, in the case of the diesel propulsion engines there were no information of thermography so the Equation for calculus of FMECA-H-CM, so that parameter will not be considered. On the seawater filters and air filters system from diesel propulsion engine the condition monitoring data considered should be the temperature (CMP) and CMText. For the low pressure air compressor´s, marine gasoil purifier´s and oil lubricant purifier, in the present case the included variables are CMText values and the threat state.

5.2. The selected equipment's for study

The selected equipment's were auxiliars equipment´s of the diesel engine propulsion that are installed on the "house of diesel propulsion engines".

Diesel engine

The diesel engines chosen for the present investigation are internal combustion engines, diesel engines installed a ship class of Portuguese Navy and are part of a combined propulsion system diesel or gas (CODOG, where diesel are from an alternative internal combustion engine and gas are aeroderivative gas turbine), Figure 36. The propulsion system has respectively to portside and starboard two gear boxes, two main propeller shafts (starboard and portside) with controlled pitch propeller (CPP) and bearings. This diesel propulsion engines are called 12V 1163 TB 83 from the Germany Company MTU.

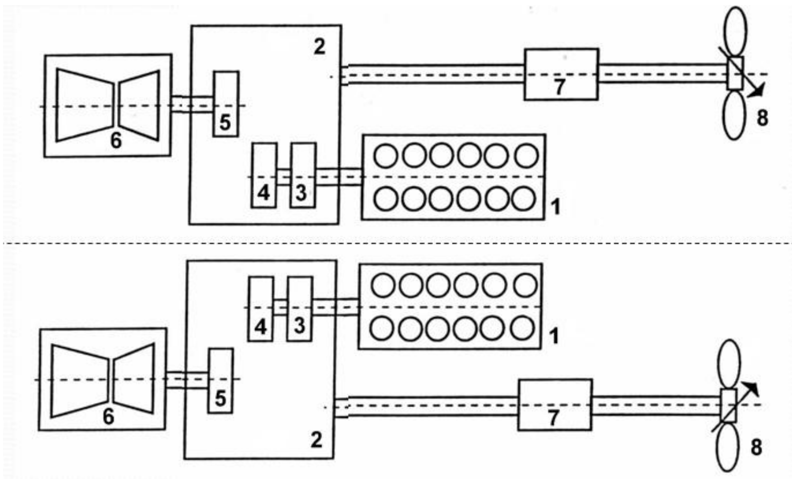


Figure 36 - CODOG propulsion
Source: Marinha_g (2008)

Specifications of the diesel propulsion engine, Figure 36:

- 12 cylinders in V (60º);
- 1163 – Engine series, 100 strokes from a cylinder in litters;
- Four strokes,
- T – turbocharger engine;
- B – air cooler, with cooled pistons;
- 8 – Maritime propulsion engine;
- 3 – Project digit;
- Continuous power – 3250 kW with 1160 rpm, 9.75:1 compression ratio;
- Overload power – 2 hours in 12 functioning hours 3600 kW with 1200 rpm;
- Ref. Conditions – air admission temperature: 27ºC;
- Ref. Conditions – Sea water admission: 27ºC;
- Barometric pressure – 1000 mbar.
- Combustion order A1, B1, A4, B4, A2, B2, A6, B6, A3, B3, A5, B5.

This is a supercharged engine, Figure 37, with three sequential superchargers with intercoolers/heaters that come into operation according to engine speed and boost pressure. Supercharger B2 is always in operation, supercharger A1 goes into service for speeds above 800 rpm and goes out of service for speeds below 750 rpm, and supercharger B1 goes into service with the following conditions: 2.7 bar and 1100 rpm and goes out service whenever one of the following conditions is not fulfilled: 1.7bar of charge air and 1050 rpm. It should also be noted that Bank A of the engine works as an engine, with internal combustion, if one of the following conditions exists: >930 rpm, >1.6 bar, >(R+8)º, and works as a compressor (compressing only air for bank B) as soon as at least one of the following conditions is met: <900 rpm, <0.2 bar, Rº and <900 rpm.

Figure 37 - MTU 1163 – class 1 Navy ships
Source: Old photo taken by the author

For Seawater Filters and Air Filters System from Propulsion Engine, although its light complexity, these are subsystems that are fundamental for propulsion engines. These systems were included on FMECA-H-CM, but vibration is not appliable, there were no database with temperature registered of this system (but the author has the information that it was normal, category 1 for it were considered), and neither from CMTex.

Low pressure air compressor

The general characteristics of air compressor, Figure 38, are:

- 2 cylinders;
- 3 stages;
- Working pressure, maximum: 40bar;
- Maximum speed: 1170 rpm;
- Sense of rotation: anti-clockwise;
- Setting of safety valve: 1st stage 8 bar, 2nd stage 12 bar, 3rd 42 bar;
- Fill-up capacity at 30 bar relative to 20ºC and 1013 mb: 62+- 5% m^3/h;
- Power consumption at 30 bar end pressure: 14 kW;
- Air cooled by fan.

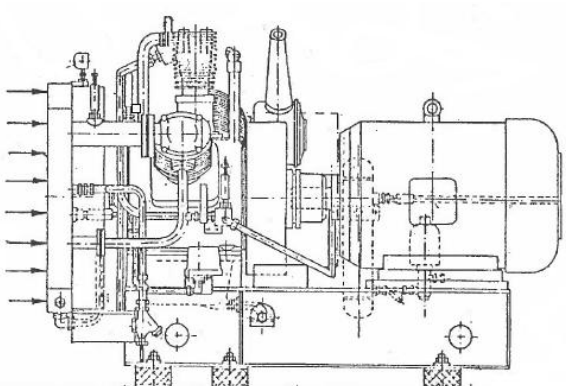


Figure 38 - Low pressure air compressor
Source: Marinha_i (1988)

Marine gasoil purifier and oil lubricant purifier

The characteristic of marine gasoil purifier and oil lubricant are the same. The marine gasoil purifier and oil lubricant purifier are a Westfalia Separator AG Type OSA 20-02-366 with the next generic characteristics, Figure 39 (Marinha, 1991):

- Is an electro-oil purifier, with a bowl;
- Total weight: 1204 kg;
- Sediment holding space: 4.2 dm^3;
- Nominal capacity: 10000 l/h;
- Optimum capacity with F75 fuel oil: 7500 l/h;
- Power consumption: 8.5 kW;
- Centripetal pump: output of 10000 l/h and a delivery head of 2-3bar;
- Starting time: 4 to 7 min;
- With flexible connection pipes;
- Hot water feed line assembly;
- Three-way diaphragm valve for dirty oil feed;
- Compressed-air control assembly;
- It has a Gear pump;
- Typically used in surface ships.

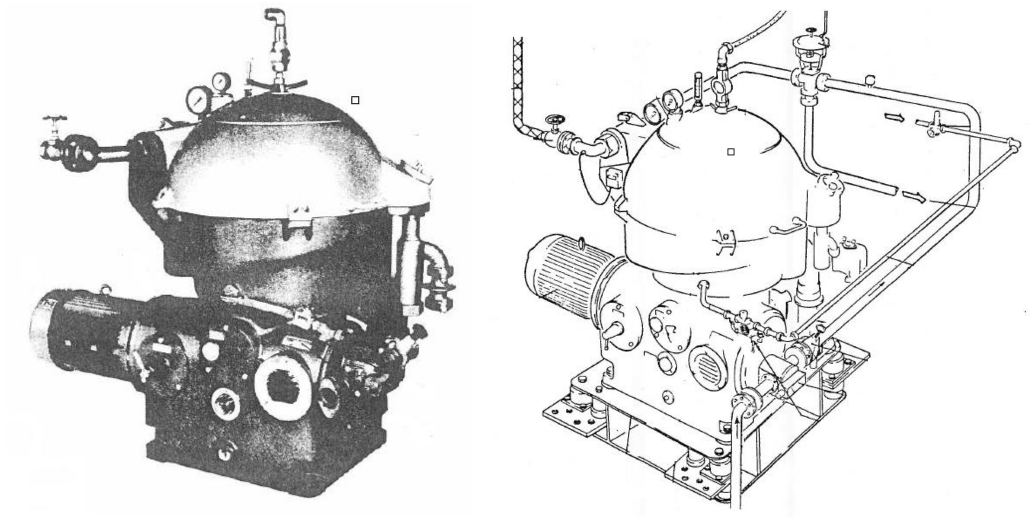


Figure 39 - Marine gasoil purifier and oil lubricant
Source: Marinha_j (1991)

For the oil purifier on the ship understudy there were no data of any occurrence on DSM58, so CMTex are on category 1. This information shows that this equipment isn´t usually used, and the conclusion is because the lubricant oil of the diesel propulsion system is changed regularly on certain time of functioning and not according to the result of an oil analysis like engines with bigger dimensions.

Ship equipment's dependencies

The ship equipment's connections or dependencies for the equipment´s selected for study are, Figure 40:

- The lubricant oil purifier only serves the diesel propulsion engine;
- The marine gasoil purifiers (nr 1 and nr 2) serve diesel propulsion engine, gas turbine, diesel generators, and boilers;
- The air compressor serves both propulsion engines, diesel generators, low pressure air compressed services, command and control of various services like gear boxes. It was considered that only one air compressor can be in intervention each time;
- The seawater filters and air filters system serve various equipment's. It will be treated that it can be in intervention at the same time as the propulsion engines.

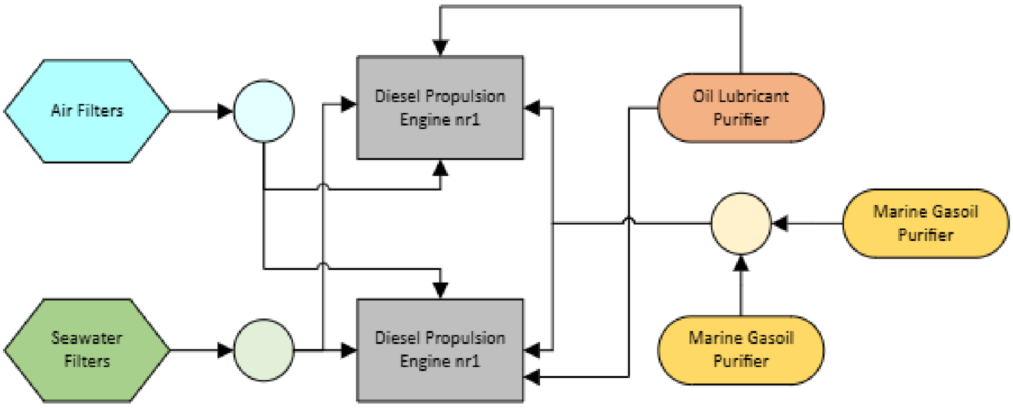


Figure 40 - Block diagram of selected equipment's dependencies

5.3. Condition control data

On the present subchapter it will be present the condition monitoring parameters and its way of being integrated in the FMECA-H-CM. For reasons of study limitation, but also because of lack of data registration, not all the parameters of the original FMECA-H-CM, Equation 3, will be used, has had been referred on very previous Subchapter 5. The knowledge of reliability from, although the author believed that the contained information on DSM58 may be enough to that calculation. Reliability studies will be kept for future research.

The three considered condition monitoring data for diesel propulsion was vibration that directly influence and potentiate an eventual anomaly in the diesel engines, the thermodynamic parameters and maintenance registrations (temperature). For the thermography there was no registering of this data, and considering the data from propulsion engine temperature normal it was considered that, there wasn´t probably any anomaly respecting to this parameter of the FMECA-H-CM. So, it will not be included on FMECA-H-CM calculus or more developed or used on this research.

For the others selected equipment only the CMTex was considerate, because da database from the Ship Technical Direction hasn´t available information about other methods of condition monitoring or maintenance of it.

5.3.1. Condition control – vibrations

In what follows data results from vibration monitoring of propulsion diesel propulsion engines installed in a Portuguese Navy ship will be one of the targets on condition monitoring on the present research. The data resulted from vibration measures taken by specialized experts, Technicians from Ship Technical Direction with a portable device.

The collected data was obtained was from three ships of the same class (Table 26, Table 27 and Table 28), but the data chosen for case study are from ship 3.

The vibration data was collected using a portable collector SKF Microblog Analyzer Model: CMXA80 S/N:100327, and Sensor SKF Model: CMSS2200 S/N: S37482 and the observed values are the root mean squares (rms) after the vibration signal is transformed by FFT. Plots of Fourier Frequencies of vibrations measures are also available for visual inspection, but its values were not used in what follows.

The set OP of Observation Points in each diesel engine is represented on Figure 41.

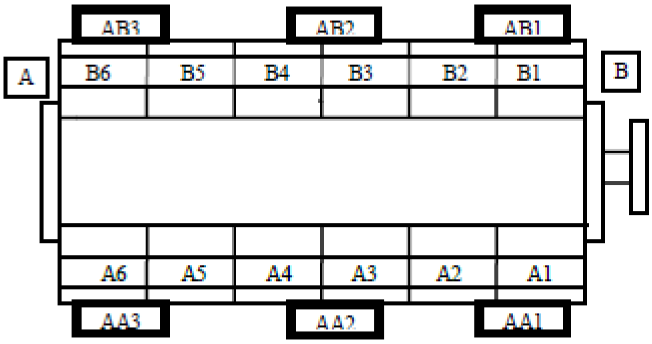


Figure 41 - Diesel engines vibration measurement
Source: Marinha_h (2019)

For each observation point three values are supplied for the diesel propulsion engines, giving the vibration measures in the horizontal, vertical and axial axis, Figure 42.

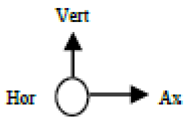


Figure 42 - Axis direction
Source: Marinha_h (2019)

The points of measure are defined by the Ship Technical Direction. In Table 25 it can be observed the names of the points of vibration measures.

Table 25 - Propulsion engines points of measure

Equipment	Measure Points 1	Measure Points 2	Measure Points 3
Diesel Engine nr 1 (SB) and nr 2 (PS)	− Motor A-A − Motor A-H − Motor A-H Env − Motor A-V − Motor B-A − Motor B-H − Motor B-H Env − Motor B-V − Motor A-A	− Cilindro A1 − Cilindro A6 − Cilindro B1 − Cilindro B6 − Apoio AA1 N − Apoio AA1 V − Apoio AA2 N − Apoio AA2 V − Apoio AA3 N − Apoio AA1 V	− Apoio AB1 N − Apoio AB1 V − Apoio AB2 N − Apoio AB2 V − Apoio AB3 N − Apoio AB3 V − Turbo B2-A A − Turbo B2-A H − Turbo B2-A H Env − Turbo B2-A V

Note: motor – engine; cilindro – cylinder; apoio – support,). Suffixes A, H, V mean, respectively: Axial, H-Horizontal V-Vertical. H-Env mean High frequency Envelope and N means that measurement was performed against the block.

In this investigation, if RMS value is an outlier, the frequency should also be analysed, but this will not carry out, because is not the focus of the research. But if the risk is high, the priority will be high, or closer to 1.

In the research it was available vibration data for the three ships of the class in pdf files that was adapted to Table 26, Table 27 and Table 28.

Table 26 - Vibration measures on ship 1

	MD-PS	**MD-SB**	**MD-PS**	**MD-SB**	
Measure Point	Last Value	Last Value	Last Value	Last Value	Units
RPM MD	729,972	657,674	976,531	973,907	RPM
Motor A-A	10,791	7,462	12,661	13,202	mm/s
Motor A-H	7,337	7,72	11,845	14,201	mm/s
Motor A-H Env	36,587	29,669	48,872	26,588	gE
Motor A-V	6,93	7,521	14,523	12,58	mm/s
Motor B-A	4,015	4,304	9,252	9,682	mm/s
Motor B-H	4,594	5,171	9,111	9,614	mm/s
Motor B-H Env	8,256	7,482	28,672	13,102	gE
Motor B-V	6,124	4,346	8,044	10,325	mm/s
Cilindro A1	5,683	5,71	9,814	10,43	mm/s
Cilindro A6	4,664	4,929	8,145	9,156	mm/s
Cilindro B1	5,041	5,183	8,606	8,434	mm/s
Cilindro B6	5,131	4,518	8,296	9,999	mm/s
Apoio AA1 N	2,064	1,974	3,442	3,284	mm/s
Apoio AA1 V	7,285	6,051	14,355	12,538	mm/s
Apoio AA2 N	1,661	2,198	3,769	2,86	mm/s
Apoio AA2 V	7,921	7,448	15,981	17,736	mm/s
Apoio AA3 N	2,488	2,374	4,34	4,609	mm/s
Apoio AA1 V	6,914	6,943	11,336	14,566	mm/s

Apoio AB1 N	2,507	1,765	4,694	3,948	mm/s
Apoio AB1 V	7,515	7,597	14,753	16,398	mm/s
Apoio AB2 N	2,297	2,435	4,211	3,649	mm/s
Apoio AB2 V	8,73	8,362	16,341	16,366	mm/s
Apoio AB3 N	2,839	2,349	4,229	3,948	mm/s
Apoio AB3 V	7,925	7,395	13,002	15,038	mm/s
Turbo B2-A A	19,91	17,402	44,058	41,617	mm/s
Turbo B2-A H	8,552	8,253	13,234	14,048	mm/s
Turbo B2-A H Env	6,018	4,541	8,637	7,247	gE
Turbo B2-A V	15,028	25,961	12,828	16,111	mm/s

Table 27 - Vibration measures on ship 2

	MD-PS	**MD-SB**	**MD-PS**	**MD-SB**	**MD-PS**	**MD-SB**	
Measure Point	Last Value	Last Value	Last Value	Last Value	Last Value	Last Value	Units
RPM MD	729,972	729,972	1057,466	1049,684	1159,856	1159,856	RPM
Motor A-A	10,303	7,729	14,334	14,01	16,021	16,98	mm/s
Motor A-H	7,69	8,026	13,58	13	16,372	19,808	mm/s
Motor A-H Env	18,683	19,479	33,204	53,444	46,719	63,829	gE
Motor A-V	9,261	9,047	15,072	12,29	17,373	17,91	mm/s
Motor B-A	4,588	3,964	7,084	8,414	9,648	11,255	mm/s
Motor B-H	4,234	5,633	9,866	9,872	17,227	13,732	mm/s
Motor B-H Env	9,023	7,764	13,376	16,98	14,265	19,556	gE
Motor B-V	4,591	4,253	10,568	9,601	10,958	9,391	mm/s
Cilindro A1	6,231	9,146	9,319	9,581	22,346	21,573	mm/s
Cilindro A6	5,561	5,283	7,496	7,462	12,179	25,475	mm/s
Cilindro B1	4,196	12,07	8,511	9,061	12,357	19,871	mm/s
Cilindro B6	7,222	5,386	9,061	8,662	17,043	10,169	mm/s
Apoio AA1 N	1,72	1,891	3,099	3,403	4,535	5,303	mm/s
Apoio AA1 V	6,648	7,59	12,072	12,707	13,771	16,729	mm/s
Apoio AA2 N	1,449	1,417	3,37	3,704	4,561	5,72	mm/s
Apoio AA2 V	9,632	7,566	16,81	17,328	16,64	16,621	mm/s
Apoio AA3 N	2	2,066	3,682	3,159	5,494	6,383	mm/s
Apoio AA1 V	6,409	6,075	10,308	13,269	13,36	15,086	mm/s
Apoio AB1 N	1,965	1,459	3,57	3,147	4,541	5,111	mm/s
Apoio AB1 V	7,998	9,57	13,264	14,388	15,698	16,099	mm/s
Apoio AB2 N	1,729	1,846	3,241	3,246	5,124	4,628	mm/s
Apoio AB2 V	6,724	9,436	15,478	17,494	14,97	17,31	mm/s
Apoio AB3 N	1,591	1,665	3,434	2,813	6,712	5,482	mm/s
Apoio AB3 V	7,215	7,46	11,227	13,741	14,648	13,575	mm/s
Turbo B2-A A	9,432	10,091	43,417	49,738	21,794	20,164	mm/s
Turbo B2-A H	5,968	5,052	27,686	24,431	9,789	10,485	mm/s
Turbo B2-A H Env	3,76	7,129	11,662	10,031	11,092	11,548	gE
Turbo B2-A V	9,928	11,221	18,531	21,624	18,75	15,625	mm/s

Table 28 - Vibration measures on ship 3

	MD-PS	**MD-SB**	**MD-PS**	**MD-SB**	**MD-PS**	**MD-SB**	
Measure Point	Last Value	Last Value	Last Value	Last Value	Last Value	Last Value	Units
RPM MD	726,981	719,993	1049,989	1039,918	1159,856	1159,856	RPM
Motor A-A	7,894	9,341	14,854	10,783	19,926	12,247	mm/s
Motor A-H	8,798	6,972	12,728	11,55	22,154	14,747	mm/s
Motor A-H Env	23,351	26,084	26,002	39,666	31,074	73,132	gE
Motor A-V	7,446	7,127	10,032	9,417	18,258	13,082	mm/s
Motor B-A	3,745	4,023	9,126	9,788	11,047	10,829	mm/s
Motor B-H	5,093	5,273	10,338	9,041	11,708	13,655	mm/s
Motor B-H Env	4,607	8,102	18,144	10,208	12,478	11,374	gE
Motor B-V	4,064	4,869	8,088	9,555	11,681	10,326	mm/s
Cilindro A1	5,166	7,662	9,011	9,115	13,146	14,174	mm/s
Cilindro A6	5,773	4,528	7,797	8,838	12,271	11,909	mm/s
Cilindro B1	4,09	6,093	9,19	7,82	16,895	13,452	mm/s
Cilindro B6	11,205	5,686	7,787	13,015	14,209	15,01	mm/s
Apoio AA1 N	2,12	1,801	3,175	3,946	4,586	6,542	mm/s
Apoio AA1 V	5,348	7,897	12,72	12,736	17,253	16,429	mm/s
Apoio AA2 N	1,952	1,744	3,116	4,373	5,977	4,94	mm/s
Apoio AA2 V	6,631	7,879	16,736	16,523	15,265	15,973	mm/s
Apoio AA3 N	2,242	1,941	3,765	4,169	3,531	8,085	mm/s
Apoio AA1 V	6,435	7,223	11,488	13,239	16,631	14,431	mm/s
Apoio AB1 N	2,198	2,992	4,54	3,214	5,873	4,505	mm/s
Apoio AB1 V	6,328	6,845	14,579	17,756	16,884	17,48	mm/s
Apoio AB2 N	1,735	2,138	3,988	3,558	6,598	4,179	mm/s
Apoio AB2 V	8,364	7,496	15,101	16,974	19,208	19,756	mm/s
Apoio AB3 N	1,732	1,498	4,943	3,74	4,872	5,467	mm/s
Apoio AB3 V	6,494	7,47	15,151	16,253	15,434	16,643	mm/s
Turbo B2-A A	14,778	13,443	20,412	23,528	32,595	38,275	mm/s
Turbo B2-A H	9,867	10,793	13,174	15,23	15,681	17,66	mm/s
Turbo B2-A H Env	4,186	3,968	5,357	8,714	10,561	8,514	gE
Turbo B2-A V	16,532	15,574	16,334	18,449	17,174	27,294	mm/s

Representation of vibrations of the diesel propulsion engines from the three ships are represented on Figure 43.

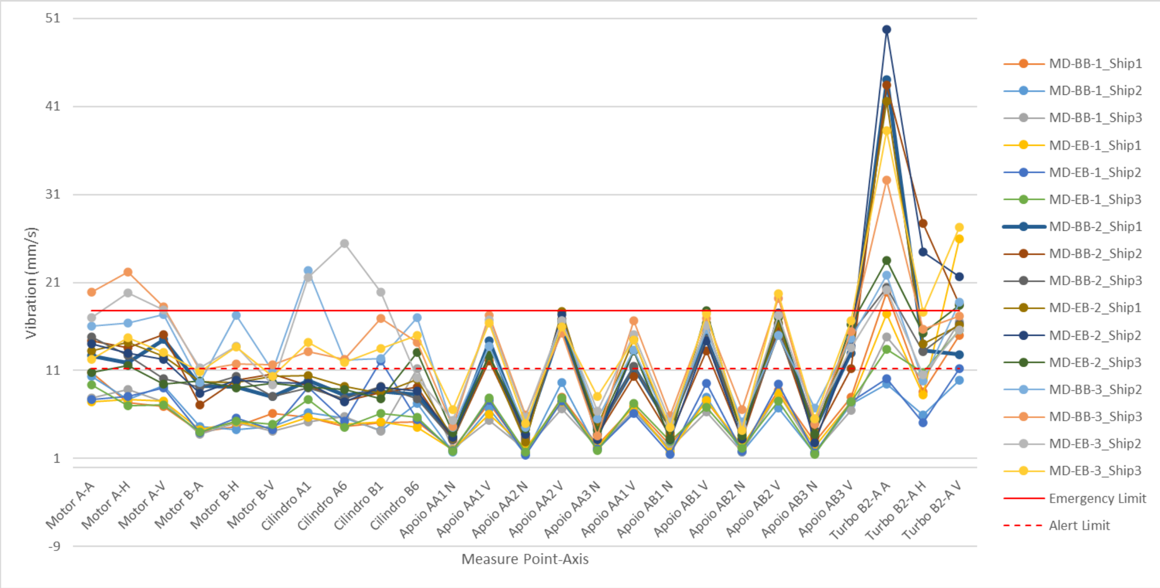


Figure 43 - Diesel propulsion vibration from three ships

At Table 29 are present the vibration series names of the represented observations on Figure 43.

Table 29 - Diesel propulsion engine vibration name series per velocity

	Velocity 1	**Velocity 2**	**Velocity 3**
	730 rpm	**1050**	**1160**
Ship 1	MD-BB-1_Ship1 MD-EB-1_Ship1	MD-BB-2_Ship1 MD-EB-2_Ship1	MD-BB-3_Ship1 MD-EB-3_Ship1
Ship 2	MD-BB-1_Ship2 MD-EB-1_Ship2	MD-BB-2_Ship2 MD-EB-2_Ship2	MD-BB-3_Ship2 MD-EB-3_Ship2
Ship 3	MD-BB-1_Ship3 MD-EB-1_Ship3	MD-BB-2_Ship3 MD-EB-2_Ship3	MD-BB-3_Ship3 MD-EB-3_Ship3

The velocity of the engines on the time of measure vibration was considered approximately the values constant on the Table 28, because of the specific characteristic and calibration of the mechanical and associated electronic systems, it does not allow the velocity to be established precisely.

The vibration limits admitted by the diesel propulsion engines are the alert on 11.2 mm/s and danger limit at 17.8 mm/s. For the three ships and respective three velocities, the vibration measured in the various selected points and axis are represented on Figure 44, Figure 45 and Figure 46.

For both Figure 44 and Figure 45 it is possible observed that may exist an anomaly on Turbo B2 form diesel propulsion engine, because point A-A is above the upper level for both engines of for ship 1, but also for both engines of ship 3 the results are between the alert and upper level. The confirmation of previous result is the measure on other axis of same supercharge point A-V. On Figure 46, with higher velocities, the results became higher on point A-A reading.

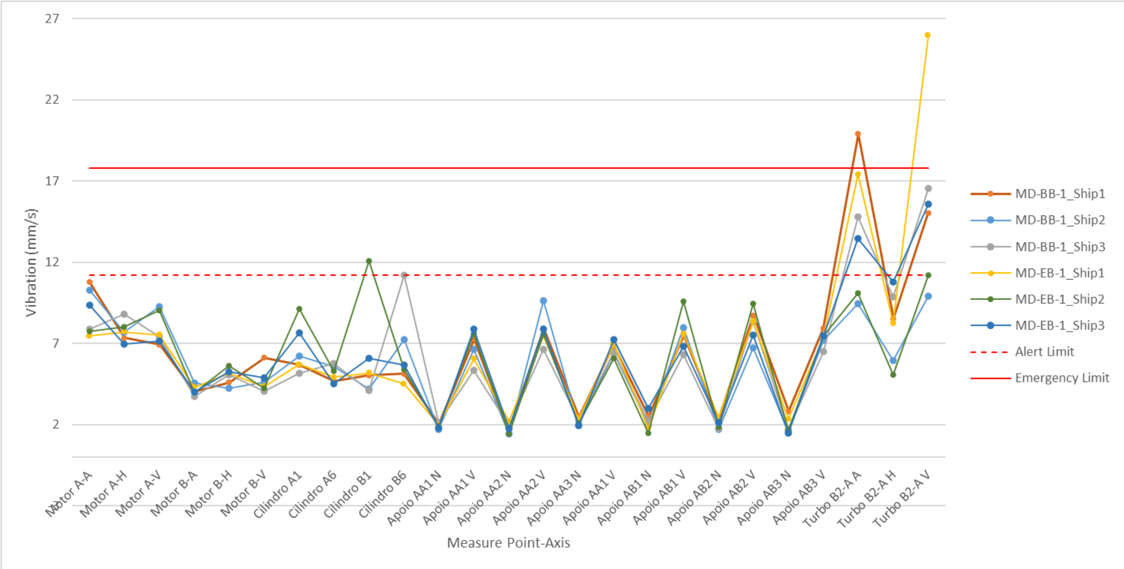


Figure 44 - Vibration – diesel propulsion engine – velocity 1

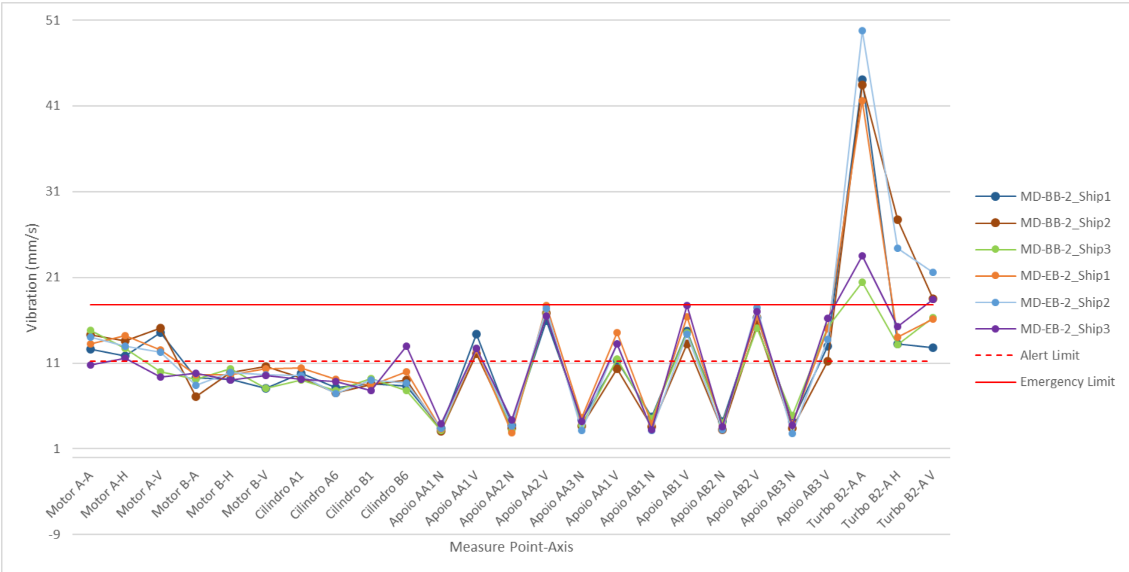


Figure 45 - Vibration – diesel propulsion engine – velocity 2

With higher velocity the supercharge performance (B2-A-A) from engine improves, Figure 46, it is when although higher equipment power, more compressed air are entering the combustion chamber, and the engine behaviour improves.

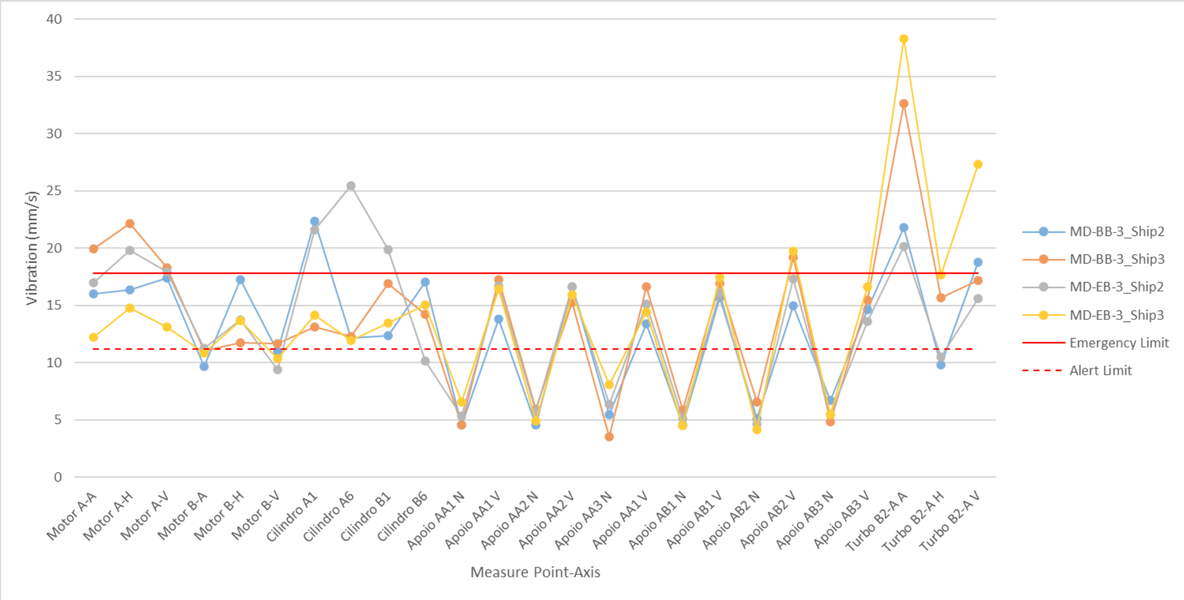


Figure 46 - Vibration – diesel propulsion engine – velocity 3

Considering the presented results for vibration, it was decided to use this vibration data for the velocity nr 2 because it represents an average velocity, and correspondent oil temperature represented on the next sub-chapter, where the modified Q charts will also be used, with original data and simulated data. The obtained thermodynamic data is representative of how the engines performed at that machine regime.

To apply the Modified Q Chart to vibration random values were chosen through simulation in excel considering the two extreme values obtained for the vibrations in the supercharger B2 at point Turbo B2-A-A for the engines of ship 3 (20.412 mm/s and 23.528 mm/s) whose condition monitoring results will be included in the demonstration of the applicability of the FMECA-H-CM methodology.

The next table, Table 30, present the application of QM control chart to vibration data of ship nr 3 (the one that was used in the present work, which the name will not be referred, for reasons of confidentiality), the considered $(T_L)_N$ is:$(T_L)_N$= 17,8 (RMS). Because the results are out of control, there were made other random simulations to test the limits and control of the chart (simulation nr 1 and nr 2).

Table 30 - QM control chart from vibration with the random values from 20.412 mm/s and 23.528 mm/s

r	X	$\bar{X}$	S	s	T_L	w_r	G(w)	Q(X)	LC	LA	LSC
1	23,471	23,4706							0	2,5	3
2	22,275	22,8727	0,8455	1,0597					0	2,5	3
3	23,440	23,0616	0,6816	0,7691	14,6209				0	2,5	3
4	23,347	23,1330	0,5745	0,6236	15,4926	11,087	0,9960	2,65	0	2,5	3
5	20,800	22,6664	1,1560	1,2297	15,9291	8,262	0,9981	2,90	0	2,5	3
6	20,855	22,3646	1,2711	1,3359	14,1108	3,890	0,9912	2,37	0	2,5	3
7	22,074	22,3230	1,1655	1,2149	13,7924	5,800	0,9989	3,07	0	2,5	3
8	23,427	22,4610	1,1475	1,1891	14,1554	7,732	0,9999	3,67	0	2,5	3
9	20,557	22,2495	1,2469	1,2864	14,2328	5,260	0,9994	3,25	0	2,5	3
10	21,648	22,1893	1,1909	1,2243	13,9409	5,642	0,9998	3,49	0	2,5	3
11	22,069	22,1784	1,1303	1,1588	14,1272	6,508	0,9999	3,87	0	2,5	3
12	20,601	22,0469	1,1699	1,1967	14,3235	5,484	0,9999	3,64	0	2,5	3
13	21,514	22,0060	1,1298	1,1536	14,2098	5,905	0,9999	3,88	0	2,5	3
14	21,368	21,9604	1,0988	1,1201	14,3393	6,105	1,0000	4,04	0	2,5	3
15	22,645	22,0061	1,0735	1,0928	14,4398	7,303	1,0000	4,53	0	2,5	3
16	21,656	21,9842	1,0408	1,0582	14,5216	6,509	1,0000	4,35	0	2,5	3
17	20,666	21,9066	1,0572	1,0739	14,6254	5,727	1,0000	4,11	0	2,5	3
18	21,923	21,9075	1,0257	1,0409	14,5784	6,708	1,0000	4,56	0	2,5	3
19	21,402	21,8809	1,0035	1,0176	14,6774	6,475	1,0000	4,54	0	2,5	3
20	22,086	21,8912	0,9778	0,9908	14,7473	7,196	1,0000	4,88	0	2,5	3
21	21,867	21,8900	0,9531	0,9650	14,8276	7,105	1,0000	4,91	0	2,5	3
22	22,949	21,9381	0,9571	0,9685	14,9049	8,325	1,0000	5,41	0	2,5	3
23	20,709	21,8847	0,9696	0,9807	14,8944	5,931	1,0000	4,50	0	2,5	3
24	21,747	21,8790	0,9487	0,9590	14,8580	6,919	1,0000	4,99	0	2,5	3
25	23,263	21,9343	0,9691	0,9792	14,9229	8,680	1,0000	5,73	0	2,5	3

The representation of the first simulation based on real data are present on Figure 47.

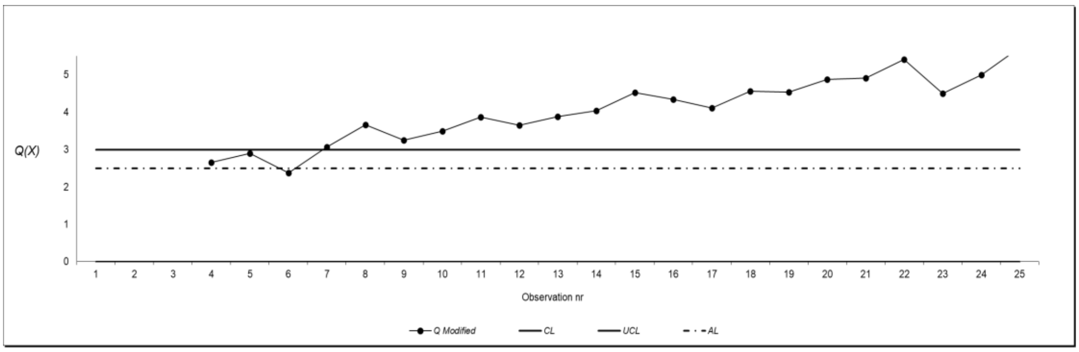


Figure 47 - Vibration – MD – simulation 0 Turbo B2-A-A for velocity 2

Considering the result on Figure 47 and the defined categories for vibration, sub-chapter 4.2.1.1 the attributed category is 5.

Other simulation of vibration value for the same point of measure can be observed on Figure 48 and Figure 49. Whereby considering the define rules, on Figure 48, because there are 3 to 5 consecutive values above the Alert Level it will be considered the Criteria with value 2 to be included on FMECA-H-CM. In Table 31 is the result of application of QM chart for simulation nr 1.

Table 30 - QM control chart from vibration with vibration simulation nr 1

r	X	$\bar{X}$	S	s	T_L	w_r	G(w)	Q(X)	LC	LA	LSC
1	23,167	23,1673							0	2,5	3
2	15,345	19,2560	5,5315	6,9325					0	2,5	3
3	15,856	18,1226	4,3763	4,9383	-2,9976				0	2,5	3
4	28,957	20,8311	6,4895	7,0438	2,9850	6,323	0,9879	2,26	0	2,5	3
5	13,370	19,3390	6,5359	6,9531	-3,3314	1,431	0,8761	1,16	0	2,5	3
6	23,951	20,1077	6,1416	6,4547	-3,0592	3,811	0,9905	2,35	0	2,5	3
7	18,633	19,8970	5,6342	5,8726	-1,5641	3,270	0,9889	2,29	0	2,5	3
8	22,253	20,1915	5,2823	5,4739	0,1822	3,954	0,9962	2,67	0	2,5	3
9	17,802	19,9260	5,0049	5,1635	1,3783	3,145	0,9919	2,40	0	2,5	3
10	20,895	20,0230	4,7286	4,8614	2,3096	3,699	0,9970	2,75	0	2,5	3
11	21,843	20,1884	4,5194	4,6334	3,2159	3,939	0,9983	2,93	0	2,5	3
12	14,942	19,7512	4,5675	4,6722	3,8998	2,484	0,9838	2,14	0	2,5	3
13	12,473	19,1913	4,8165	4,9178	3,7834	1,803	0,9506	1,65	0	2,5	3
14	16,025	18,9652	4,7042	4,7953	3,0467	2,449	0,9847	2,16	0	2,5	3
15	19,172	18,9790	4,5334	4,6151	3,4140	3,312	0,9972	2,77	0	2,5	3
16	29,957	19,6651	5,1685	5,2553	3,9546	5,669	1,0000	4,02	0	2,5	3
17	23,713	19,9032	5,0998	5,1801	2,0342	3,709	0,9989	3,08	0	2,5	3
18	10,024	19,3543	5,4681	5,5491	2,2597	1,523	0,9263	1,45	0	2,5	3
19	7,684	18,7401	5,9504	6,0336	1,1527	0,966	0,8261	0,94	0	2,5	3
20	28,659	19,2361	6,2018	6,2841	-0,3009	4,506	0,9999	3,64	0	2,5	3
21	17,711	19,1634	6,0539	6,1299	-1,0524	2,834	0,9947	2,56	0	2,5	3
22	18,696	19,1422	5,9089	5,9794	-0,5898	3,187	0,9977	2,83	0	2,5	3
23	28,882	19,5656	6,1198	6,1897	-0,1383	4,878	1,0000	3,94	0	2,5	3
24	19,706	19,5715	5,9853	6,0507	-0,7692	3,174	0,9978	2,85	0	2,5	3
25	16,905	19,4648	5,8835	5,9454	-0,3520	2,893	0,9959	2,64	0	2,5	3

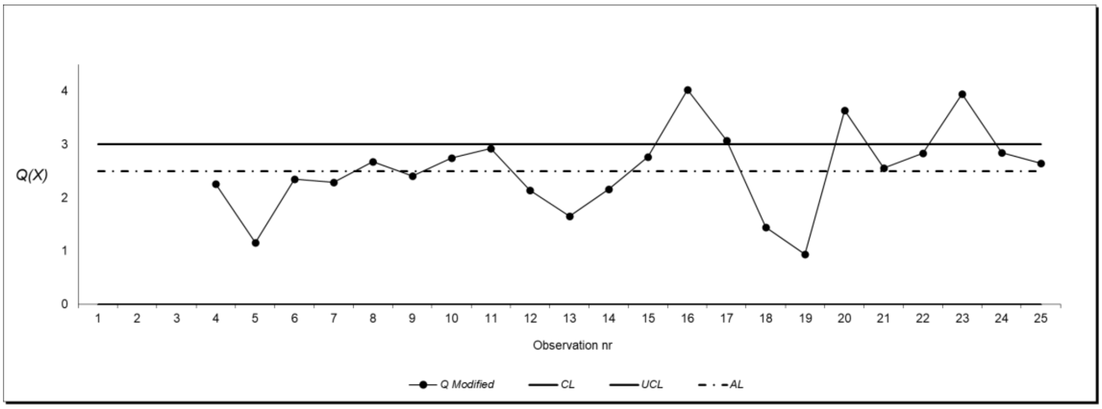


Figure 48 - Vibration – MD – simulation 1 –Turbo B2-A-A for velocity 2

The results of QM control chart for simulation nr 2 are represented In Table 32.

Table 31 - QM control chart from vibration with vibration simulation nr 2

r	X	$\bar{X}$	S	s	T_L	w_r	G(w)	Q(X)	LC	LA	LSC
1	26,900	26,8996							0	2,5	3
2	23,110	25,0049	2,6794	3,3581					0	2,5	3
3	34,405	28,1384	5,7485	6,4867	7,7257				0	2,5	3
4	26,336	27,6878	4,7794	5,1877	-1,6601	2,804	0,9464	1,61	0	2,5	3
5	23,369	26,8240	4,5675	4,8591	2,2370	4,684	0,9908	2,36	0	2,5	3
6	34,765	28,1476	5,2154	5,4813	3,2228	6,501	0,9986	2,98	0	2,5	3
7	29,054	28,2771	4,7733	4,9753	1,3562	4,585	0,9970	2,75	0	2,5	3
8	32,963	28,8628	4,7196	4,8908	2,8740	6,194	0,9996	3,35	0	2,5	3
9	27,425	28,7031	4,4407	4,5814	3,1277	4,904	0,9991	3,13	0	2,5	3
10	24,937	28,3265	4,3528	4,4750	4,0559	4,659	0,9992	3,15	0	2,5	3
11	17,171	27,3123	5,3260	5,4603	4,3750	2,873	0,9908	2,36	0	2,5	3
12	13,565	26,1667	6,4449	6,5926	1,4191	1,652	0,9352	1,52	0	2,5	3
13	31,474	26,5749	6,3437	6,4771	-1,9777	4,480	0,9995	3,31	0	2,5	3
14	35,756	27,2307	6,5702	6,6974	-1,6313	5,732	1,0000	3,90	0	2,5	3
15	18,398	26,6419	6,7294	6,8506	-2,2923	2,945	0,9943	2,53	0	2,5	3
16	22,178	26,3629	6,5963	6,7069	-2,7519	3,521	0,9983	2,93	0	2,5	3
17	24,484	26,2524	6,4031	6,5039	-2,3208	4,006	0,9994	3,25	0	2,5	3
18	18,035	25,7959	6,5068	6,6032	-1,7116	3,090	0,9965	2,70	0	2,5	3
19	25,748	25,7934	6,3235	6,4120	-2,0096	4,108	0,9996	3,38	0	2,5	3
20	18,682	25,4378	6,3569	6,4413	-1,4359	3,189	0,9975	2,80	0	2,5	3
21	30,468	25,6773	6,2924	6,3714	-1,5239	4,898	1,0000	3,89	0	2,5	3
22	28,296	25,7964	6,1661	6,2398	-1,3143	4,630	0,9999	3,77	0	2,5	3
23	18,351	25,4727	6,2212	6,2923	-0,9193	3,119	0,9974	2,80	0	2,5	3
24	16,269	25,0892	6,3679	6,4374	-1,0769	2,705	0,9935	2,49	0	2,5	3
25	15,756	24,7159	6,5073	6,5757	-1,5122	2,590	0,9918	2,40	0	2,5	3

Observing Figure 49 it was obtained between 6 to 10, 3 to 5 values consecutive above the Alert Level (AL) and from 16 to 23 observations six consecutive values above the AL which mean the respective criteria's to be included on FMECA-H-CM will be 3.

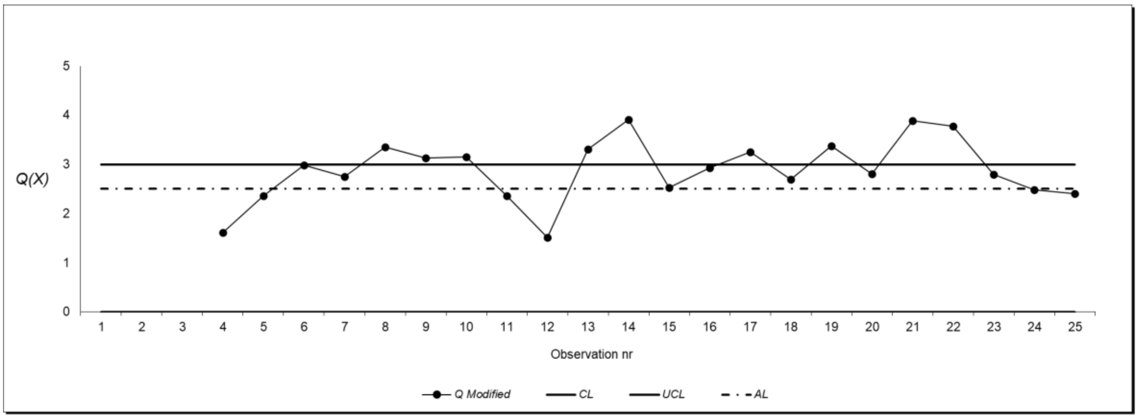


Figure 49 - Vibration – MD – simulation 2 - Turbo B2-A-A for velocity 2

5.3.2. Condition monitoring – thermodynamic parameters

For condition monitoring based on oil lubricant temperature and pressure from propulsion engines, respectively OT0114 and OP0155 were chosen. For the present research on FMECA-H-CM only OT0114 will be used. The levels considered are as defined in 4.2.1.2.

The values used in CMP are present in Table 33.

Table 32 - Values from temperature and pressure of lubricant

Base Values		1st Simulation		2nd Simulation	
OP0155	OT0114	OP0155	OT0114	OP0155	OT0114
6,68	70,80	4,15	95,80	5,55	103,00
5,74	71,40	4,97	96,40	4,77	98,00
5,65	70,80	5,91	95,80	5,09	115,00
5,71	71,50	6,57	96,50	5,87	101,00
5,89	74,80	6,21	88,00	7,04	113,00
6,00	71,50	7,04	84,00	4,18	109,00
6,23	73,10	5,53	98,10	5,02	123,10
6,69	73,00	6,72	98,00	5,49	123,00
3,50	76,50	4,66	83,00	6,30	108,00
6,54	65,50	6,31	85,00	5,60	110,00
6,68	70,90	6,74	95,90	5,09	101,00
6,19	78,50	4,91	90,00	5,97	98,00
6,45	70,50	6,32	95,50	4,40	105,00
6,73	72,20	4,53	91,00	4,51	116,00
6,60	73,10	4,10	95,00	6,88	108,00
6,13	73,70	6,90	81,00	7,01	106,00
6,91	72,90	4,84	97,90	4,63	104,00
6,42	72,50	4,25	97,50	4,13	103,00
4,10	71,00	4,10	96,00	5,87	99,00
5,71	73,00	6,32	98,00	6,88	106,00

7,44	72,70	5,40	93,00	5,76	107,00
6,74	71,70	5,98	96,70	4,30	105,00
5,31	72,80	6,22	97,80	4,46	102,00
5,71	71,50	5,34	96,50	6,61	101,00
5,84	71,40	5,23	96,40	5,01	96,00

Modified QM Control Chart for Temperature with $(T_L)_N$= 95 (ºC), with real data the results were under control, so the results for Q(x) are equal to zero.

Table 33 - QM control chart from oil temperature using real data

r	X	$\bar{X}$	S	s	T_L	w_r	G(w)	Q(X)	LC	LA	LSC
1	70,800	70,8000							0	2,5	3
2	71,400	71,1000	0,4243	0,5317					0	2,5	3
3	70,800	71,0000	0,3464	0,3909	93,4048				0	2,5	3
4	71,500	71,1250	0,3775	0,4097	93,8273	-54,762	0,0002	0,00	0	2,5	3
5	74,800	71,8600	1,6757	1,7827	93,7708	-45,083	0,0000	0,00	0	2,5	3
6	71,500	71,8000	1,5060	1,5828	89,6520	-12,132	0,0001	0,00	0	2,5	3
7	73,100	71,9857	1,4599	1,5217	90,2517	-10,175	0,0001	0,00	0	2,5	3
8	73,000	72,1125	1,3984	1,4491	90,4348	-11,054	0,0000	0,00	0	2,5	3
9	76,500	72,6000	1,9621	2,0243	90,6526	-9,395	0,0000	0,00	0	2,5	3
10	65,500	71,8900	2,9092	2,9908	88,9271	-12,161	0,0000	0,00	0	2,5	3
11	70,900	71,8000	2,7760	2,8460	86,0276	-5,908	0,0001	0,00	0	2,5	3
12	78,500	72,3583	3,2782	3,3533	86,4621	-2,596	0,0133	0,00	0	2,5	3
13	70,500	72,2154	3,1806	3,2475	84,9402	-4,678	0,0003	0,00	0	2,5	3
14	72,200	72,2143	3,0559	3,1150	85,2574	-3,860	0,0011	0,00	0	2,5	3
15	73,100	72,2733	2,9536	3,0068	85,6549	-3,844	0,0010	0,00	0	2,5	3
16	73,700	72,3625	2,8756	2,9239	85,9797	-3,919	0,0008	0,00	0	2,5	3
17	72,900	72,3941	2,7874	2,8312	86,2284	-4,413	0,0003	0,00	0	2,5	3
18	72,500	72,4000	2,7042	2,7443	86,5063	-4,786	0,0001	0,00	0	2,5	3
19	71,000	72,3263	2,6476	2,6847	86,7671	-5,581	0,0000	0,00	0	2,5	3
20	73,000	72,3600	2,5814	2,6157	86,9460	-5,068	0,0000	0,00	0	2,5	3
21	72,700	72,3762	2,5171	2,5487	87,1530	-5,386	0,0000	0,00	0	2,5	3
22	71,700	72,3455	2,4607	2,4901	87,3538	-5,998	0,0000	0,00	0	2,5	3
23	72,800	72,3652	2,4060	2,4335	87,5298	-5,785	0,0000	0,00	0	2,5	3
24	71,500	72,3292	2,3597	2,3855	87,6996	-6,522	0,0000	0,00	0	2,5	3
25	71,400	72,2920	2,3175	2,3418	87,8436	-6,768	0,0000	0,00	0	2,5	3

Q Modified control chart for oil temperature with real data is presented in the Figure 50, for these data there aren´t significant observations.

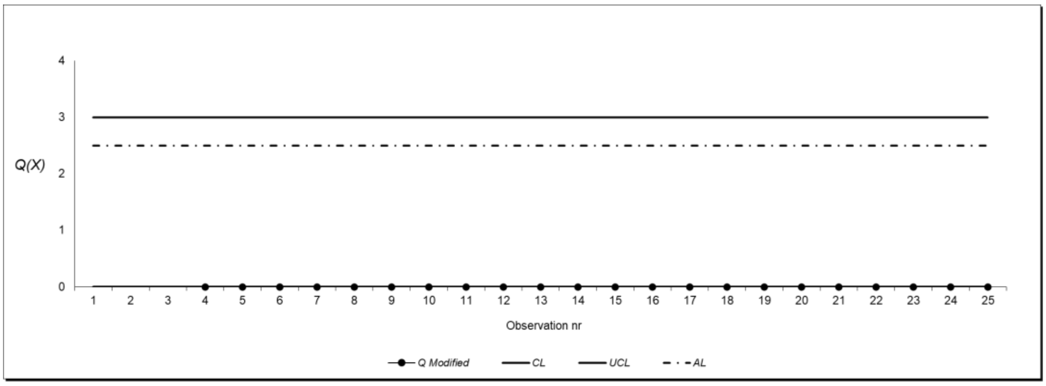


Figure 50 - Oil temperature – MD – simulation with real data, for velocity 2

By applying the QM charts for the real data there was no registered observation, Figure 50, so, for oil temperature of diesel propulsion engine the category is 1.

Then to test limits, it was simulated data using the function random values between an interval that include values higher than the defined limit. The simulation/aggravation nr 1 for oil temperature are represented in Table 35.

Table 34 - QM control chart from oil temperature for aggravation nr 1

r	*X*	$\bar{X}$	*S*	*s*	T_L	w_r	*G(w)*	*Q(X)*	*LC*	*LA*	*LSC*
1	95,800	95,8000							0	2,5	3
2	96,400	96,1000	0,4243	0,5317					0	2,5	3
3	89,000	93,7333	4,1102	4,6379	93,4048				0	2,5	3
4	96,500	94,4250	3,6299	3,9399	81,0862	0,652	0,7094	0,55	0	2,5	3
5	78,000	91,1400	7,9899	8,4999	83,1802	-0,760	0,2511	0,00	0	2,5	3
6	84,000	89,9500	7,7180	8,1114	69,5004	0,094	0,5351	0,09	0	2,5	3
7	98,100	91,1143	7,6895	8,0149	70,6659	3,431	0,9907	2,35	0	2,5	3
8	98,000	91,9750	7,5238	7,7967	70,9553	3,325	0,9920	2,41	0	2,5	3
9	94,000	92,2000	7,0702	7,2941	71,6099	2,888	0,9883	2,27	0	2,5	3
10	85,000	91,4800	7,0440	7,2417	73,1177	1,797	0,9449	1,60	0	2,5	3
11	95,900	91,8818	6,8141	6,9859	73,2750	3,084	0,9935	2,48	0	2,5	3
12	90,000	91,7250	6,5196	6,6690	74,0422	2,350	0,9797	2,05	0	2,5	3
13	95,500	92,0154	6,3293	6,4624	74,9929	3,162	0,9955	2,61	0	2,5	3
14	91,000	91,9429	6,0870	6,2049	75,6128	2,437	0,9843	2,15	0	2,5	3
15	95,000	92,1467	5,9185	6,0251	76,3852	3,077	0,9956	2,62	0	2,5	3
16	81,000	91,4500	6,3607	6,4674	76,9246	0,755	0,7686	0,73	0	2,5	3
17	97,900	91,8294	6,3543	6,4543	75,5977	3,199	0,9970	2,75	0	2,5	3
18	97,500	92,1444	6,3078	6,4013	75,6370	3,350	0,9980	2,87	0	2,5	3
19	96,000	92,3474	6,1936	6,2802	75,7962	3,142	0,9970	2,75	0	2,5	3
20	98,000	92,6300	6,1595	6,2412	76,1593	3,494	0,9987	3,01	0	2,5	3
21	93,000	92,6476	6,0041	6,0794	76,2763	2,668	0,9924	2,43	0	2,5	3
22	96,700	92,8318	5,9227	5,9934	76,7617	3,323	0,9983	2,93	0	2,5	3
23	97,800	93,0478	5,8785	5,9457	77,0197	3,474	0,9989	3,05	0	2,5	3
24	96,500	93,1917	5,7923	5,8556	77,1628	3,244	0,9981	2,90	0	2,5	3
25	96,400	93,3200	5,7066	5,7665	77,4333	3,254	0,9983	2,92	0	2,5	3

On Figure 51 can be observed the results obtained in Table 35.

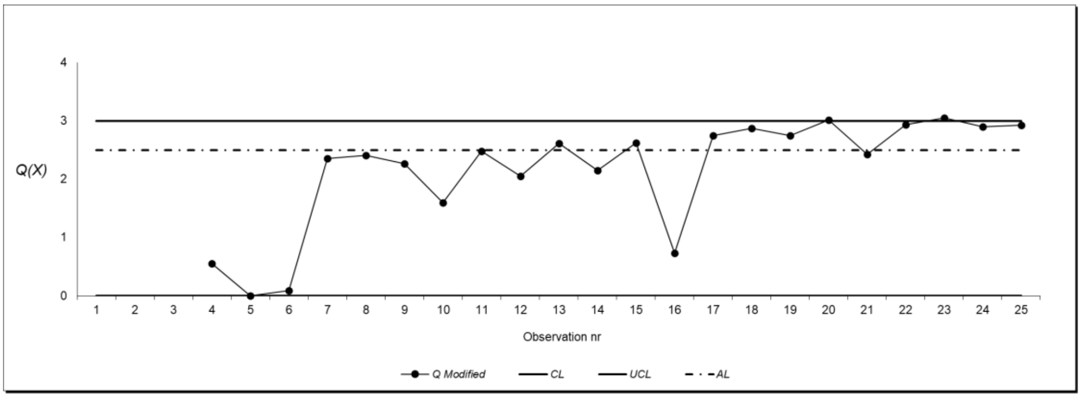


Figure 51 - Oil temperature – MD – simulation 1

According to the results on Figure 51, simulation 1, and the defined categories on 4.2.1.2 the obtained value are 2 on observation nr19 till 20 and then since observation nr 24 to 25 also category nr 2.

In Table 36 are represented the data to fulfil QM control chart for the oil temperature for simulation/aggravation nr 2.

Table 35 - QM control chart from oil temperature for simulation nr 2

r	*X*	$\bar{X}$	*S*	*s*	T_L	w_r	*G(w)*	*Q(X)*	*LC*	*LA*	*LSC*
1	103,000	103,0000							0	2,5	3
2	98,000	100,5000	3,5355	4,4310					0	2,5	3
3	115,000	105,3333	8,7369	9,8588	81,7069				0	2,5	3
4	101,000	104,2500	7,4554	8,0923	65,4235	1,912	0,9020	1,29	0	2,5	3
5	113,000	106,0000	7,5498	8,0317	70,7231	5,708	0,9947	2,55	0	2,5	3
6	109,000	106,5000	6,8629	7,2128	70,9048	4,628	0,9951	2,58	0	2,5	3
7	123,100	108,8714	8,8666	9,2418	73,3617	7,041	0,9996	3,32	0	2,5	3
8	123,000	110,6375	9,6092	9,9577	67,2747	5,237	0,9990	3,10	0	2,5	3
9	108,000	110,3444	9,0315	9,3175	65,1268	3,996	0,9974	2,79	0	2,5	3
10	110,000	110,3100	8,5157	8,7547	67,0474	4,714	0,9992	3,17	0	2,5	3
11	101,000	109,4636	8,5525	8,7682	68,7360	3,802	0,9979	2,86	0	2,5	3
12	98,000	108,5083	8,8004	9,0020	68,6955	3,276	0,9958	2,64	0	2,5	3
13	105,000	108,2385	8,4817	8,6601	67,9940	3,963	0,9989	3,06	0	2,5	3
14	116,000	108,7929	8,4088	8,5717	69,0197	5,454	0,9999	3,80	0	2,5	3
15	108,000	108,7400	8,1055	8,2516	69,2849	4,478	0,9997	3,42	0	2,5	3
16	106,000	108,5688	7,8606	7,9925	70,2452	4,386	0,9997	3,42	0	2,5	3
17	104,000	108,3000	7,6912	7,8123	71,0226	4,166	0,9996	3,34	0	2,5	3
18	103,000	108,0056	7,5654	7,6775	71,5630	4,041	0,9995	3,31	0	2,5	3
19	99,000	107,5316	7,6370	7,7439	71,9674	3,530	0,9987	3,01	0	2,5	3
20	106,000	107,4550	7,4412	7,5400	71,7683	4,343	0,9998	3,55	0	2,5	3

21	107,000	107,4333	7,2535	7,3446	72,3800	4,621	0,9999	3,74	0	2,5	3
22	105,000	107,3227	7,0977	7,1824	72,9663	4,394	0,9999	3,63	0	2,5	3
23	102,000	107,0913	7,0227	7,1030	73,4527	4,001	0,9997	3,41	0	2,5	3
24	101,000	106,8375	6,9800	7,0562	73,6910	3,840	0,9996	3,32	0	2,5	3
25	96,000	106,4040	7,1686	7,2439	73,8313	3,132	0,9977	2,83	0	2,5	3

Observing Figure 52, simulation 2 considering the results in Table 36, till observation nr 7 the risk is on level 1, on observation nr 9 the category is 2, the category 3 is not verified, on observation nr 17 the category is 4, and finally since observation nr 18 the category are nr 5.

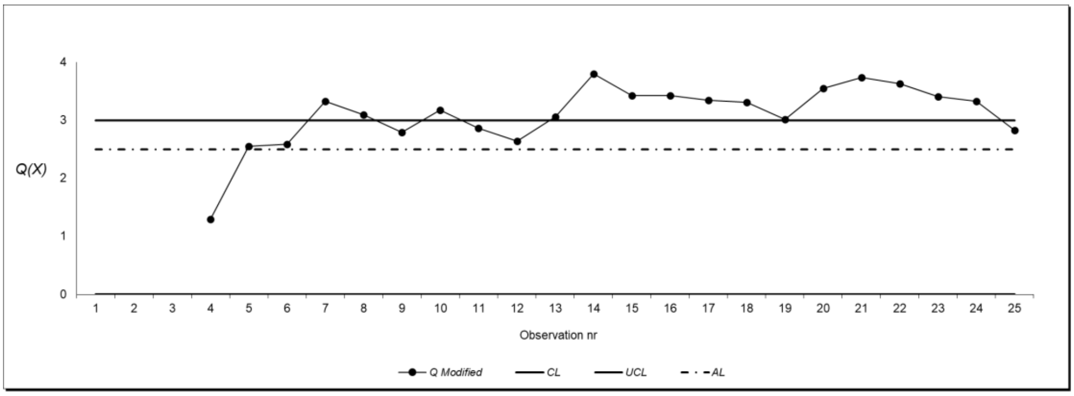


Figure 52 - Oil temperature – MD – simulation 2

5.3.3. Condition monitoring based on text from DSM58 Data

For condition monitoring based on text from DSM58 database, the present investigation was focused on the diesel engines propulsion to search for the quantity of occurrence of maintenance on it, considering the functional number and the description, where the words “corrective” or “corrective” are cumulatively searched. The procedure will also be made for the others selected equipment´s on this research.

The detection of the specific equipment and for description, it was used the existing data on the interventions database from DN (DSM58), where it was found data from the ships of the ship class understudy for the various equipment´s and systems that exist onboard.

An extract from DSM58 database for diesel engine, marine gasoil purifier and low pressure air compressor, can be observed in Table 37, Table 38 and Table 39.

For diesel propulsion engine in Table 37, it is observed 2 maintenances of the 3rd stage, and the last one are from the 1st stage.

Table 36 - Extract from DSM58 database for diesel engine propulsion

Nr	Unit	Necessity date	Functional Nr	Intervention Description	MT
1	Ship3	07/19/2018 00:00:00	2331000000	BLOCOS DE FILTROS PRIMÁRIOS	33
2	Ship3	10/17/2018 00:00:00	2331000000	BOMBAS ACOPLADAS DE ÁGUA SALGADA DOS MOTORES PRINCIPAIS	33
3	Ship3	11/27/2017 00:00:00	2331000000	C1 - PURGA COMBUSTÍVEL	13

Note: "Blocos De Filtros Primários" is Primary Filter Blocks, "Bombas Acopladas de Água Salgada dos Motores Principais" is Main Engine Seawater Pumps and "C1 - Purga Combustível" is C1 - Fuel Purge.

An extract from DSM58 database for marine gasoil purifier nr 1 in Table 38, the types of maintenance are the three from 1st stage.

Table 37 - Extract from DSM58 database for marine gasoil purifier

Nr	Unit	Necessity date	Functional Nr	Intervention Description	MT
1	Ship3	03/03/2016 00:00:00	2613121000	C1 - CENTRIFUGADOR DE COMBUSTIVEL	13
2	Ship3	04/01/2019 00:00:00	2613121000	C1 - FERODOS CENTRIFUGADOR COMBUSTIVEL	11
3	Ship3	03/23/2016 00:00:00	2613121000	C1 - POST16- CENTRIFUGADOR DE COMBUSTIVEL	13

Note: "Centrifugador de Combustivel" is Marine Gasoil Purifier, "Ferodos Centrifugador de Combustivel" is Ferodos of Marine Gasoil Purifier and "POST16 - Centrifugador de Combustivel" is POST16 - Marine Gasoil Purifier.

An extract from DSM58 database for Low Pressure Air Compressor can be observed in Table 39. The observed maintenance is from the 1st stage.

Table 38 - Extract from DSM58 database for low pressure air compressor

Nr	Unit	Necessity date	Functional Nr	Intervention Description	MT
1	Ship3	08/02/2018 00:00:00	5515300000	C1- BUJÃO FUSÍVEL COMPRESSOR BAIXA	13
2	Ship3	04/24/2016 00:00:00	5515300000	C2 - SUSTENTAÇAO LOGISTICA NATO16 - VALVULAS DE SEGURANÇA COMPRESSOR BP	13
3	Ship3	08/10/2018 00:00:00	5515300000	COMPRESSOR DE B.P	13

Note: "Bujão Fusível Compressor Baixa" is Compressor Fuse Plug Low, "Sustentação Logistica NATO16 - Válvulas de Segurança Compressor BP" is NATO16 Logistics Support - BP Compressor Safety Valves and "Compressor de B.P." is BP compressor.

The considered maintenance registered on SRTD DSM58 document are between a period of 4 years, the quantity of maintenance for ship 3, can be observed on Figure 53.

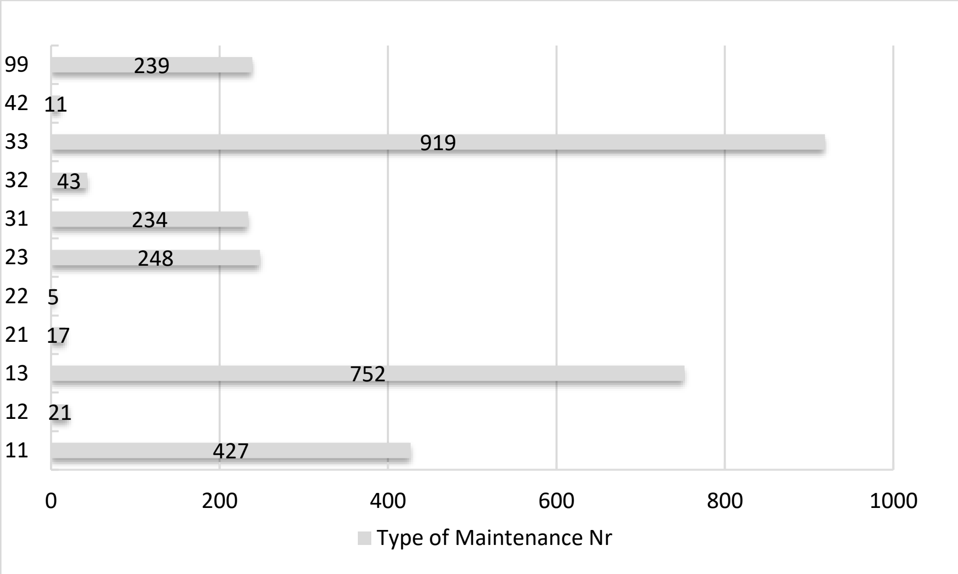


Figure 53 - Type of maintenance occurrences for all maintenance registers in ship 3

For diesel propulsion engines the quantity of maintenance, considered its type and from DSM58 registered document´s on SRTD, can be observed on Figure 54. The NI is the documents that have the type of maintenance not identified (NI), but observing the detailed information of it, all were corrective and preventive maintenance of first level. It was decided to present the quantity of not identified maintenance to give the perception of the relatively number of errors of badly introduced information that can happened, the continuous personnel education on SRTD must be a reality, so the maintenance executers and managers can register reliable information for a support decision system.

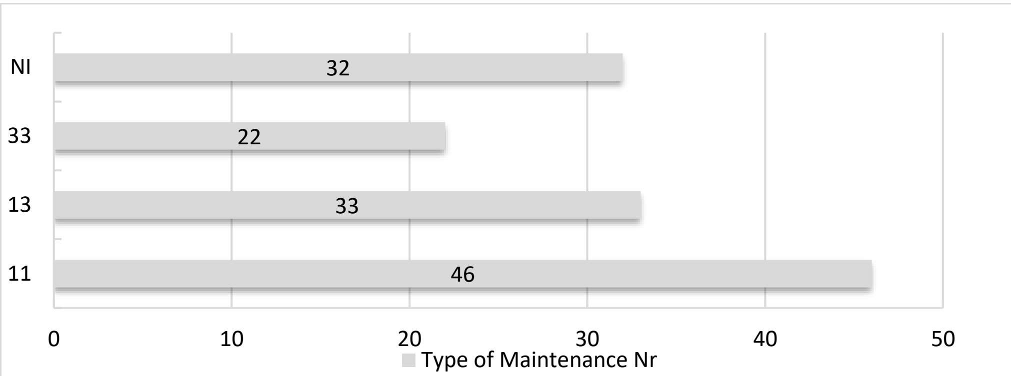


Figure 54 - Type of maintenance occurrences for the MD´s

To counting the occurrence of corrective maintenance in the DSM58 document according to the defined categories on Subchapter 4.2.3, it was developed a simple language on Python (Table 40) to counting the number of occurrences of corrective maintenance of each selected equipment between the years of 2017 to 2022. It was obtained the next results of occurrence and respective categorization:

- Diesel propulsion engine: 42 occurrences, the category is 5;
- Low pressure air compressor: 2 occurrences, so the category is 3;
- Marine gasoil purifier: 1 occurrence, the category is 2;
- Oil purifier: 0 occurrences, the category is 1.

The previous results were obtained by the next extract of the development of Python language for counting the corrective maintenance on the database of DSM58, Table 40.

Table 39 - Software language for counting text

```
cmtex_mp=transform_into_cmtex(count_corrective_motor_propulsor)
cmtex_mg=transform_into_cmtex(count_corrective_marine_gasoil)
cmtex_cpa=transform_into_cmtex(count_corrective_pressure_air)
cmtex_op=transform_into_cmtex(count_corrective_oil_purifier)
print(f'cmtex of the motor_propulsor is {cmtex_mp}')
print(f'cmtex of the marine_gasoil is {cmtex_mg}')
print(f'cmtex of the low pressure air compressor is {cmtex_cpa}')
print(f'cmtex of the oil purifier is is {cmtex_op}')
```

And the obtained results of the language in the original format are in Table 41.

Table 40 - Software results for counting text

```
number of corrective appointments at propulsion diesel engines 42
number of corrective appointments at marine_gasoil 1
number of corrective appointments at Low Pressure air compressor 2
number of corrective appointments at Oil purifier 0
```

And the obtained results on Python ton the transformation of number of occurrences on categories are in Table 42.

Table 41 - Software results for transform the counting text on categories

```
cmtex of the motor_propolsor is 5
cmtex of the marine_gasoil is 2
cmtex of the low pressure air compressor is 3
cmtex of the oil purifier is is 1
```

5.4 Data structure development - relations between data

It is proposed a decentralized system with various certification level by the user of database, like a blockchain structure, or an automatic certification using artificial intelligence algorithm. It will be considered a private database giving the military environment, because most of the data deliverable information about operationality of ships equipment´s which can be traduced in ship operationality or other information.

In general database data flux enter the database system. The data flux contain the SMP data, CMV, CMP, CMT, CMText and the threat information, then the data filled the discriminated equipment´s information, from that the data are converted in useful data with the methods presented on chapter nr 4, and FMECA-H-CM is applied to support decisions, Figure 55, and the data flux is validated in automatic but supervised by various responsible managers or technicians.

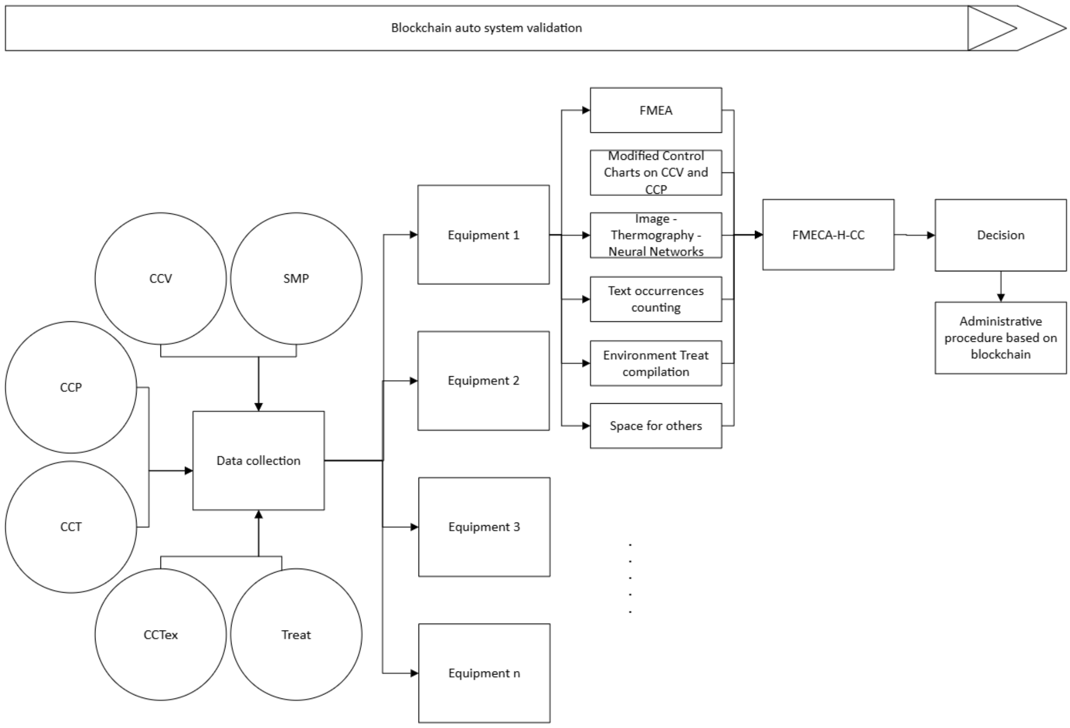


Figure 55 - Data flux

5.4.1 Integrating threat and auxiliary equipment

On the database there will be considered data from parameters developed in chapter 4, according and limited to the constraints of data previous presented on Subchapter 5.3.

Introducing the threat level on the Python language it was decided to putt that manually by the user, otherwise it should be integrated on operation system for decision support that integrate various threat landscapes variables and automatically generate the threat category. The threat language that integrates the software language are presented in Table 43.

Table 42 - Software language for threat introducing

```
fT=input('What is the Threat level? ')
print(f'The define Threat level is {T}')
```

If detected some auxiliary and adjacent equipment's liable of intervene the decision method should show the maintenance opportunities of the other selected equipment's for study. On the software developed on Python it was not finally streamlined, although, from the software result the risk, priorities of interventions and options on maintenance for all selected equipment´s are demonstrated, and by observing results the user may decide to intervene the auxiliary equipment´s of the diesel engine propulsion based on an opportunity maintenance.

Only when the result is to procedure to maintenance intervention come out from diesel propulsion engine, the software will search for other equipment´s that are also with risk in category 3 or higher. In this case the option of maintenance of the other equipment, considering the limited time and to simplify software development will be the same of the diesel propulsion engine. Considering that a same maintenance activity can be subdivided in other mode and effects of that activity, for the other equipment will be considered the highest value of the risk value associated to the respective activity maintenance.

To refer that, before the final decision of also intervene auxiliary and adjacent equipment, these equipment´s should also be subject to the analysis performed for the original equipment, considering the methodology on Figure 33.

5.4.2 Database cybersecurity concerns and blockchain structure

In terms of cybersecurity of maintenance database, it was made a risk assessment present on the referred article in annex (article nr a.1.16). For diesel propulsion engine was considered seven factors on the database for a cyber-safety environment in the maintenance related to SICALN that can contribute for the risk: the ship, other ships, equipment's, authentications, software monitoring, risk analysis, personal, Figure 56.

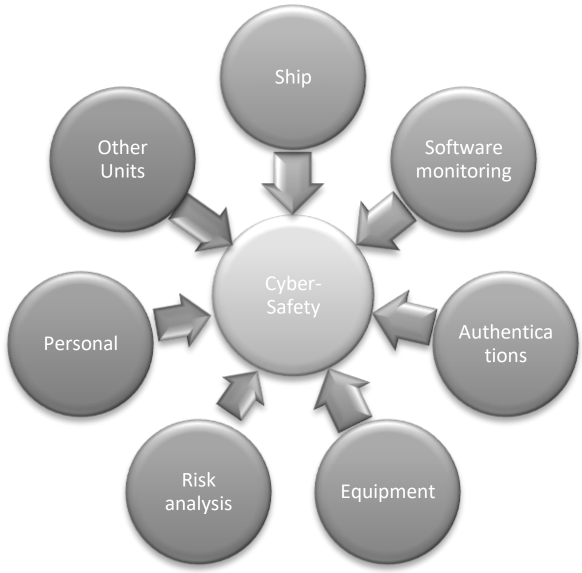


Figure 56 - Maintenance database factors - SICALN

Source: adapted from Lampreia et al. (2022)

The presented factors and their correlation can affect cyber security not only because of directly administrative management of database, but also because of the cyber-measures implemented in the access of the web that support the assessment to SRTD database.

For maintenance database risk assessment, a sample of eight maintenance activities representative and related to SRTD for the diesel propulsion engines were considered (discriminated FMEA presented online on a link constant on the end of point a.1 of Annex A and FMECA-H-CM on Appendix C) (Lampreia et al., 2022). The calculus of risk was made on the ship perspective, it has connection with other administrative organizations from the Navy, which can increase the risk level in case of a cyber-threat. The results of risk assessment were considered acceptable, but if the SRTD database in future could be directly collecting data from equipment, it can increase the safety risk of the equipment's and the ship itself.

It was possible to observe that, for the ship propulsion diesel engine, on risk assessment, the higher results on cyber risk exposure were obtained for the SICALN library access. It happened because mostly the operators of SICALN can access it; if there is a networking hacker, access to some classified information can be obtained, or some maintenance information can be changed or lost" (Lampreia et al., 2022).

To guarantee the safety of ships and its equipment's, the maintenance database should be included in the safety monitoring systems. A factor that should be considered is in the existence of "different networks, the security system procedure and access should be adapted to various security levels. For example, if maintenance software requests are introduced by access to the World Wide Web (WWW) or on a private web, or even ship to land. For different situations, the cyber risk is different, the security levels and aggregated security software should be adapted" (Lampreia et al., 2022).

The cybersecurity risk on maintenance data that a warship may be exposed may be:

a. Maintenance data will be the loss,
b. Mixing or alteration of its history for erroneous data (E.g., alteration of operating hours, the recording of condition monitoring readings, among others. In the present investigation, only maintenance data is mentioned
c. Loss of equipment command if connected to database of sensors collecting data;
d. Broken database connections, delays in decision-making and maintenance (e.g., between ships, ground support systems and electromechanical workshops);
e. Loss of ship if the manoeuvring system may be accessed through maintenance database.

Because of the reasons presented before, the concept and access to database structure may affect its security and the ship platform. And that was the reason that the author decided to explore the blockchain data structure.

The Failure Modes, Effects, and Criticality Analysis with Condition monitoring (FMECA-CM) methodology offers a systematic approach to assess and mitigate potential failures in equipment. When monitoring the condition of critical equipment, ensuring data integrity, security, and traceability is paramount. Traditional maintenance databases, while effective, often face challenges related to centralized data storage, vulnerability to cyber-attacks, and difficulties in ensuring data immutability. Blockchain technology, with its decentralized and tamper-evident ledger system, presents a promising solution to these challenges. The cybersecurity of a maintenance database is critical not only to operational safety but also to mission assurance. A breach that manipulates the health management system of a propulsion subsystem or the equipment itself, for instance, could delay necessary maintenance and induce catastrophic failure.

A correspondence of maintenance database cybersecurity concerns with blockchain data structure solutions was made on Figure 57.

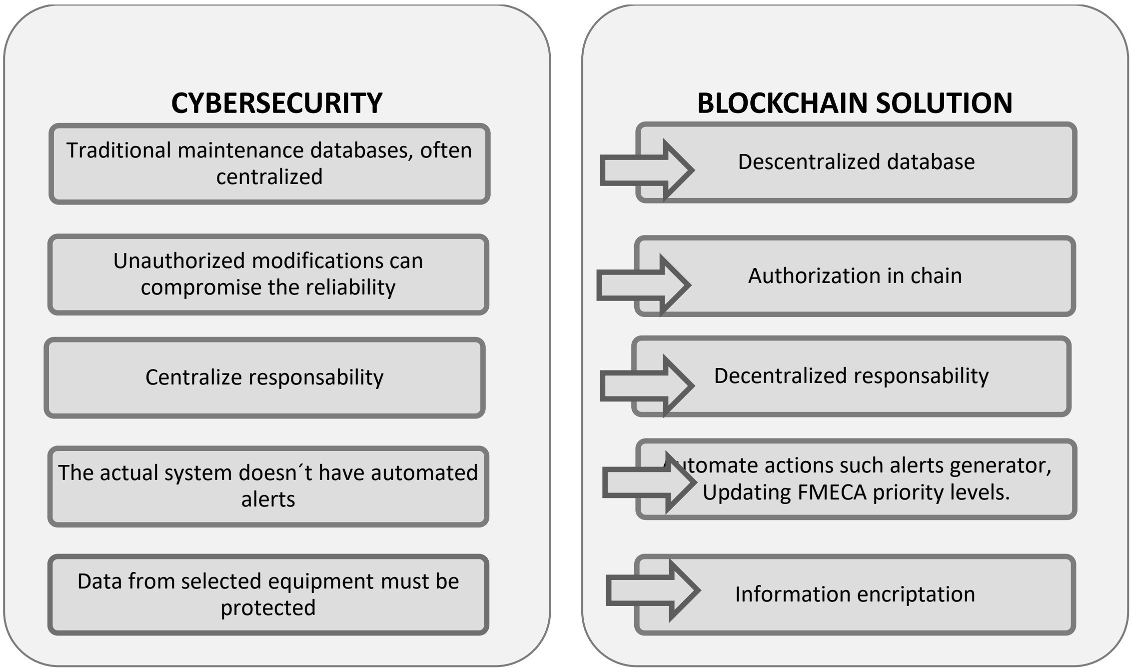


Figure 57 - Cybersecurity with blockchain structure

For Blockchain Data Structure the technology involved should record information across multiple nodes of a network. The information and the processes on this type of database should be designed with blocks in a chain that should contain a list of registering actions on the database organized by time and protected memory of the previous block, ensuring a chronological and immutable record. The decentralized nature of blockchain will eliminate the need for a central authority, reducing single points of failure and enhancing data resilience. Although the DN should have the autonomy to approve or not requested maintenance actions.

To guarantee safer blockchain protocols of access and to ensure agreement among network participants on the validity of maintenance requests and reports, the users should have training on using the maintenance database. When data is recorded in a blockchain concept it cannot be altered retroactively without the consensus of the network.

The implementation of a blockchain structure will enhance data integrity and immutability: each equipment's condition data, once recorded on the blockchain, may become immutable, ensuring that maintenance decisions are based on trustworthy data.

By integrating blockchain into the FMECA-H-CM methodology, organizations can enhance the reliability and security of their maintenance data, leading to more informed decision-making and improved equipment uptime.

Blockchain as a data structure in maintenance systems may enable the decentralized recording of condition-monitoring data, maintenance events, and failure histories. Each data entry whether a sensor reading, a fault detection, or a scheduled inspection can be warned.

The FMECA-H-CM model dynamically adjusts critical assessments based on real-time condition trends. However, such dynamism introduces data volume and integrity challenges. Integrating blockchain into the maintenance database may allow each critical event or threshold violation to be recorded as a validated action on the chain.

Adopting blockchain-based structures in naval maintenance introduces both disruptive potential and strategic challenges. In operational settings, the balance between security, performance, and interoperability must be carefully managed. Simulation studies and pilot deployments using digital twins of key equipment can offer insights into practical feasibility and scalability.

Moreover, the integration of blockchain must align with overarching maritime cybersecurity frameworks (e.g., NATO cyber defense policies) and remain adaptable to evolving threat models. The FMECA-H-CM methodology, enriched by blockchain, may thus serve as a testbed for resilient, transparent, and accountable maintenance systems. On Figure 58 is shown a data flow through a possible blockchain system.

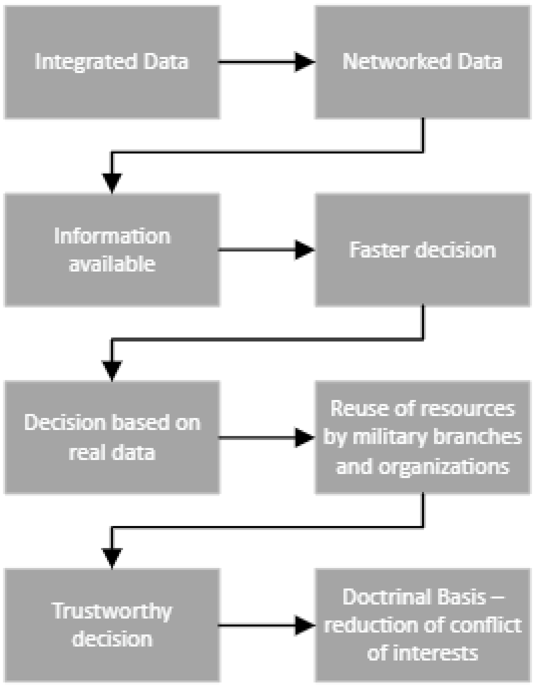


Figure 58 - Blockchain on a FMECA-H-CM database

Blockchain may offer a change in how data can be secured and shared in military systems. When an applied on the FMECA-H-CM it strengthens trust in condition-monitoring data, enhances the decision-making, and mitigates a range of cybersecurity threats.

A FMECA-H-CM structure by blockchain can be consider one block with the information of the equipment, where the manuals and maintenance plan information are, then the next block the CM information are introduced if it is available (in this one various sub-blocks should exist, the third block the information of text, the fourth block the threat state, and the fifth the results, Figure 59.

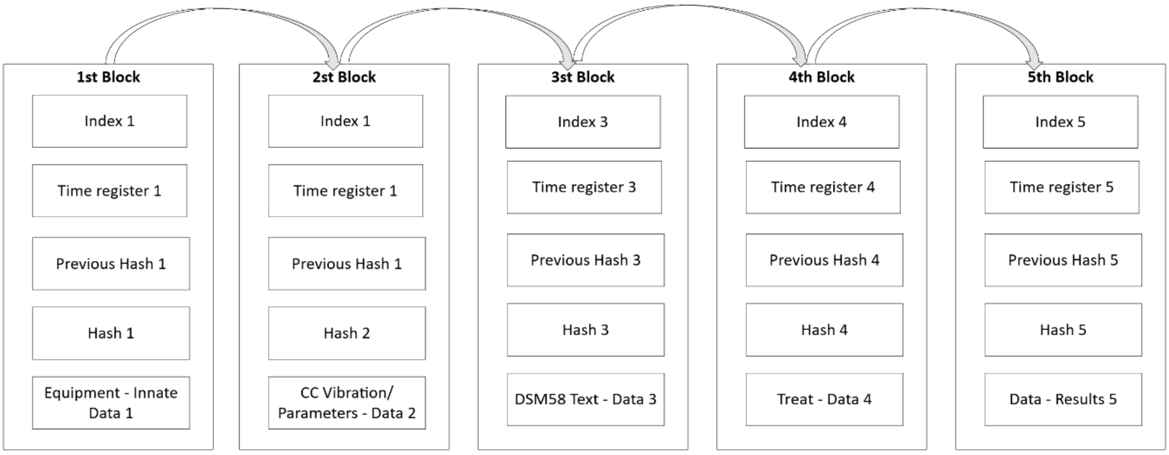


Figure 59 - FMECA-H-CM database with blockchain

It is believed that a blockchain data structure, allied with other security measures may be a solution to a cybersafe maintenance database considering the integrative FMECA-H-CM approach developed on chapter 4.

5.4.3 Data processing methodology

On Appendix C can be seen the complete data that integrate the FMECA-H-CM result. Where resulted a FMECA application, considered the various presented severities, the occurrence, detection, data from condition monitoring and the threat state.

According to the risk and priorities the options of maintenance actions will be the one´s presented in Table 18 present on Subchapter 4.4.

To demonstrate the dynamic of the developed research using Python language, for reasons of executability it was used to count the number of occurrences of a certain text referred on 4.2.3, and according to the result it was obtained the respective attributed value of the categorization and correspondent prioritization. This result will be considered for the final FMECA-H-CM calculus.

To process the existing data the FMECA-H was considered a static, and the previous real result for vibration and parameter control (vibration was considered on category 5 and Temperature on category 1).

The threat option was also included. The threat option choices depend on an operator decision, or to introduce the environment threat category on the software. On the present study the category 2 was considered when only exist Threat or bluff information or marketing. The developed language was based on the table of categorization of the threat referred on sub-chapter 4.2.4.2.

Considering the methodology fluxogram presented on sub-chapter 4.4, the development software is considered since step nr 15 where the question of risk level is asked. It was decided only to intervene with different procedures on equipment only when the risk is above 2. The risk is considered for some maintenance action, although online monitoring, since the result of category equal to nr 3. And the resulting actions will be the ones defined in Table 18 on Subchapter 4.4.

It was considered that, if one of the diesel propulsion engine activities analysed with FMECA are in risk higher then 2, and the others equipment’s understudy are also on category higher than 2, the other equipment should be analysed the possibility of maintenance either, considering that represents an opportunity to do maintenance at the same time not expanding the immobilized time of the ship. And the maintenance option (Table 18) should be the same of the main equipment understudy, the diesel propulsion engine.

The data processing with Python considering FMECA-H, with available condition monitoring and threat are compiled on subchapter 6.4. An extract from data processing with Python considering the calculation of FMECA-H-CM for the diesel propulsion engine are present in Table 44.

Table 43 - Extract of Python for FMECA-H-CM – Risk calculation

```
df1_main_engine= pd.read_csv('Main_Engine.csv', sep=';') # Try semicolon
df1_main_engine=df1_main_engine.drop(['FMECA_H_CM','CMTex'],axis=1)

df1_main_engine=df1_main_engine.set_index('Nr Act')
df1_main_engine['FMECA_H_CM'] = df1_main_engine['FMECA-H'] * np.log(((CMtex_mp + df1_main_engine['CMV'] + df1_main_engine['CMT'] + df1_main_engine['CMP'])/4) * T)
df1_main_engine['Risk Level']=df1_main_engine['FMECA_H_CM'].apply(transform_into_risk)
df1_main_engine['Prioritization']=df1_main_engine['FMECA_H_CM'].apply(transform_into_prioritizatio
n)
```

In Table 45 it can be observed an extract from language used for prioritization of maintenance activities.

Table 44 - Extract of data processing with Python for FMECA-H-CM – Prioritize

```
mask_priority_1= df1_main_engine['Prioritization']==1
priority_1_activities_df=df1_main_engine[mask_priority_1]

mask_priority_2= df1_main_engine['Prioritization']==2
priority_2_activities_df=df1_main_engine[mask_priority_2]

mask_priority_3= df1_main_engine['Prioritization']==3
priority_3_activities_df=df1_main_engine[mask_priority_3]
```

5.5 Chapter elations

In sub-chapter 5.1 is made an introduction of the subject of chapter 5, then on 5.2 were presented the selected equipment's for study, then in 5.3 the selected sensors or databases to condition that was considered to define the equipment's state, and in 5.4 were define the risk levels according the results of FMECA-H-CM, then the concerns with database structure and its cybersecurity and finally there are presented some of the methods considered to process the data with Python to obtain the risk, the prioritising and the options of actions that will support decisions.

To prioritizing and determine the opportunity of maintenance it was considered the application of FMECA modified to integrate condition monitoring data and the threat state, considering the main equipment on study, the diesel propulsion engine, and other selected equipment. The demonstrate that these results may be automatize in a software language it was used Python language.

With this procedure the risk level of the various equipment´s will be calculated, then prioritize and then a decision result considering the maintenance of other equipment's based on the opportunity.

6. Applying FMECA-H-CM in a dynamic maintenance concept

6.1. Chapter introduction

Now to finally is going to be applied the dynamic maintenance methodology based on FMECA, the data exposed in the previous chapter will be integrated considering the data from other equipment from a Navy military ship.

The developed methodology is nothing more than an intelligence decision support system that is proposed to disrupt the good sense maintenance dogma implemented in surface warship maintenance management system. To do that it was used existing data and transform it in the information it is needed (maintenance data processing and treatment) to take decisions to proceed to a maintenance intervention, or not, prioritizing and evaluate the opportunity of maintenance of others equipment´s.

In a first phase there are applied to data the methods present at chapter 4 to obtain the equipment state accordingly so it can fill the integration in criteria's, then in second phase there are attributed weights for each values range, and then, on the third phase that information of each data treatment from each database are related between them to obtain a general risk, and finally on the fourth phase there are suggested solutions, that are called "options" for the founded problems.

The methodology will pass for coding in Python connected with Excel database, then the code does it work, giving results and directions for action, Figure 60.

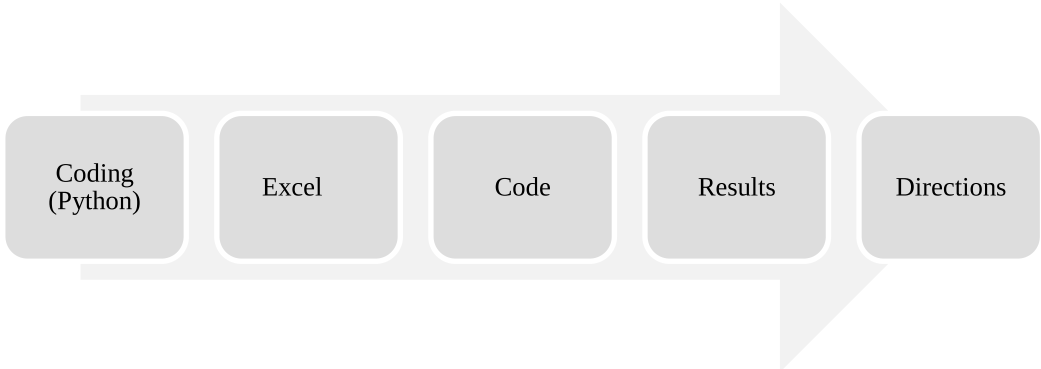


Figure 60 - Methodology through software

To partially automatize the FMECA-H-CM it was used the Python, where the code was introduced to counting the corrective maintenances based on DSM58 of the SRTD and categorized it. Then the risk was calculated per equipment´s and then the priorities were defined. And finally, according to the results there are suggested options, according to the responses to Step´s (Step 16, Step 17, Step 18 and Step 19) of the methodology presented on Fig. 33 on subchapter 4.4.

6.2. FMEA applied to selected equipment´s

It was built a database including a FMEA and FMECA integration study to weight the risk of don´t fulfilled a plan maintenance that are defined for the selected equipment´s.

The first step for applying the FMEA it was chosen the target equipment´s, then defined the parameters to evaluate related to the equipment maintenance, follow by the rules to be considered, the algorithm was defined and tested considered the rules and considerations of the author of this work, the failure modes related to the absence of some maintenance actions was identified, and then the failure effects was analysed, and finally the process should feedback for eventual continuous actualization.

The chosen equipment's for FMEA Categorization was the diesel propulsion engines from a Class of Portuguese warships, which the name will not be exposed, and some auxiliary equipment´s directly related to its operationally such as air filters and sea water filters, low-pressure air compressors (40 bar), diesel purifier and oil purifier. The other subsystems in the propeller shafts were considered operational or as demo for the present investigation.

To fulfil the FMEA desideratum data from maintenance plan system from the chosen ship, Marinha_d (1999) was used, constant on the column of the name of activities for each understudy selected equipment.

The follow extracts are from FMEA equipment data, the complete FMECA-H-CM, including FMEA and the attributed values considering the categorization from 4.2.1 to 4.2.4.2 are present on the link at the end of point a.1 of Annex A and Appendix C.

In Table 46 it can be observed FMEA applied to diesel propulsion engine maintenance activities. The higher the complexity of an equipment, or complex system, it is, the higher number of maintenance activities it has. The diesel propulsion system it is a complex system with many periodically activities. Some performed on 1st stage, others on 2nd stage and also on 3rd stage. For example, change the lubrification oil is a type of maintenance performed on 1st stage, by the military specialists onboard a ship, if analysis or diary checks are not performed it may result in an anomaly with more damage, because of lack of lubrification that may cause grip, one way of detection is made physicochemical analysis. Decarbonization is an activity which involves more material and personnel resources, that may cause poor combustion, clogging of the evacuation system, accelerated contamination of the lubricating oil, and the equipment loss its full performance, it may be detected by observing thermodynamic parameters during functioning on various velocities.

In Table 46, are present an extract of FMEA applied to 77 maintenance activities that are defined on the diesel propulsion engine SMP.

Table 45 - FMEA diesel propulsion engine

Maintenance Activity	Potential Failure Mode	Failure Cause	Failure Effect	How detect/detection
Change lubrication oil	Non-normal parameters - water > 0.2%	Contaminated oil due to improper operation or lack of replacement	Grip	Physicochemical analysis, presence of filings
Change oil filters	Non-normal parameters - material presence of wear on tie rod covers	Inability to filter properly	Grip	Physicochemical analysis, material presence of wear of the covers
Navigating, check the color of the evacuation gases, condensation, obstructions, etc.	Inappropriate gas color	Miscalibrated injectors/Excessive fuel consumption	Contamination of lubricating oil, risk of explosion/fire	Method of observing gases outside
Check/Adjust valves	Engine out of tune/valves out of adjustment	Lack of maintenance	Incomplete burning/fire hazard	Pressure and temperature sensors
Check the sequential system of the supercharging groups	Superchargers do not operate according to specifications	Improper temperatures and boost pressures/wrong combustion stoichiometric mixture	Change to normal combustion temperatures	Reading temperature and pressure sensors
Change fuel filters	Saturated/Clogged Filters	Contaminated fuel	Low fuel pressure	Fuel pressure sensor
Oil sample collection and analysis	Unnormal parameters - accelerated wear of tie rod covers	Material wear due to lubricating oil not being chemically within the expected parameters, or engine being out of balance.	Grip	Physicochemical analysis, material presence of wear of the covers
Cleaning Sea Filters	Filters with material deposit	Filter elements in poor condition or lack of maintenance/cleaning	Low Seawater Pressure/Engine Heating	sea water pressure sensor
Inspect and calibrate the injectors	Injector dripping	Incomplete combustion/dark exhaust gases	Incomplete combustion/dark exhaust gases	Exhaust gases observation
Inspect supercharging system, perform overspeed test	Inadequate boost pressure/residue in the circuit	Low boost pressure/Inadequate combustion.	Change to normal combustion temperatures	Hearing method, speed sensor reading
Decarbonization	Excessive carbonization in the combustion chamber and evacuation system	Poor management in engine operation/driving	Loss of engine performance	Observation of engine operating parameters
Decarbonization	Out of tune engine valves	Lack of maintenance	Inadequate operating parameters	Measurement of abnormal vibrations

				and observation of engine pressure gauges
Decarbonization	Material fatigue	Lack of maintenance due to decarbonization, poor engine driving	Fracture of moving parts of the head (e.g. valves arms)	Measurement of abnormal vibrations and observation of engine pressure gauges
General Review	Out of tune engine valves	Lack of maintenance	Engine out of time	Measurement of abnormal vibrations and observation of engine pressure gauges
General Overhaul	Poor general condition of the engine	Lack of maintenance due to general inspection	Unusual operating parameters	Measurement of abnormal vibrations and observation of engine pressure gauges
General Overhaul	Material fatigue	Poor engine driving, lack of maintenance	Grip	Measurement of abnormal vibrations and observation of engine pressure gauges

The author decided to subdivide the activities. That decision was taken because it is interpretated that a same activity may have various potential failure, the potential failure may have various causes and the effect or even the detection technique may sometimes be by various ways (the detailed FMEA may be observed on point a.1 of Annex A).

In Table 47 and Table 48 it can be observed a sample of FMEA with maintenance activities respectively for seawater filter and air filters from diesel propulsion engines, where one maintenance activity was considered for both systems.

Table 46 - FMEA Sea water filter diesel propulsion engines

Maintenance Activity	Potential Failure Mode	Failure Cause	Failure Effect	How detect/detection
Cleaning seawater suction filters	Clogging Filters	Suction in highly dirty water areas	Propulsion engine heating	Temperature sensors, low pressure in the respective circuit
Cleaning seawater suction filters	Pump suction failure	Valve closed, residue at pump inlet (e.g. mussels)	Overheating in the pump and drive motor	Temperature sensors, low pressure in the respective circuit
Cleaning seawater suction filters	Cavitation in pipes	Pipeline fracture	Pipeline fracture	Measuring vibrations, anomalous noise

Usually, the presented maintenance to sea water filters, Table 47, if isolation valves, are made in 1st stage by specialist on board. And for the presented maintenance for air filters on the intake air, Table 48.

Table 47 - FMEA Air filters diesel propulsion engines

Maintenance Activity	Potential Failure Mode	Failure Cause	Failure Effect	How detect/detection
Washing the intake air filter panels	Impurity deposit	Navigation in areas with high particles suspended in the air	Decrease in air intake	Low pressure in intake air
Washing the intake air filter panels	Low pressure in the charge air circuit	Supply air failure, supercharger problems	Mixture in non-stoichiometric combustion	Low pressure in the intake air, combustion problems
Washing the intake air filter panels	Combustion failure	Supply air failure, supercharger problems	Imbalance in the engine, non-uniform temperatures	Low pressure in the intake air, combustion problems, vibrations

In Table 49 is represented an extract of FMEA applied to maintenance activities low pressure air compressor, where for example not cleaning the air filter every 1000 hours of functioning may traduce a filter with excessive impurities (failure cause) and may allow enter of impurities for the air system or even the clogged, resulting on a pressure under the normal or low flow rate.

Table 48 - FMEA low pressure air compressor

Maintenance Activity	Potential Failure Mode	Failure Cause	Failure Effect	How detect/detection
Clean air filter - Perform every 1000 hours of operation	Filter with impurities	Lack of intake filter replacement, high number of suspended particles	Entry of impurities into the compressor	Clogged filter, low compression pressure
Clean air filter - Perform every 1000 hours of operation	Filter collapse	Inadequate filter, lack of replacement	Compressor does not compress	Method of observing pressure gauges, alarms on consoles
Clean air filter - Perform every 1000 hours of operation	Filter with impurities/air compressor system with impurities	Lack of intake filter replacement, high number of suspended particles	Compressor damage	Internal inspection of the compressor if it is impossible to detect damage by visual inspection or non-destructive testing.
Cleaning the filter between the compressor and the charging reservoir	Impurities in the bottle	Lack of filter replacement, high number of suspended particles	Compressed air bottle degradation	Method of observing the outside of the bottle
Check the charging time of the 63lt/40 bar reservoir	Slow bottle loading	Failure to replace the filter, high number of suspended particles, clogged filter, malfunction do compressor	Equipment start-up and operation failures	Low pressure, automatic compressor does not stop
Oil change	Oil outside normal parameters/contaminated	Failure to replace the filter, high number of suspended particles, clogged filter, malfunction	Air compressor degradation	Compressor takes longer to load compressed air bottles. Lubrication oil analysis.
Oil change	Oil outside normal parameters/contaminated	Failure to replace the filter, high number of suspended particles, clogged filter, malfunction	Particle entrainment in the circuit/performance losses	Lubrication oil analysis.
Oil change	Oil outside normal parameters/contaminated	Failure to replace the filter, high number of suspended particles, clogged filter, malfunction	Particle entrainment in the circuit/trapping in intermediate components (e.g. valves)	Lubrication oil analysis.

For Table 50 it is present an extract of FMEA for the marine gasoil purifier, where not verifying the oil level, it may represent a low oil level, caused by a leakage resulting on low oil pressure. This situation may be detected by observing oil gauge or check the level on local.

Table 49 - FMEA marine gasoil purifier

Maintenance Activity	Potential Failure Mode	Failure Cause	Failure Effect	How detect/detection
Check oil level.	Low oil level	Oil leak	Low oil pressure	Oil pressure gauge observation
Check oil level.	Low oil level	Oil leak	Centrifuge grip	Oil analysis, filings in the oil
Check oil level.	High oil level	Lubricating oil was added above the normal and recommended level	Centrifuge does not clarify fuel	Fuel analysis, residue detection on display, combustion problem
Check the automatic program	System does not perform periodic cleaning	Problems with the centrifuge automation	Clogging of injection pumps and/or injectors of internal combustion engines	Fluctuation in rotations of internal combustion engines, temperature of internal combustion engines out of adjustment
Clean and putty the dome locking ring	Waste deposit	Lack of cleaning maintenance and filter changes	Bad seal	Low fuel flow, fuel leak
Clean and putty the dome locking ring	Corrosion	Lack of cleaning maintenance	Fracture during operation	Excessive vibrations, fuel leak
Check flow detector adjustment; check pressure switch operation and adjustment	Incorrectly functioning system	Equipment with misadjusted/uncalibrated pressure switch	Clogging of injection pumps and/or injectors of internal combustion engines	Oil analysis, presence of residues or filings
Every six months or every 750 hours, change the oil and clean the crankcase	Lubricating oil does not meet normal properties	Lack of preventive maintenance on the respective components and fluids	Degradation of centrifuge components	Oil analysis

In Table 51 is present the FMEA applied to oil purifier.

Table 50 - FMEA oil purifier

Maintenance Activity	Potential Failure Mode	Failure Cause	Failure Effect	How detect/detection
Check oil level	Low oil level	Oil leak	Centrifuge seizing	Oil analysis, filings in the oil
Check oil level	High oil level	Lubricating oil added above the normal and recommended level	Centrifuge does not clarify fuel	Fuel analysis, residue detection on display, combustion problem
Check the automatic program	System does not perform periodic cleaning	Problems with the centrifuge automation	Inefficient centrifugation/diesel contamination	Fuel analysis, residue detection on display, combustion problem
Clean and putty the dome locking ring	Corrosion	Lack of cleaning maintenance	Fracture during operation	Excessive vibrations, fuel leak
Check flow detector adjustment; check pressure switch operation and adjustment	Incorrectly functioning system	Equipment with misadjusted/uncalibrated pressure switch	Poorly centrifuged fuel/fuel contamination	Detection of fluctuation in rotations of internal combustion engines, temperature of internal combustion engines out of adjustment

Oil change and crankcase cleaning	Lubricating oil does not meet normal properties	Lack of preventive maintenance on the respective components and fluids	Lubrication failure	Oil analysis, presence of residues or filings
Disassemble the dome, clean and inspect all components; lubricate, assemble and test	Excess waste	Lack of preventive maintenance on the respective components and fluids	Centrifuge failure/incorrectly centrifuged fuel	Fuel analysis, residue detection on display, combustion problem
Check the tightness of the fixing screws, check the condition of the supports and vibration dampers.	Loosen screws	Lack of preventive maintenance on the respective components	Vibrations and/or misalignment/possible damage	Vibration measurement, electric vs centrifugal motor alignment

6.3. FMECA application and validation

After the FMEA be designed, selected and defined the parameters categorization, the responses to the diverse severities, occurrence and detection were given to other persons, so its responses could be considered, and the basis matrix decision could be validated and it was called a humanized matrix, based on the mean of various expertise responses.

Although an integrated logistic system enhances the decision-making process, it brings other cyber security preoccupations, but we believed that with the blockchain developed data structure part of cyber safety will be guaranteed, matters to this theme can be developed in further studies.

For validation of the risk the analysis, and for approximating the result of human rationing, it was asked the collaboration of four persons with knowledge in mechanical engineer area, to complement the considerations of the author, which the author called Humanize the FMECA. Their contribute was to apply criteria to the severity, occurrence and detection.

For reasons of reliable data, on FMECA-H-CM only the humanized data form was considered on original calculus and on the Python language development. On Appendix C we can observe the results of FMECA, FMECA-H and FMECA-H-CM. But for the Python language only the Humanized results were used.

It is worth noting that for the construction of the risk matrix, the ship's maintenance cycle was considered in accordance with the maintenance cycles provided by the publication of Navy (Marinha_f, 2020), namely with regard to the probability of occurrence when it is stated that the anomaly did not occur in the last 4 years (considering a 4 year operational cycle with one year of downtime at the shipyard, as Figure 11 on 2.4.2).

6.3.1. FMECA-H-CM data integration – diesel propulsion engines

Now it will be applied FMECA-H-CM considering 6 severity levels, and accordingly Equation 20.

FMECA-H-CM were calculated for the various equipment considered the data selection of control condition as defined on 4.4. and resume results will be presented to give an example from Appendix C.

For the Thermodynamic parameters, in this case temperature it was considering the maximum admissible has being 95ºC. For oil pressure, if considered in future study it is the minimum (4 bar). After applying the modified short run control charts the results were distributed according to the defined categories.

In table 52 are present an extract of the results for FMECA-H-CM based on real data. Observing the results of FMECA and FMECA-H in Table 52 it is shown different results which are the expected changes considering the responses of various persons. The first maintenance activity is on risk level 3, so the priority maintenance is also 3, for maintenance activity nr 9 and nr 10 the risk is level 2 and the priority of maintenance decreases to 4.

Table 51 - FMECA-H-CM for diesel propulsion engine

Nr Act	Maintenance Activity	FMECA	FMECA-H	CMV	CMP	CMTex	TS	FMECA-H-CM	Risk Level	Priority
1	Navigating, check the color of the evacuation gases, condensation, obstructions.	28,0	33,4	5,0	1,0	5,0	2,0	66,6	3	3
9	Inspect supercharging system, perform overspeed test	6,0	21,7	5,0	1,0	5,0	2,0	43,2	2	4
10	Check the sequential system of the supercharging groups	12,0	13,9	5,0	1,0	5,0	2,0	27,6	2	4

An extract of the results on Python software language applied to diesel propulsion engines to risk and maintenance priority definition may be observed in Table 53, the first result corresponds to the first maintenance in Table 52, which demonstrate the functionality and applicability of the developed software language.

Table 52 – Results of software for MD risk and priorities

df1_main_engine

Nr Act	Maintenance Activity	Potential Failure Mode	Failure Cause	Failure Effect	How detect/detection	FMECA-H	CCV	CCP	FMECA_H_CC	Risk Level	Prioritization
1	Navigating, check the color of the evacuation ...	Inappropriate gas color	Inadequate fuel mixture/Valves out of tune	Contamination of lubricating oil, risk of expl...	Method of observing gases outside	33.41520	5	1	66.577452	3	3
2	Navigating, check the color of the evacuation ...	Inappropriate gas color	Miscalibrated injectors/Excessive fuel consump...	Contamination of lubricating oil, risk of expl...	Method of observing gases outside	30.70144	5	1	61.170475	3	3
3	Navigating, check the color of the evacuation ...	Inappropriate gas color	Fuel drag	Contamination of lubricating oil, risk of expl...	Method of observing gases outside	28.80640	5	1	57.394740	3	3
4	Navigating, check the color of the evacuation ...	Inappropriate gas color	Lack of rim seal/lubrication oil carryover	Contamination of lubricating oil, risk of expl...	Method of observing gases outside	33.16544	5	1	66.079823	3	3

In Table 54 are represented the results of FMECA-H-CM for air filters and in Table 55 it can be observed the seawater filters.

Table 53 - FMECA-H-CM air filters

Nr Act	Maintenance Activity	FMECA-H	CMP	CMTex	TS	FMECA-H-CM	Risk Level	Priority
1	Washing the intake air filter panels	8,2	1,0	1,0	2,0	16,4	1	5
2	Washing the intake air filter panels	11,0	1,0	1,0	2,0	15,7	1	5
3	Washing the intake air filter panels	11,9	1,0	1,0	2,0	16,0	1	5

Table 54 - FMECA-H-CM sea water filters

Nr Act	Maintenance Activity	FMECA-H	CMP	CMTex	TS	FMECA-H-CM	Risk Level	Priority
1	Cleaning seawater suction filters	23,7	1,0	1,0	2,0	5,7	1	5
2	Cleaning seawater suction filters	22,6	1,0	1,0	2,0	7,6	1	5
3	Cleaning seawater suction filters	23,1	1,0	1,0	2,0	8,3	1	5

The sea water filters, and air filters will not be integrated the breve development of software language that define the priority and suggest maintenance, only because the result will not be significative, the results of risk to all maintenance activity are on 1 category, the lowest level, and the priorities. These are systems where, on frequently basis, maintenance is made on 1st stage of maintenance, so usually it should be, and are, in very high performance state.

Like presented on Subchapter 5.3.1 and 5.3.2 it was respectively used the obtained categories for simulation 1 and simulation 2 considering vibration and temperature, for FMECA-H-CM calculation and observation of the changes on the results. Considering FMECA-H-CM for simulation 1 the threat was considered on category 4 and on simulation 2 category 5. And it was decided to maintain the others FMECA-H-CM parameters, the unknown CMT wasn´t used, and the text counting stayed equal, category 5.

In Table 56 and Table 57 can be observed how the changes on FMECA-H-CM occurred. Because it was considered the mean of condition monitoring parameters of the engine, if simultaneously part of the parameters acquired higher values and others decrease, there aren´t significative different results on the FMECA-H-CM, the risk maintained, but if the threat category increases the risk is higher. In other words, to face major threat challenges and to reduce risks, maintenance should be carried out, considering the perspective of the introduction of the threat, in which a high level of threat increases the risk to material and personnel.

On simulation 1 the risk level maintains and so the priority of intervention, Table 56. In Table 57 with results of simulation 2, the risk on maintenance activity nr 9 increase and also, he priority to maintenance. For activity nr 10 the results of risk and priority maintain.

Table 55 - FMECA-H-CM for MD – simulation 1

Nr Act	Maintenance Activity	FMECA-H	CMV	CMP	CMTex	TS	FMECA-H-CM	Risk Level	Priority
1	Navigating, check the color of the evacuation gases, condensation, obstructions, etc.	33,4	2,0	3,0	5,0	4,0	86,6	3	3
9	Inspect supercharging system, perform overspeed test	21,7	2,0	3,0	5,0	4,0	41,2	2	4
10	Check the sequential system of the supercharging groups	12,9	2,0	3,0	5,0	4,0	26,3	2	4

Table 56 - FMECA-H-CM for MD – simulation 2

Nr Act	Maintenance Activity	FMECA-H	CMV	CMP	CMTex	TS	FMECA-H-CM	Risk Level	Priority
1	Navigating, check the color of the evacuation gases, condensation, obstructions, etc.	33,4	3,0	1,0	5,0	5,0	102,8	3	3
9	Inspect supercharging system, perform overspeed test	13,9	3,0	1,0	5,0	5,0	66,8	3	3
10	Check the sequential system of the supercharging groups	26,0	3,0	1,0	5,0	5,0	42,7	2	4

It was only made simulation for the enunciated parameters on the previous paragraph, and only for the diesel propulsion engines, because it is believed that with the calculation based on real data for this equipment, the variation of those two parameters it's a confirmation that the developed methodology can be applied to these systems and others. The application of FMECA-H-CM with the existed data for the others equipment´s are now will be presented on the next Subchapter, 6.3.2.

6.3.2. FMECA-H-CM on other selected equipment's

For the others selected equipment´s it was applied Equation 3, where only one condition monitoring parameter, text occurrence (CMTex), are used. In Table 58, Table 59 and Table 60, it can be observed the obtained FMECA-H-CM results.

Table 57 - FMECA-H-CM for low pressure air compressor

Act Nr	Maintenance Activity	FMECA	FMECA-H	CMTex	TS	FMECA-H-CM
1	Clean air filter - Perform every 1000 hours of operation	120,0	35,9	3	2	64,2
6	Cleaning the filters of 40/6 bar reducing stations	100,0	11,2	3	2	20,0
12	Check the charging time of the 63lt/40 bar reservoir	125,0	40,3	3	2	72,3
14	Oil change	125,0	30,9	3	2	55,3

Table 58 - FMECA-H-CM for marine gasoil purifier

Act Nr	Maintenance Activity	FMECA	FMECA-H	CMTex	TS	FMECA-H-CM
1	Check oil level.	120,0	37,2	2	2	51,5
6	Clean and putty the dome locking ring	30,6	12,0	2	2	16,7
10	Every six months or every 750 hours, change the oil and clean the crankcase	125,0	34,4	2	2	47,6

Table 59 - FMECA-H-CM oil purifier

Act Nr	Maintenance Activity	FMECA	FMECA-H	CMTex	TS	FMECA-H-CM
1	Check oil level	34,0	20,3	1	2	14,1
6	Clean and putty the dome locking ring	6,6	9,8	1	2	6,8
10	Oil change and crankcase cleaning	48,0	22,6	1	2	15,6

In Table 61 are present the software results for low pressure air compressor risk and priorities.

Table 60 - Software results for low pressure air compressor risk and priorities

```
Low Pressure Air Maintenance Acitivities
First Priority maintenance:
Series([], Name: Maintenance Activity, dtype: object)
Second Priority maintenance:
Series([], Name: Maintenance Activity, dtype: object)
Third Priority maintenance:
Nr Act
1    Clean air filter - Perform every 1000 hours of...
3    Clean air filter - Perform every 1000 hours of...
4    Clean air filter - Perform every 1000 hours of...
```

```
5     Clean air filter - Perform every 1000 hours of...
7     Cleaning the filters of 40/6 bar reducing stat...
11    Cleaning the filter between the compressor and...
12    Check the charging time of the 63lt/40 bar res...
13                                    Oil change
14                                    Oil change
Name: Maintenance Activity, dtype: object
```

In Table 62 are present the software results for marine gasoil purifier risk and priorities.

Table 61 - Software results for marine gasoil purifier risk and priorities

```
Diesel Purifier Maintenance Activities
First Priority maintenance:
Series([], Name: Maintenance Activity, dtype: object)
Second Priority maintenance:
Series([], Name: Maintenance Activity, dtype: object)
Third Priority maintenance:
Nr Act
1          Check oil level.
14    Clean dirty oil filter
Name: Maintenance Activity, dtype: object
```

For the oil purifier there is no results of occurrences on SRTD. Because of it and considering the defined criteria the oil purifier was under control. That corroborates to the fact that the author believed the inexistence of DSM58 data from means that usually it doesn´t operate.

6.4. Integrating data and action options according to the equipment risk

On Appendix C may be seen all the risk level results of FMECA-H-CM application for each maintenance activity for each equipment, and the respective priority.

In Table 63 it can be observed an extract of the language adopted according the obtained to FMECA-H-CM results for the diesel propulsion engine and respective suggestion of maintenance of it, pursued by the maintenance suggestion of other equipment´s considering the decision based on: if the risk of those equipment´s are also higher of 2, it should proceed to the option equal to the diesel propulsion engine, if it is also above category 2. The suggested options of actions are accordingly the presented in Table 18.

Table 62 - Extract language to define the option of action on equipment´s

```
results=[]
for activity in priority_3_activities_df['Maintenance Activity']:
print(activity)
  possible_measures=input("Are measures possible (Nr17)? ")
  if possible_measures=='yes':
  planned_maintenance=input("Time/shipyard for Planned Maintenance (Nr18)? ")
.
.
.
    if equipment_funcioning == 'yes':
      print('Option 4: Continuous monitoring, Not evasive maintenance. Prepare emergency (Nr 23)')
      results.append("Continuous monitoring")
    else:
      print('Option 5: Prepare to Maintenance or Hibernate (Nr24)')
      results.append("Prepare to hibernate")
```

When running the developed language, the results are a question of threat level is made to the user; then threat is introduced by the user, like in the application of FMECA-H-CM it was decided to use category 2, Table 64.

Table 63 - Extract language to define the threat level

The question on threat is asked as follow:

```
fT=input('What is the Treat level? ')
print(f'The define Treat level is {T}')
```

```
What is the Treat level? 2
```

And result in the next:

```
What is the Threat level? 2
The define Threat level is 2
```

Given the results of risk, the priority of maintenance activity is defined considering risk higher then 2, Table 65. There were not activities on level 1 or level 2, the next activities were on level 3: Act nr 1 to nr 5, Act nr 14 to nr 15, Act nr 41 and Act nr 75.

Table 64 - Extract of priorities results for the activities of diesel engine

```
Main Engine maintenance activities
First Priority maintenance:
Series([], Name: Maintenance Activity, dtype: object)
Second Priority maintenance:
Series([], Name: Maintenance Activity, dtype: object)
Third Priority maintenance:
Nr Act
1    Navigating, check the color of the evacuation ...
2    Navigating, check the color of the evacuation ...
3    Navigating, check the color of the evacuation ...
4    Navigating, check the color of the evacuation ...
5    Inspect supercharging system, perform overspee...
```

```
14              Oil sample collection and analysis
15              Oil sample collection and analysis
41   Check operation of the expansion tank level valve
75                          General Overhaul
Name: Maintenance Activity, dtype: object
addCódigo
addTexto
```

Follow the Steps on the methodology considering risk higher than 2 result the options according to the responses on the various Steps, Table 66. For the activity of when navigating, check the colour of the evacuation gases, condensation, obstructions the resulting Option are nr 2 where planned maintenance should be made.

Table 65 - Extract of options results of diesel engine propulsion

The question of Step nr 17:

```
Navigating, check the color of the evacuation gases, condensation, obstructions, etc.
Are measures possible (Nr17)?
```

The result of Step 17 and question on Step 18:

```
Navigating, check the color of the evacuation gases, condensation, obstructions, etc.
Are measures possible (Nr17)? yes
Time/shipyard for Planned Maintenance (Nr18)?
```

The result of Step 18 and the option it gives:

```
Navigating, check the color of the evacuation gases, condensation, obstructions, etc.
Are measures possible (Nr17)? yes
Time/shipyard for Planned Maintenance (Nr18)? yes
Option 2: Planned Maintenance Measures (Nr21):
Navigating, check the color of the evacuation gases, condensation, obstructions, etc.
```

The language was defined to for each activities the users should decide and evaluate the Step 16, Step 17, Step 18 and Step 19. In future study with responses of various experts' managers, it may be generate a machine learning algorithm to automatically made the decision based on the other data on the conceptualization project presented on Figure 29 and pillars on Figure 30.

Considering the Option 2, if the other equipment´s are above risk level 2 that should be also the decision to proceed to maintenance on those equipment´s.

Finally, in Table 67, is presented an extract from general developed Python language with the use of Google Colab platform.

Table 66 - Developed software language

Calculate the number of corrective maintenances

```
df = pd.read_csv('counting_DS.csv', sep=',') # Try comma first (default)
except ParserError:
 try:
df = pd.read_csv('counting_DS.csv', sep=';') # Try semicolon
```

```
  except ParserError:

df['FuN_split_3']=df['FuN'].str[:3]
df['FuN_split_7']=df['FuN'].str[:7]

df['Mtdesc']=df['Mtdesc'].str.lower()

mask_motor_propulsor=df['FuN_split_3']== '233'
df_motor_propulsor=df.loc[mask_motor_propulsor,:]
df_motor_propulsor['Mtdesc']=df_motor_propulsor['Mtdesc'].fillna('')

 df_motor_propulsor['Mtdesc']=df_motor_propulsor['Mtdesc'].fillna('')
mask_marine_gasoil=df['FuN_split_7']=='2613120'
df_marine_gasoil=df.loc[mask_marine_gasoil,:]
df_marine_gasoil['Mtdesc']=df_marine_gasoil['Mtdesc'].fillna('')

mask_low_pressure_air=df['FuN_split_7']=='5515321'
df_low_pressure_air=df.loc[mask_low_pressure_air,:]
df_low_pressure_air['Mtdesc']=df_low_pressure_air['Mtdesc'].fillna('')

df_low_pressure_air['Mtdesc']=df_low_pressure_air['Mtdesc'].fillna('')
mask_oil_purifier= df['FuN_split_7']=='2643111'
df_oil_purifier=df.loc[mask_oil_purifier,:]
df_oil_purifier['Mtdesc']=df_oil_purifier['Mtdesc'].fillna('')
count_corrective_motor_propulsor=
df_motor_propulsor['Mtdesc'].str.contains('correctiva|corretiva').sum()
count_corrective_marine_gasoil=df_marine_gasoil['Mtdesc'].str.contains('corretiva|correctiva').sum()
count_corrective_pressure_air=df_low_pressure_air['Mtdesc'].str.contains('corretiva|correctiva').sum()
count_corrective_oil_purifier=df_oil_purifier['Mtdesc'].str.contains('corretiva|correctiva').sum()
print(f'number of corrective appointments at propulsion diesel engines
{count_corrective_motor_propulsor}')
print(f'number of corrective appointments at marine_gasoil {count_corrective_marine_gasoil}')
print(f'number of corrective appointments at Low Pressure air compressor
{count_corrective_pressure_air}')
print(f'number of corrective appointments at Oil purifier {count_corrective_oil_purifier}')
number of corrective appointments at propulsion diesel engines 42
number of corrective appointments at marine_gasoil 1
number of corrective appointments at Low Pressure air compressor 2
number of corrective appointments at Oil purifier 0
```

Conversion into CMTex

```
def transform_into_CMtex(x):
  if x==0:
    y=1
  elif x==1:
    y=2
  elif 2<=x<=5:
    y=3
  elif 5<x<=10:
    y=4
  elif x>10:
    y=5
  return y
CMtex_mp=transform_into_CMtex(count_corrective_motor_propulsor)
CMtex_mg=transform_into_CMtex(count_corrective_marine_gasoil)
CMtex_cpa=transform_into_CMtex(count_corrective_pressure_air)
CMtex_op=transform_into_CMtex(count_corrective_oil_purifier)
print(f'CMTex of the motor_propulsor is {CMtex_mp}')
print(f'CMTex of the marine_gasoil is {CMtex_mg}')
print(f'CMTex of the Low Pressure Air compressor is {CMtex_cpa}')
print(f'CMTex of the Oil Purifier is is {CMtex_op}')

CMTex of the motor_propulsor is 5
CMTex of the marine_gasoil is 2
CMTex of the Low Pressure Air compressor is 3
```

CMTex of the Oil Purifier is is 1

Threat level

```
fT=input('What is the Threat level? ')
print(f'The define Threat level is {fT}')
What is the Threat level? 2
The define Threat level is 2
T= float(fT)
```

Formulas for the calculation of FMECA-H-CM, followed by the transformation into risk and prioritization

```
[ ] def FMECA_H_CM (FMECA_H,CMtex,T):
return FMECA_H*np.log(CMtex*T)
def transform_into_risk(x):
if 0<=x<=20:
w=1
elif 20<x<=50:
w=2
elif 50<=x<=160:
w=3
elif 160<x<=250:
w=4
else:
w=5
return w
def transform_into_prioritization (x):
if 0<=x<=20:
z=5
elif 20<x<=50:
z=4
elif 50<=x<=160:
z=3
elif 160<x<=250:
z=2
else:
z=1
return z
```

Oil purifier

```
df1_oil_purifier=df1_oil_purifier.set_index('Nr Act')
df1_oil_purifier['FMECA_H_CM']=df1_oil_purifier['FMECA-H'].apply(lambda x: FMECA_H_CM(x,
CMtex_op, T))
df1_oil_purifier['Risk Level']=df1_oil_purifier['FMECA_H_CM'].apply(transform_into_risk)
df1_oil_purifier['Prioritization']=df1_oil_purifier['FMECA_H_CM'].apply(transform_into_prioritization)
```

Low Pressure Air compressor

```
df1_low_pressure_air=df1_low_pressure_air.set_index('Nr Act')
df1_low_pressure_air['FMECA_H_CM']=df1_low_pressure_air['FMECA-H'].apply(lambda x:
FMECA_H_CM(x, CMtex_cpa, T))
df1_low_pressure_air['Risk Level']=df1_low_pressure_air['FMECA_H_CM'].apply(transform_into_risk)
df1_low_pressure_air['Prioritization']=df1_low_pressure_air['FMECA_H_CM'].apply(transform_into_pri
oritization)
```

Marine Gasoil purifier

```
df1_diesel_purifier=df1_diesel_purifier.drop(['FMECA_H_CM', 'Threat Status'], axis=1)
df1_diesel_purifier=df1_diesel_purifier.set_index('Nr Act')
df1_diesel_purifier['FMECA_H_CM']=df1_diesel_purifier['FMECA-H'].apply(lambda x:
FMECA_H_CM(x, CMtex_mg, T))
df1_diesel_purifier['Risk Level']=df1_diesel_purifier['FMECA_H_CM'].apply(transform_into_risk)
df1_diesel_purifier['Prioritization']=df1_diesel_purifier['FMECA_H_CM'].apply(transform_into_prioritiz
ation)
```

Diesel propulsion engine

```
df1_main_engine= pd.read_csv('Main_Engine.csv', sep=';') # Try semicolon
df1_main_engine=df1_main_engine.drop(['FMECA_H_CM','CMTex'],axis=1)
df1_main_engine=df1_main_engine.set_index('Nr Act')
df1_main_engine['FMECA_H_CM'] = df1_main_engine['FMECA-H'] * np.log(((CMtex_mp +
df1_main_engine['CMV']  + df1_main_engine['CMP'])/3) * T)
df1_main_engine['Risk Level']=df1_main_engine['FMECA_H_CM'].apply(transform_into_risk)
df1_main_engine['Prioritization']=df1_main_engine['FMECA_H_CM'].apply(transform_into_prioritizatio
n)
```

Returns a table with the risk and priorities defined

Maintenance Activities suggestion

```
ask_priority_1= df1_main_engine['Prioritization']==1
priority_1_activities_df=df1_main_engine[mask_priority_1]
mask_priority_2= df1_main_engine['Prioritization']==2
priority_2_activities_df=df1_main_engine[mask_priority_2]
mask_priority_3= df1_main_engine['Prioritization']==3
priority_3_activities_df=df1_main_engine[mask_priority_3]
print('Main Engine maintenance activities')
print('First Priority maintenance:')
print(priority_1_activities_df['Maintenance Activity'])
print('Second Priority maintenance:')
print(priority_2_activities_df['Maintenance Activity'])
print('Third Priority maintenance:')
print(priority_3_activities_df['Maintenance Activity'])
```

Main Engine maintenance activities

```
First Priority maintenance:
Series([], Name: Maintenance Activity, dtype: object)
Second Priority maintenance:
Series([], Name: Maintenance Activity, dtype: object)
```

Third Priority maintenance:

```
Nr Act
1    Navigating, check the color of the evacuation ...
2    Navigating, check the color of the evacuation ...
3    Navigating, check the color of the evacuation ...
4    Navigating, check the color of the evacuation ...
5    Inspect supercharging system, perform overspee...
14              Oil sample collection and analysis
15              Oil sample collection and analysis
41   Check operation of the expansion tank level valve
75                            General Overhaul
Name: Maintenance Activity, dtype: object
```

```
results=[]
for activity in priority_1_activities_df['Maintenance Activity']:
  print(activity)
  possible_measures=input("Are measures possible (Nr17)? ")
  if possible_measures=='yes':
    planned_maintenance=input("Time/shipyard for Planned Maintenance (Nr18)? ")
    if planned_maintenance=='yes':
      print('Option 2: Planned Maintenance Measures (Nr21):')
      results.append("Planned Maintenance")
    else:
      print('Option 3: Contigency/Maintenance Measures (Nr22):')
      results.append("Contigency Maintenance")
  else:
    equipment_funcioning=input("Is the equipment functioning")
    if equipment_funcioning == 'yes':
      print('Option 4: Continuous monitoring, Not evasive maintenance. Prepare emergency (Nr 23)')
      results.append("Continuous monitoring")
    else:
      print('Option 5: Prepare to Maintenance or Hibernate (Nr24)')
      results.append("Prepare to hibernate")
```

```
results=[]
for activity in priority_2_activities_df['Maintenance Activity']:
  print(activity)
```

```
  possible_measures=input("Are measures possible (Nr17)? ")
  if possible_measures=='yes':

    planned_maintenance=input("Time/shipyard for Planned Maintenance (Nr18)? ")

    if planned_maintenance=='yes':
      print('Option 2: Planned Maintenance Measures (Nr21):')
      results.append("Planned Maintenance")
    else:
      print('Option 3: Contigency/Maintenance Measures (Nr22):')
      results.append("Contigency Maintenance")
  else:

    equipment_funcioning=input("Is the equipment functioning")

    if equipment_funcioning == 'yes':
      print('Option 4: Continuous monitoring, Not evasive maintenance. Prepare emergency (Nr 23)')
      results.append("Continuous monitoring")
    else:
      print('Option 5: Prepare to Maintenance or Hibernate (Nr24)')
      results.append("Prepare to hibernate")
```

```
results=[]
for activity in priority_3_activities_df['Maintenance Activity']:
  print(activity)
  possible_measures=input("Are measures possible (Nr17)? ")
  if possible_measures=='yes':

    planned_maintenance=input("Time/shipyard for Planned Maintenance (Nr18)? ")

    if planned_maintenance=='yes':
      print('Option 2: Planned Maintenance Measures (Nr21):')
      results.append("Planned Maintenance")
    else:
      print('Option 3: Contigency/Maintenance Measures (Nr22):')
      results.append("Contigency Maintenance")
  else:
    equipment_funcioning=input("Is the equipment functioning? ")

    if equipment_funcioning == 'yes':
      print('Option 4: Continuous monitoring, Not evasive maintenance. Prepare emergency (Nr 23)')
      results.append("Continuous monitoring")
    else:
      print('Option 5: Prepare to Maintenance or Hibernate (Nr24)')
      results.append("Prepare to hibernate")
```

```
Navigating, check the color of the evacuation gases, condensation, obstructions, etc.
Are measures possible (Nr17)? yes
Time/shipyard for Planned Maintenance (Nr18)? no
Option 3: Contigency/Maintenance Measures (Nr22):
Navigating, check the color of the evacuation gases, condensation, obstructions, etc.
Are measures possible (Nr17)? yes
Time/shipyard for Planned Maintenance (Nr18)? yes
Option 2: Planned Maintenance Measures (Nr21):
Navigating, check the color of the evacuation gases, condensation, obstructions, etc.
Are measures possible (Nr17)? tes
Is the equipment functioning? yes
Option 4: Continuous monitoring, Not evasive maintenance. Prepare emergency (Nr 23)
Navigating, check the color of the evacuation gases, condensation, obstructions, etc.
Are measures possible (Nr17)? yes
Time/shipyard for Planned Maintenance (Nr18)? yes
Option 2: Planned Maintenance Measures (Nr21):
Inspect supercharging system, perform overspeed test
Are measures possible (Nr17)? yes
Time/shipyard for Planned Maintenance (Nr18)? yes
Option 2: Planned Maintenance Measures (Nr21):
```

Oil sample collection and analysis
Are measures possible (Nr17)? f
Is the equipment functioning? f
Option 5: Prepare to Maintenance or Hibernate (Nr24)
Oil sample collection and analysis
Are measures possible (Nr17)?
Is the equipment functioning? f
Option 5: Prepare to Maintenance or Hibernate (Nr24)
Check operation of the expansion tank level valve
Are measures possible (Nr17)? f
Is the equipment functioning? f
Option 5: Prepare to Maintenance or Hibernate (Nr24)
General Overhaul
Are measures possible (Nr17)? f
Is the equipment functioning? f
Option 5: Prepare to Maintenance or Hibernate (Nr24)

Recommendation for the other equipment's

```
mask_priority_1= df1_diesel_purifier['Prioritization']==1
priority_1_activities_df_dp=df1_diesel_purifier[mask_priority_1]
mask_priority_2= df1_diesel_purifier['Prioritization']==2
priority_2_activities_df_dp=df1_diesel_purifier[mask_priority_2]
mask_priority_3= df1_diesel_purifier['Prioritization']==3
priority_3_activities_df_dp=df1_diesel_purifier[mask_priority_3]
print('Diesel Purifier Maintenance Activities')
print('First Priority maintenance:')
print(priority_1_activities_df_dp['Maintenance Activity'])
print('Second Priority maintenance:')
print(priority_2_activities_df_dp['Maintenance Activity'])
print('Third Priority maintenance:')
print(priority_3_activities_df_dp['Maintenance Activity'])
```

Diesel Purifier Maintenance Activities
First Priority maintenance:
Series([], Name: Maintenance Activity, dtype: object)
Second Priority maintenance:
Series([], Name: Maintenance Activity, dtype: object)

Third Priority maintenance:
Nr Act
1 Check oil level.
14 Clean dirty oil filter
Name: Maintenance Activity, dtype: object

```
mask_priority_1= df1_low_pressure_air['Prioritization']==1
priority_1_activities_df_lpa=df1_low_pressure_air[mask_priority_1]
mask_priority_2= df1_low_pressure_air['Prioritization']==2
priority_2_activities_df_lpa=df1_low_pressure_air[mask_priority_2]
mask_priority_3= df1_low_pressure_air['Prioritization']==3
priority_3_activities_df_lpa=df1_low_pressure_air[mask_priority_3]
print('Low Pressure Air Maintenance Acitivities')
print('First Priority maintenance:')
print(priority_1_activities_df_lpa['Maintenance Activity'])
print('Second Priority maintenance:')
print(priority_2_activities_df_lpa['Maintenance Activity'])
print('Third Priority maintenance:')
print(priority_3_activities_df_lpa['Maintenance Activity'])
```

Low Pressure Air Maintenance Activities
First Priority maintenance:
Series([], Name: Maintenance Activity, dtype: object)
Second Priority maintenance:
Series([], Name: Maintenance Activity, dtype: object)
Third Priority maintenance:
Nr Act
1 Clean air filter - Perform every 1000 hours of...
3 Clean air filter - Perform every 1000 hours of...
4 Clean air filter - Perform every 1000 hours of...
5 Clean air filter - Perform every 1000 hours of...

```
7     Cleaning the filters of 40/6 bar reducing stat...
11    Cleaning the filter between the compressor and...
12    Check the charging time of the 63lt/40 bar res...
13                               Oil change
14                               Oil change

Name: Maintenance Activity, dtype: object
mask_priority_1= df1_oil_purifier['Prioritization']==1
priority_1_activities_df_op=df1_oil_purifier[mask_priority_1]
mask_priority_2= df1_oil_purifier['Prioritization']==2
priority_2_activities_df_op=df1_oil_purifier[mask_priority_2]
mask_priority_3= df1_oil_purifier['Prioritization']==3
priority_3_activities_df_op=df1_oil_purifier[mask_priority_3]

print('Oil Purifier Maintenance Acitivities')
print('First Priority maintenance:')
print(priority_1_activities_df_op['Maintenance Activity'])
print('Second Priority maintenance:')
print(priority_2_activities_df_op['Maintenance Activity'])
print('Third Priority maintenance:')
print(priority_3_activities_df_op['Maintenance Activity'])
```

Oil Purifier Maintenance Acitivities
First Priority maintenance:
Series([], Name: Maintenance Activity, dtype: object)
Second Priority maintenance:
Series([], Name: Maintenance Activity, dtype: object)
Third Priority maintenance:
Series([], Name: Maintenance Activity, dtype: object)

6.5. FMECA and FMECA-H-CM results analysis

On the present research only the parameters of condition monitoring with existing registered data were considered, for that the FMECA-H-CM are adjusted so the results may be more reliable.

Applying the control charts to data, the not significative results should be automatically excluded, in the present case only the significative results for the Turbo B2-A-A were considered.

The results of applying control chart on vibration reaffirms that diesel propulsion engine has a problem on supercharger B2, reeded on the point Turbo B2-A-A.

The consider FMECA integrated not only one severity but five: security severity, environment severity, equipment severity, severity on people, operational severity. To integrate these variables the mean of it resulted on S_m.

Observing the results between the FMECA and FMECA-H it was different because of the integration of responses from various persons.

FMECA-H-CM should be agile to allow be adapted to integrate various types of parameters, according to the existence of that data or not. An example of that is the opted parameters to integrate on diesel propulsion engine study and the ones chosen to be used on the others equipment´s.

If the category of vibration or other on condition monitoring is high, even if FMECA-H-CM is not in a risk level higher than 2, the vibrations frequency should be checked, because although the others condition monitoring parameters eventually with low values, we may be in the presence of a possible anomaly that in time will be traduced in higher temperatures, consequently more occurrences of text occurrences on DM58 documents.

Considering the considered threat category the defined measures on 4.2.4.2 the reinforcement of surveillance systems in the 5 types of affect/failure modes should be made.

First the risk matrix system and its variables must be understood, and the results should be evaluated by the maintenance managers and deciders. On database results there are two adjacent columns of FMECA-H-CM result which give the maintenance manager the maintenance activity risk and respective priority.

On the FMECA-H-CM, for this ship class, for platform safety and for the propulsion system both diesel engine propulsion should be operational. But on real conditions it is possible to navigate with crossed propulsion, a gas turbine on a shaft and diesel engine propulsion on the other. A gas turbine is important for some manoeuvres but also for propulsion redundancy, but for the present research only diesel propulsion was considered and the FMECA-H-CM were applied considered only the diesel propulsion engines, and the auxiliary equipment´s: low pressure air compressor, marine gasoil purifier, oil lubricant purifier and a sample of other appliance as air filters and seawater filters.

Given the database concerns, blockchain database concept with various certification levels may be considered a safe system to keep the maintenance system integrity.

The developed language software had the objective to show that it is possible to auxiliar maintenance managers with a decision support system, and for that it was made the counting of number of occurrences of a certain text. In present case it was demonstrating the counting of “corrective” maintenance on the DSM58 document from SRTD for the equipment’s under study. Then it was calculated the FMECA-H-CM for each equipment´s resulting the risk and the priorities according to Table 18 and then flow the STEP 15 of the developed methodology on Chapter 4 it was given the options of maintenance or not for the equipment’s. The threat option choices depend on an operator decision, by introducing the environment threat category on the software. On the present study the category of nr 2 was considered when only exist bluff information or marketing. The developed software was made on Python language because it is a free tool and nowadays it has various directories that can be used and applied on a methodology in maintenance management.

The resulting FMECA-H-CM had demonstrated that it can be applied on equipment´s from warships.

6.6. Chapter elations

On this chapter the FMEA applied to the selected equipment´s on Subchapter 5.2 was built and demonstrated, then FMECA-H-CM integrated FMEA data, data from equipment´s condition monitoring and the category of threat environment. It resulted on the final calculation of level of criticality. According to the results of criticality the risk level was ranked, and then the priorities were stablished. Given the resulting priorities and fulfilling the methodology, developed on Subchapter 4.4, the option of action for the diesel propulsion engine result, and the opportunity of maintenance of other auxiliar equipment´s are given.

Through this methodology is possible not to proceed maintenance but still have the knowledge of equipment state and take measures of contingency or reinforcement of condition monitoring. But if it is possible, it can be also suggested other maintenance measures.

7. Conclusions

7.1 Theme framework and summary

The present thesis proposed a dynamic methodology for warship equipment maintenance.

The decision for this study is related to the researcher interest, and to the actual reality of scarcity and instability of specialist personnel, limited resources, the bureaucratic system of contractility, partner shipyard with difficulties on specialists retain and financial resources. But, in the perspective of the author, mostly to the urgent need of enhancing maintenance performance, to reduce cost on warship lifecycle and decide warship missions based on data and on risk.

Initially it was made a state of the art considering maintenance management, and examples of electromechanical condition monitoring measures and methods of data treatment. Because exist data from various types, vibration, temperature, text, it was decided to use a method that could integrate various data format, the elected were the FMECA. But to integrated condition monitoring data and threat environment it was called the FMECA-H-CM. The FMECA-H-CM integrate on the basis FMECA other responses from persons to prove that it could enhance the performance and the reality of the author responses.

On the present research, four equipment's were chosen to demonstrate the application of the developed methodology: the diesel propulsion engines which are the main equipment understudy on this investigation, and three other related equipment's, the oil purifier, the marine gasoil purifier, and the low-pressure air compressor from the propulsion diesel propulsion engines room.

The integration of condition monitoring data changed the performance of original FMECA and if performed continuously may give online an equipment risk state for each maintenance activity, and its priority on maintenance. Allied to the results of FMECA-H-CM the developed methodology when follow gives options of action.

To demonstrate the functionality of the methodology it was developed a software language tant could evaluate the risk on the equipment, its priority of maintenance and the options of it, and the opportunities of maintenance of others.

7.2 Results obtained and accomplishments

It was verified the importance of alert the users from maintenance software to fill correctly the information systems, like SICALN used in the surface ships.

FMECA may be an essential system to be implemented in Portuguese Navy, if integrated on warships it may work as a support decision system for maintenance management. A FMEA and FMECA-H-CM should be implemented on warship on the project phase.

It is believed that the proposed methodology may be a basis for maintenance improvement in Portuguese Navy.

Automated alerts for maintenance action, according to the FMECA-H-CM results.

The fusion of blockchain technology with the FMECA-H-CM methodology may represent a transformative approach to equipment maintenance. Blockchain may improve the reliability of maintenance operations. As Navy seeks to modernize their maintenance strategies, embracing blockchain offers a pathway to more resilient and efficient systems.

It was observed that some data on the DSM58 document from SRTD were not correctly fulfilled.

Given the results and the formulated central question: "Can a dynamic maintenance system manage intervention priorities in Portuguese Navy ships?", the response is yes, considering a dynamic maintenance system concept using various applicable and adapted methods and methodologies that can process the data from systems and equipment's. In the present research it was used various kind of data, methods and methodologies and the biggest challenge was the perception and then choose the one that will allow various kind of data and "basilar" methodology being integrated, "talking" the same language and in the end give a reliable result for supporting a decision of the deciders of maintenance on ships, for this it was chosen FMECA methodology. Still considering the FMECA, other preoccupations were cautioned: how to build the database and how data will be processed, for that were considered some cybersecurity principles, and was suggested to build a database inspired in blockchain concept.

For the derived question nr 1 (QD1): "Can a dynamic maintenance system be an asset in the operational management of military ships?", the response is also yes, although in the beginning, when the system is implemented the decision should be based in the result, but the maintenance responsible should be critic, and the indicators should be checked, and may be some alternative measures of diagnostic should be taken, or using the developed system use data from other sensors, like other thermodynamic sensors.

For the derived question nr 2 (QD2): "How to develop the system for prioritizing interventions in a maintenance system?" to integrate data of different sources it should chose a method that can integrate the various data origin and should be calculated the risk of not performing a maintenance activity so the intervention priority should be defined.

The derived question nr 3 (QD3): “What are the variables to consider in the decision support system algorithm for ship maintenance?” The information collected by the actual system, SRTD, from the surface ships may represent valuable information to be integrated on a system that may be a support decision system for the maintenance managers, but also a system that allow the knowledge of the risk degree on the material perspective when a warship is sent on a mission. Other data to be integrated are data collected from non destructive test, like vibration of thermodynamic parameters or others may improve the results on a calculus of risk matrix. And considered the environment threat, so it can be use not only with military threat but also threat no security of computer system that nowadays affects the functionality of various services like communications and energy. This data may represent a system that online can give the users the risk on equipment´s and suggest solutions for reduce it.

The original data used on the research was real data from Navy ships.

The obtained results demonstrate that a dynamic maintenance methodology when implemented and applied to warships may work as a decision support system that support the knowledge of equipment state and the priority of actions to take given the resulting risk.

The modified FMECA-H-CM demonstrated that integration of condition monitoring data from electromechanical equipment´s and systems and military or environment of threat is possible and can support a maintenance management decision versus operational decisions of commitment ships on certain missions, contributing for a well-known system.

The developed methodology can be considered a generalization of the concept of CBM to dynamic maintenance in an environment of corrective and contingency maintenance and demonstrated a military application on fast changing priorities and scarce data for critical situations.

7.3 Research limitations

Along the years of research during the PhD on military sciences and facing the approved project of the thesis, the author became aware not only of the complexity of the proposed work, but also the quantity of work and scientific knowledge that she had to include in the thesis. Because the thesis has its size limit and time limitation, various data treatment was simplified, but still the aim of accomplish of building system where the maintenance is dynamic, and where its database is feeding with various parameters like some data of equipment sensors or other measures or data in SRTD.

The fundamental research limitation was the quantity of various data to integrate and the methodology that could align the information in a reliable and credible way. Also, the available time to pursue the objective of built a dynamic methodology that integrated various data, giving a risk state related to equipment’s, it´s the priorities of maintenance and the opportunity of maintenance of related equipment´s.

7.4 Recommendations and future studies

7.4.1 Recommendations

The education of personnel related to maintenance activities, software and documents should be continuous, so documents and eventual software for maintenance support decisions be correctly fulfilled.

It is proposed that the SICALN database is reconfigured and full integrated, to make data available in a dynamic way and with transparency for all interested navy organisms, for example show multilayers pages of equipment’s state graphs, anomaly tendency, available spare parts, available ships, and its performance to all interested navy organisms and shipyard. Only then it will be not only a logistic software but a decision software.

Participation of more experts on the FMECA-H validation, making eventually a learning language, madding various approximations of the Human Thinking, or engineering thinking, to enhance performance of the developed methodology. Also, the samples of condition monitoring parameters should be continuously measured and registered to increase the samples and validate the results adjusting for example the limits considered between the defined categories.

It should be developed user platform integrating the present research ideas, and made them more user friendly, considering the databases to be sufficiently malleable to eventually be adaptable to other equipment´s and to other ship class.

7.4.2 Future studies

For future studies it is proposed to include the pillar of persons of the “house” considered in sub-chapter 4.1.

It is also suggested to explore and maybe introduce in this methodology the Bayesian concept by applying it to the information registered in the SRTD in the impress (DSM59, DSM60).

Collect thermographic data from the propulsion diesel engines and test the adaption of neural network for treatment of thermal images from equipment condition monitoring and then categorize the level like in the application of control charts in this thesis.

On extracted data from SRTD, DSM58 document, and may be adding other register data from equipment´s, test the appliance of reliability calculus, categorized and eventually reintegrate on the FMECA-H-CM.

The optimisation of blockchain configurations should be explored for real-time equipment operational constraints, considering the AI incorporation on anomaly detection and the adaptive prioritisation in maintenance planning.

Deepen the study of blockchain on developed database for a safer cyber-structure.

Extended the study to others equipment's on warship to test an even complex dynamic maintenance.

Develop and test an algorithm for machine learning considering the result of FMECA-H-CM and the respective decision of the maintenance manager, so in the future does not depend only on specialized persons, because they may not be available.

The opportunity maintenance of others equipment´s, according to the calculations of risk, priorities, methodology on Figure 33 since Step 15 and the options in Table 18, should be automatically suggested by the language on Python.

For further studies, when humanizing the responses, other expert responses should be used, or the responses should be discussed before implementation the developed methodologies is warships.

Also next to database priorities results there should be an adjacent column where the maintenance manager can introduce his option on maintenance, so on the future may exist a machine learning algorithm, that allow the system learning from "good sense process" of human being decisions, to enhance the option and final decisions.

It should also be integrated the coloured code for each parameter and risk calculus presented on Subchapter 4.4.

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Annex A - References of published articles and other scientific work

The present annex presents scientific works, and all first pages of the articles and abstracts related to the thesis, presented or published by the author during the period of the present research, only the articles form journals or considered very significant to support this thesis are presented in a complete form. They are numbered with “A”, “.” and the “number”. After end of the point a.1 of Annex A there is two links that allows the access to the completed articles.

a.1. Scientific articles directly related with the thesis

a.1.1 Article as an author on IDEIA2020: Lampreia S., Vairinhos V., Lobo V., Requeijo J., & Morgado T. (2020), Análise de Condição em Turbinas a Gás – Aplicação Cartas Controlo Especiais (Condition Analysis in Gas Turbines – Application of Special Control Charts), I Conferência em Investigação, Desenvolvimento, Experimentação e Inovação - IDEIA2020, Escola Naval, Alfeite-Almada, 23 and 24 january.

a.1.2 Article as an author in proceedings IRF2020: Lampreia, S., Morgado, T., & Requeijo, J. (2020), Risk Analysis in the Context of Non-Maintenance, IRF2020, Editors J.F. Silva Gomes and S.A. Meguid, INEGI-FEUP (2020), pp. 835-838, 978-989-54756-1-2.

a.1.3 Article as an author in proceedings IRF2020: Morgado, T., Carvalho, M., Navas, H. & Lampreia, S. (2020), Development of a Maintenance Management Model Based on Continuous Improvement, IRF2020, Editors J.F. Silva Gomes and S.A. Meguid, INEGI-FEUP (2020), pp. 843-846, 978-989-5m206944756-1-2.

a.1.4 Article as an author in proceedings on MARTECH2020: Lampreia, S., Vairinhos, V., Lobo, V. & Morgado, T. (2020), Condition Analysis of Air Conditioning Cooling Water Pumps, 5th International Conference on Maritime Technology and Engineering - MARTECH2020, 16-19nov.

a.1.5 Article as an author on Jornadas de Manutenção APMI2020: Lampreia S., Vairinhos V., Lobo V. & Requeijo J. (2020), Análise do Controlo de Condição de Compressores de Ar (Condition monitoring Analysis of Air Compressors). Jornadas de Manutenção APMI2020, 18-19nov.

a.1.6 Article as an author on IDEIA2021: Lampreia S., Vairinhos V., Lobo V. (2021), Liderança em Processos de Mudança na Manutenção de Sistemas Militares Navais (Leadership in Change Processes in the Maintenance of Naval Military Systems). 2ª Conferência em Investigação, Desenvolvimento, Experimentação e Inovação - IDEIA2021, Escola Naval, Alfeite-Almada, 26 and 27 january.

a.1.7 Article as an author on: Lampreia S. Morgado, T., Navas H., Cabrita R. & Requeijo, J. (2021), An approach to Ship Equipment Maintenance Management. MDPI2021, Chapter 41 from book Innovations in Industrial Engineering (2022), Springer, pp. 1-10.

a.1.8 Article as an author on ISMS2021: Lampreia S., Vairinhos V., Lobo V. (2021), Maritime Cybersecurity Risk Assessment: the Ship Maintenance Databases' Case Study. International Society of Military Sciences - ISMS2021, Military Science – Resilience, Cohesion, Disruption. Online conference. Canada.

a.1.9 Article as an author on EIDCM2021 com um artigo: Lampreia S., Mestre I., Morgado T. & Navas, H. (2021), Metodologias Fuzzy na Monitorização Equipamentos (Fuzzy Methodologies in Equipment Monitoring) 3º Encontro de Investigação e Desenvolvimento em ciências Militares - EIDCM2021, Academia Militar, Amadora-Lisboa, 22 November.

a.1.10 Article as an author on 16.º Congresso Nacional de Manutenção 2021: Lampreia S. Morgado, T., Navas H., Mestre I. (2021). Aplicação de Metodologias Fuzzy na Monitorização de Sistemas Marítimos (Application of Fuzzy Methodologies in Monitoring Maritime Systems). 16.º Congresso Nacional de Manutenção, APMI, november, Aveiro.

a.1.11 Article as an author on IDEIA2022: Lampreia S., Vairinhos V., Lobo V. (2022), Sistema Integrado de Dados Para Gestão dos Meios das Componentes Militares - Definição Requisitos (Integrated Data System for Management of Military Component Resources - Requirements Definition). 3ª Conferência em Investigação, Desenvolvimento, Experimentação e Inovação - IDEIA2022, Escola Naval, Alfeite-Almada, 26 and 27 jannuary.

a.1.12 Article as an author on M2D2022: Lampreia S., Vairinhos V., Lobo V. & Morgado, T. (2022). Air Compressor Condition Monitoring Analysis. 9th International Conference on Mechanics and Materials in Design - M2D2021, june, Funchal.

a.1.13 Article as an author on M2D2022: Lampreia S., Vairinhos V., Lobo V. & Morgado, T. (2022). The Process Of Dynamic Maintenance On Naval Ships. 9th International Conference on Mechanics and Materials in Design - M2D2021, june, Funchal.

a.1.14 Article as an author on ISMS2022: Lampreia S., Lobo V. & Vairinhos V. (2022), Dynamic Maintenance in Ships. International Society of Military Sciences - ISMS2022, Military Science – Resilience, Cohesion, Disruption. IUM, Lisboa.

a.1.15 Article as an author on Jornadas da Manutenção APMI2022: Lampreia S., Vairinhos, V., Lobo, V., Morgado, T. & Navas H. (2022). Manutenção Dinâmica em Navios - Aplicando IoT (Dynamic Maintenance on Ships - Applying IoT). Jornadas da Manutenção, APMI, november, Porto.

a.1.16 Article as an author on Journal of Military Technology: Lampreia S., Lobo V. & Vairinhos V. (2022), Cybersecurity Risk Assessment: the Ship Maintenance Databases´Case Study, Journal of Military Technology, pp. 49-55, Vol. 5, Nº 2, Dec. 2022.

a.1.17 Article as an author on ICQUIS2022: Lampreia, S., Morgado, T., Navas, H., Mestre, I. (2023). Application of Fuzzy Methodologies in Navy Systems Maintenance. In: de Oliveira Matias, J.C., Oliveira Pimentel, C.M., Gonçalves dos Reis, J.C., Costa Martins das Dores, J.M., Santos, G. (eds) Quality Innovation and Sustainability. ICQUIS 2022. Springer Proceedings in Business and Economics. Springer, Cham. https://doi.org/10.1007/978-3-031-12914-8_31.

a.1.18 Article as an author on ICQIS2023: Lampreia S., Morgado T., Navas H., Vairinhos V., Lobo V. & Alves J. (2023), Blockchain in a Maintenance Database. 4 th International Conference on Quality Innovation and Sustainability, Polytechnic of Setúbal 22-23 May 2023.

a.1.19 Article as an author on ICEM2023: Lampreia S., Vairinhos V., Lobo V. & Morgado, T. (2023), Maintenance In Ships - A Dynamic Concept. Experimental Mechanics in Engineering and Biomechanics - Proceedings ICEM20 20th International Conference on Experimental Mechanics, pp 605-606, Porto 2-7 July 2023.

a.1.20 Article as an author on ECM2023: Lampreia S., Vairinhos V., Lobo V. & Morgado, T. (2023), FMECA Adaptado para Apoiar Ações de Manutenção. Encontro de Ciências Militares 2023, 27October2023.

a.1.21 Article as an author on APMI2023: Lampreia S., Vairinhos V., Lobo V., Morgado, T. & Navas, H. (2023), Manutenção Dinâmica em Navios – Análise de Risco. 17.º Congresso Nacional de Manutenção, Coimbra 23-24 November 2023.

a.1.22 Article as an author on Icontes2023: Lampreia S., Vairinhos V., Lobo V. & Morgado, T. (2023). Adapted FMECA for Supporting Maintenance Actions. The Eurasia Proceedings of Science Technology Engineering and Mathematics. IConTES 2023, EPSTEM, Vol. 26, pp. 208-216.

a.1.23 Article as an author on ICQIS2024: Lampreia S., Vairinhos V., Lobo V. & Morgado, T. (2024). Ship Dynamic Maintenance – Risk Analysis. 5th International Conference on Quality Innovation and Sustainability - ICQIS2024, pp. 1-10/42 no Book Abstract june 16-19.

a.1.24 Article as an author on: Lampreia S., Lobo V., Policarpo H. & Vairinhos V. (2024). Implementação de FMECA em Veículos Militares Autónomos Submarinos. MICRADS2024, july 17-19, publicação na revista RISTI (Revista Ibérica de Sistemas e Tecnologias de Informação), Vol. E72, 08/24, pp. 317-326.

a.1.25 Article as an author on: Lampreia S., Vairinhos V. & Lobo V. (2024). Advanced methodologies applied in a dynamic maintenance context. International Society of Military Sciences Annual Conference 2024, set 11-12.

a.1.26 Article as an author on Macise2024 and Journal WSEAS2025: Lampreia S., Mestre I., Morgado T. & Navas H. (2024). Dynamic Maintenance based on Fuzzy Logic. WSEAS TRANSACTIONS on BUSINESS and ECONOMICS Journal, Vol. 21, pp. 2578-2590, DOI: 10.37394/23207.2024.21.211.

a.1.27 Article as an author on ECM2024: Lampreia S., Vairinhos V. & Lobo V (2024). Navy Ship Dynamic Maintenance. ECM2024 – Encontro de Ciências Militares, 26 nov, Escola Naval.

a.1.28 Article as an author on ICQIS2025: Lampreia S., Vairinhos V., Lobo V. & Morgado, T. (2024). Modeling Maintenance Strategies Based on Dynamic Methodologies. 6th International Conference on Quality Innovation and Sustainability - ICQIS2025, may 21-23, Urbino.

The next links allows: on the first, the access to the complete articles related to the thesis, and the second gives access to FMEA file:

- Access articles:
  https://github.com/suzanalampreia/DCM_Published-Articles-2020-2025_SLampreia
- FMEA file:
  https://github.com/suzanalampreia/DCM-Thesis_Slampreia/releases/

a.2 Other scientific articles:

a.2.1 Article as a co-author on ICCSA2020: F. Teodoro., J. Batista, & Lampreia S. (2020). Waste Management and Embarked Staff. Proceedings of the 20th International Conference of Computational Science and Its Applications – ICCSA2020. Pp. 492-503. Springer International Publishing, 1-4jul.

a.2.2 Article as a author on ECM2022: Lampreia S., Teodoro F., Mendes T. (2022), Gestão de Resíduos em Submarinos – um Caso de Estudo (Submarine Waste Management – A Case Study). Encontro de Ciências Militares - ECM2022, Academia da Força Aérea, Sintra, 16 november.

a.2.3 Article as a author on TEchMA 2023: Lampreia S., Morgado T., Navas H., Vairinhos V., Lobo V. & Alves J. (2023), Towards a new technologic world - The evolution of 4th industrial revolution in maintenance. TEchMA 2023– 6th International Conference on Technologies for the Wellbeing and Sustainable Manufacturing Solutions, pp. 111, Aveiro, 22-23 May 2023.

a.2.4 Article as a co-author on RIQUALS XIII 2023: Morgado T., Navas H., Lampreia S., Simões J., & Braga D. (2023), Métodos de Extensão de Vida em Sistemas Complexos Marítimos (Life Extension Methods in Complex Marine Systems). Qualidade de Produtos e Serviços, Prevenção de falha, XIII Encontro de Investigadores da Qualidade, Coimbra Business School, 16 june 2023.

a.2.5 Article as a co-author on FAIM 2023: Morgado T., Pereira L., Navas H., Lampreia S., & Pereira M. (2023), Application of Lean Philosophy in a Processo f Internal Audits in Pandemic Environment. 32 nd International Conference on Flexible Automation and Intelligent Manufacturing, Instituto de Engenharia do Porto, 18-22 june 2023.

a.2.6 Article as a co-author on ICSI 2023: Ruivo J., Navas H. & Lampreia S. (2023), Smart naval maintenance, bridging the gap. The 14th International Conference & Global Competition on Systematic Innovation (ICSI & GCSI), 13-15 outubro 2023.

a.2.7 Article as an author on NTEM 1: Lampreia S., Vairinhos V. & Lobo V. (2024). A Study on Subystems for an Unmanned Underwater Vehicle. Spring School for

Young Researchers, New Trends in Experimental Mechanics – NTEM 1, Zakopane, may 13-17.

a.2.8 Article as a co-author on: Alves, J., Morgado, T., Navas, H., Lampreia, S., Abreu, A. e Ana Dias (2024). The Transformation of Maintenance with the Arise of Industry 4.0. Conference paper, Book of Innovations in Mechatronics Engineering III, Springer, pp 180-190.

a.2.9 Article as a co-author on ICQIS2024: Alves, J., Morgado, Pereira, M. & Lampreia, S. (2024). Machine Learning applied to LCA of mechanical components obtained by SLM. Conference paper, Book 5th International Conference on Quality Innovation and Sustainability, pp. 39, ISBN 978-989-33-6225-9.

a.2.10 Article as an author in proceedings MICRADS2024: Lampreia, S. (2025). The Colombia Armed Conflict—A Review Until 2020. In: Rocha, Á., Vaseashta, A. (eds) Developments and Advances in Defense and Security. MICRADS 2024. Smart Innovation, Systems and Technologies, vol 423. Springer, Singapore. https://doi.org/10.1007/978-981-96-0235-3, ISBN 978-981-96-0235-3/ISBN 978-981-96-0234-6.

a.2.11 Article publicated as an author: Lampreia S., Vairinhos V. & Lobo V. (2025). Cybersecurity in Military Systems: Risks and Mitigations. Book of New Wars, Routledge, Cap. 4, pp. 58-69. (In the context of do ISMS, em abril de 2025, via Dra Marzena e Dr David Last ISMS).

a.3 Review of articles:

a.3.1 Performed “review” of the following scientific paper proposal for conference MICRADS2020: without authors names. “Prototipo de Sistema para Análisis de Ondas Cerebrales del Personal Militar y Determinar su Capacidad para la Toma de Decisiones en Situaciones de Estrés”(Prototype System for Analyzing Brain Waves of Military Personnel and Determining Their Decision-Making Ability in Stressful Situations). Multidisciplinary International Conference of Research Applied to Defense and Security, MICRADS2020 (January 2020).

a.3.2 Performed “review” of the following scientific paper proposal for conference MICRADS2020: Yépes, V., Arcentales, N., León, M. “Vibration effects of the fixed-wing aircraft of the Army Aviation from Ecuador on the human body” (Vibration effects of the fixed-wing aircraft of the Army Aviation from Ecuador on the human body). Multidisciplinary International Conference of Research Applied to Defense and Security, MICRADS2020 (January 2020).

a.3.3 Performed “review” of the following scientific paper proposal for MDPI: Roshanmanesh, S., Hayati, F., Papaelias, M. Utilisation of Ensemble Empirical Mode Decomposition in Conjunction with Cyclo-stationary Technique for Wind Turbine Gearbox Fault Detection. Journal Applied Sciences, MDPI (April 2020).

a.3.4 Performed “review” of the following scientific paper proposal for MPEJ: Du, X., Gai, J., Chen, C. Condition-Based Maintenance Optimization for Motorized

2 Spindles Integrating Proportional Hazards Model with SPC 3 Charts. Journal Mathematical Problems in Engineering (MPEJ), Editora: Hindawi (June2020).

a.3.5 Performed “review” of the following scientific paper proposal for: Adel, A., Noman, M., NASR, A., Al-Ahmari, A., Kamrani, A., Mahmoud, H. Optimization model of maintenance planning and process quality control based on EWMA and CUSUM control charts. Journal Mathematical Problems in Engineering, MPEJ (September, 2020).

a.3.6 Performed “review” of the following scientific paper proposal for: Stevens K. Analysis of the Advanced Turbine System Program on Innovation in 3 Natural Gas Technology. Journal Energies, MDPI (September 2020).

a.3.7 Performed “review” of the following scientific paper proposal for conference MICRADS2021: Gestión del Conocimiento como Estrategia Impulsora en Instituciones Bomberiles con Régimen Disciplinario (Knowledge Management as a Driving Strategy in Fire Brigade Institutions with Disciplinary Regime). Multidisciplinary International Conference of Research Applied to Defense and Security, MICRADS2021 (Jannuary 2021).

a.3.8 Performed “review” of the following scientific paper proposal for conference: Comparative Analysis of High Frequencies for the Broken Bar Fault Diagnosis Using MCSA and Park´s Vector Demodulation. Multidisciplinary International Conference of Research Applied to Defense and Security, MICRADS2021 (Jannuary 2021).

a.3.9 Performed “review” of the following scientific paper proposal for Journal of Australian Ocean Affairs: A RAM Extension to Enhance Ship Planned Maintenance System. Journal of Australian Ocean Affairs (September 2021).

a.3.10 Performed “review” of the following scientific paper proposal for Marstruct2023: “Experimental investigation on oblique entry of trimaran cross deck structure”. 9th International Conference on Marine Structures - Marstruct2023 (November 2022).

a.3.11 Performed “review” of the following scientific paper proposal for Marstruct2023: “A Study on the Development of FPSO Standard Model KRISO-FPSO) I: Focusing on Structural Safety Evaluation”. 9th International Conference on Marine Structures - Marstruct2023 (November 2022).

a.3.12 Performed “review” of the following scientific paper proposal for conference MICRADS2025: “Employing blockchain to support 6G communications in industrial IoT scenarios”. Multidisciplinary International Conference of Research Applied to Defense and Security, MICRADS2021 (April 2025).

a.3.13 Performed “review” of the following scientific paper proposal for conference ICQIS2025: Edge Intelligence and IoMT for Real-Time Healthcare Analytics: A Systematic Literature Review. “6th International Conference on Quality Innovation and Sustainability, ICQIS2025 (April 2025).

a.4 Juries:

a.4.1. Chairman of the Master's Thesis Juries: Paiva, G. J. D. (2020). “Desenvolvimento de um Veículo Autónomo Biomimético - Desenvolvimento da Estrutura e Mecanismo de Propulsão Alternativo“ (Development of a Biomimetic Autonomous Vehicle - Development of the Structure and Alternative Propulsion Mechanism”, Alfeite: Escola Naval - Marinha.

a.4.2. Chairman of the Master's Thesis Juries: Leandro, A.A. (2020). Controlo de vibrações no uso do mar - Isolamento e Absorção, Alfeite: Escola Naval - Marinha.

a.4.3. Jury member for expert evidence on ENIDH of José, P. D. R. (2020), whose theme of the work carried out was: “Análise e Otimização da Instalação de Climatização de um Navio de Perfuração “Offshore” e de um Navio Fluvial de Passageiros” (Analysis and Optimization of Air Conditioning Installation on Offshore Drilling Vessel and River Passenger Vessel), Paço de Arcos, Lisboa.

a.4.4. Chairman of the Master's Thesis Juries of Aspof EN-MEC Santos Batista cujo o tema da foi: “Avaliação de Falha em Sistemas de Refrigeração - Uso do método de Dempster-Shafer” (Failure Assessment in Refrigeration Systems - Use of the Dempster-Shafer Method). Escola Naval, Alfeite-Almada, 16 setember 2022.

a.4.5. Jury member for Defense innovation premium attributed by the General Army Forces 2025.

a.5 Supervision and co-supervision of dissertations and/or thesis:

a.5.1. Supervised the master's thesis in Portuguese Naval Academy: Lino, B. (2020-2021). “Sistemas de Propulsão Elétrica - Estudo de Viabilidade” (Electric Propulsion Systems - Feasibility Study), Alfeite: Escola Naval - Marinha.

a.5.2. Supervised the master's thesis: Oliveira, J. F. L. (2020-2021). “Gestão de resíduos dos navios – Perspetiva do apoio terrestre” (Ship Waste Management – Shore Support Perspective). Alfeite: Escola Naval - Marinha.

a.5.3. Supervised the master's thesis in Portuguese Naval Academy: Mendes, N. (2020-2021). “Gestão de resíduos em navios de subsuperfície - Estudo de caso dos Submarinos da Marinha Portuguesa” (Waste management on subsurface vessels - Case study of the Portuguese Navy Submarines). Alfeite: Escola Naval - Marinha.

a.5.4. Co-Supervised the master's thesis on NOVA-FCT da UNL: Mestre, I. (2020-2021). “Proposta de Metodologia para a Gestão da Manutenção Baseada no Risco Utilizando a Lógica Fuzzy” (Proposal for a Methodology for Risk-Based Maintenance Management Using Fuzzy Logic). Monte da Caparica.

a.5.5. Supervised the master's thesis in Portuguese Naval Academy: Rodrigues, M. (2022-2023). “Análise de risco de manutenção em Navios da Marinha Portuguesa” (Maintenance risk analysis on Portuguese Navy ships). Alfeite: Escola Naval - Marinha.

a.5.6. Supervised the master's thesis in Portuguese Naval Academy: Mateus T. (2024): “Análise de Algoritmos de Descompressão e Respetiva Adequação aos Perfis de

Mergulho Habituais da Marinha Portuguesa" (Analysis of Decompression Algorithms and Their Adaptation to the Portuguese Navy's Usual Diving Profiles).

a.5.7. She is co-supervising a PhD Thesis on NOVA-FCT da UNL: Ruivo, J. (2022-2025). "Proposta de um Modelo de Manutenção Preditiva Eficiente Focada na Informação Significativa" (Proposal for an Efficient Predictive Maintenance Model Focused on Significant Information). Monte da Caparica.

a.6 Project submission:

a.6.1. Submitted the FCT 2020 scientific research project with other researchers, as principal investigator, whose project title is as follows: "Desenvolvimento de Metodologias de Monitorização de Sistemas Complexos Baseado em Técnicas Avançadas de Análise de Dados Multivariados e Data Streams em Ambiente de Manutenção 4.0" (Development of Complex Systems Monitoring Methodologies Based on Advanced Multivariate Data Analysis Techniques and Data Streams in Maintenance Environment 4.0).

a.6.2. Submitted a scientific research project to FCT 2021 with other researchers, as principal investigator, whose project title is as follows: Life Extension Methodologies in Complex Systems in Maintenance 4.0.

a.6.3. Applied to the FCT 2022 scientific research project with other researchers, as principal investigator, whose project title is as follows: Dynamic Methodologies Development Applied to Complex Systems Monitoring.

a.6.4. Applied with other researchers for the research, development, innovation and artistic creation project – 2022 edition of the Polytechnic Institute of Lisbon, whose project title is as follows "Life Extension Methodology in Complex Systems in Maintenance 4.0".

a.6.5. Submitted the FCT 2024 scientific research project in March 2024 with other researchers, as principal researcher, whose project title is as follows: Sustainability of Acts of Intervention on Assets with Advanced Maintenance Methodologies in Environment 5.0.

a.6.6. Applied for the FCT 2024 scientific research project, in July 2024 with other researchers and the company LUSOSPACE, as the responsible researcher, whose project title was as follows: Maintenance Support System with Augmented Reality and Artificial Intelligence for the Portuguese Navy.

a.6.7. Submitted an exploratory scientific research project to FCT 2024, in February 2025 with other researchers belonging to CINAV-Escola Naval, ISEL-IPL and Nova-FCT, as responsible researcher, whose project title was as follows: "Strategic Methods for Introducing Additive Manufacturing in the Manufacturing of Components Applied in Ship Maintenance".

a.7 Outros:

a.7.1. In 2020 he was part of the Scientific Committee of the – Scientific Committee of the 1st Conference on Research, Development, Experimentation and Innovation of the Navy - IDEIA 2020, Marinha.

a.7.2. Participated and coordinated the robotics exercises of the Portuguese Naval Academy REX2022/2023/2024, which took place at the Navy Operational Experimentation Center in Troia, as its coordinator.

a.7.3. Participated in the Jornadas do Mar 2023 at the Portuguese Naval Academy as a member of the Scientific Committee of the Conference.

a.7.4. He was part of the Evaluation Committee for the re-accreditation of the Doctoral Study Cycle in Naval and Oceanic Engineering do Instituto Superior Técnico da Universidade de Lisboa de dec2022 a jan2023.

a.7.5. She was part of the Evaluation Committee for accreditation of the new cycle of Undergraduate studies in Aerospace and Ocean Engineering at Faculdade de Ciências e Tecnologia da Universidade de Coimbra on 2024.

a.7.6. She coordinated the Military Sciences Meeting (ECM2024) locally at the Portuguese Naval Academy, which took place 26 november 2024.

a.7.7. She is currently part of the selection panel for assistant professor for Setúbal Polytechnic Institute.

Appendix A - Research design and schedule

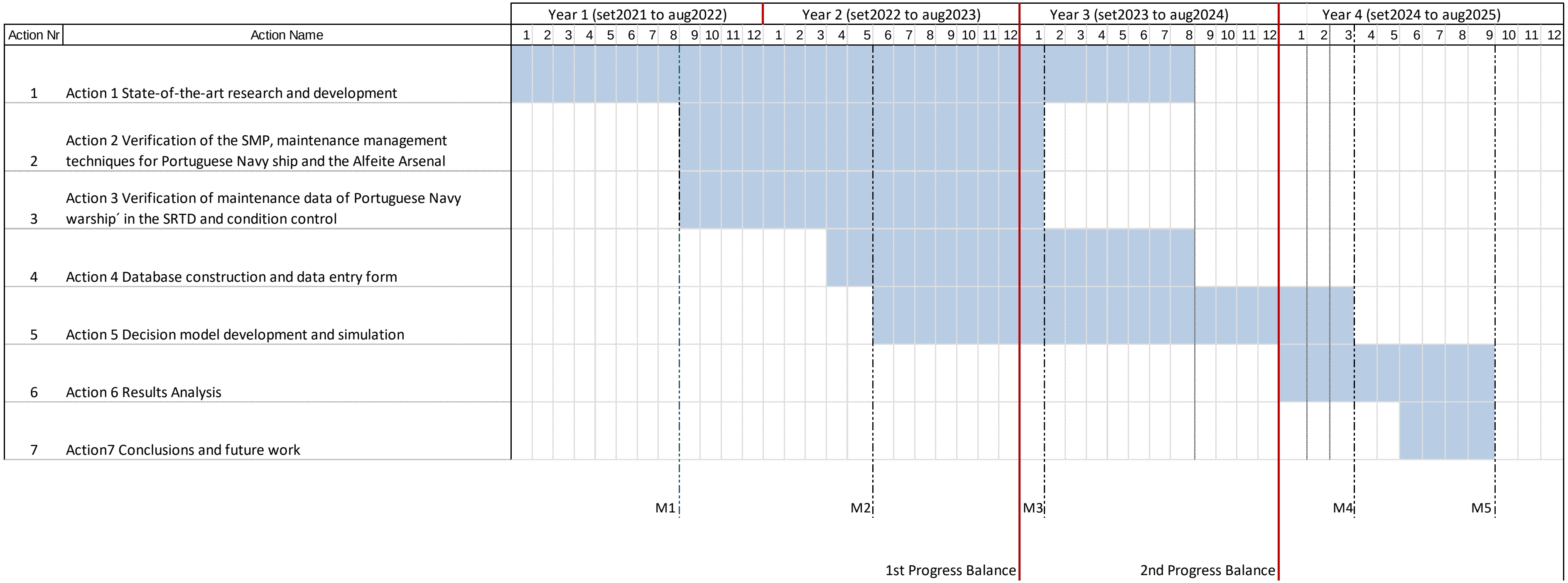
Table 67 - Research design

<table>
<tr><td colspan="2">1) Thesis Title: “MODELING DYNAMIC MAINTENANCE PRIORITIES IN WARSHIPS - A DATA DRIVEN APPROACH”
Integrated on CINAV Maintenance Management Research Line</td><td colspan="2">2) Phenomenon under study Planned Maintenance Management System implemented in the Navy, need for optimization in view of the current shortage of human, material and financial resources.</td></tr>
<tr><td>3) Topic to be investigated the maintenance systems of selected equipment and the continuous flow of data produced by sensors will be observed to carry out a continuous assessment of the risk of potential failures as well as the consequences and effects of decisions taken on equipment on Portuguese Navy (MP) ships, as well as maintenance records. By observing and processing these data, through the development, application and simulation of a model based on FMECA, we aim to obtain suggestions for decision-making and prioritization of maintenance interventions.</td><td colspan="2">4) Central Problem (CP) and Objectives. The CP of this research is the need of enhance the maintenance of surface warships. The specific problems that drive the topic to be investigated are the following: Lack of personal and spare parts, financial, mission imperatives, very specific naval resources, bureaucratic burden and partner shipyard with similar difficulties. And the objective is the development of a dynamic maintenance system or tool that allow the prioritization of interventions and evaluate maintenance opportunity of other selected equipment.
⇨ Central question: “Can a dynamic maintenance system manage intervention priorities on Portuguese Navy ships?”</td><td>5) Research framework and relevance There is a need to develop monitoring and data processing methodologies to study possible system failure processes, so that timely and data-based decisions can be made to avoid or limit the consequences of catastrophic failures. It is expected to contribute to minimizing failures and unexpected breakdowns in ship electromechanical systems in a dynamic way, increasing their lifespan and operational availability.
Keywords: Maintenance, Dynamics, Data Management, Prioritization, Warships</td></tr>
<tr><td colspan="2">6) Initial State of Art (For more, consult chapter nr 2 of this thesis.
Cullum et al. (2018) presents a scheme that presents three steps to carry out a maintenance plan on ships: “Risk Assessment-Condition Monitoring and Machine Learning”, “Maintenance Scheduling-Decision Theory” and “Quantify Availability and Overall Maintenance Cost”, which imply that the condition of ship systems is periodically monitored.
Simion et al. (2020) refers to a system proposal, the Computerized Maintenance Management System (CMMS) for application on military ships, considering ships undergoing modernization with the implementation of automation and sensors. Drago et al. (2020) propose the application of a CMMS, in which they refer to the need to perform several actions before its implementation, including planning and preparation of software where the control attributes must be included and the process of obtaining the data defined.</td><td colspan="2">7) Methodology and Method Proposal The methodology to be followed: action research, contributing to the improvement of the maintenance system implemented in the surface ships of the Portuguese Navy, to try to minimize the current issues of lack of material and human resources. Considering the collection and analysis of maintenance data on Portuguese Navy warships, a monitoring approach and methodology will be developed, predicting risk and prioritizing interventions. The method of application of the methodology will be: acquisition of data from a class of ships (3 Navy Ships), SMP from those ships; acquisition of data from equipment and systems, and how the data is being processed by the Ship Technical Direction (DN); condition monitoring variables and information to be monitored (to be selected); the creation of a model based on FMECA with condition monitoring and threat level; the development of a dynamic model that relates SMP data, resource-related data, quantitative and qualitative data on equipment and others systems related to a base system (opportunity maintenance).</td></tr>
<tr><td>8) Temporary structure
Cap.1–Introduction; Cap.2–Maintenance Management; Cap.3–Data and databases; Cap.4–Methodologies and methods on dynamic maintenance; Cap. 5–Navy ship equipment´s and data selection; Cap. 6- Applying FMECA-H-CM in a dynamic maintenance concept; Cap.7–Conclusions; Bibliographic References; Annex and Appendix A, B and C.</td><td colspan="2">9) Activity schedule (for more, see Table 69). Five milestones are considered: M1- Start data collection and evaluate the quality of it; M2- Start model development and simulation; M3- Stop data collection and start to limit and frame data on database; M4-Decision model and simulation finished; M5-Thesis finished and delivered. Two progress balance to re-think direction and to enhance the work consistency.</td><td>10) Resources Data existed and were collected from DN and warships.
Excel and Python software will be used.
Other material resources and software available at the Portuguese Naval Academy and on legal and free websites, or on academic websites.</td></tr>
<tr><td colspan="4">11) Supervised
Prof. Valter Vairinhos and Professor Vitor Sousa Lobo</td></tr>
</table>

1-4 - Introduction; 5-6 - Theoretical Framework; 7 - Methodological Framework; 8-10 - Schedule and Planning

Adapted from Vaz, 2020

Table 68 - Activity schedule 2021-2025



Appendix B - Data from DSM58 documents on SRTD

Only a sample is demonstrated for the ship understudy (ship nr 3), but for the research all data available were used (11210 lines of data from registered interventions on SRTD) to define the appliable criteria for CMText, including other equipment´s does not present in this research, Table 70, with the objective of give an example of type of equipment´s and what type of database exists. The Unit Code is represented by ship nr 3.

Table 69 - Data from SRTD database

DatN	FuN	ID	MT	Mtdesc	Fdesc
09/17/2020 00:00:00	1681225100	C1 – ESCOTILHAS	13	MANUTENÇÃO CORRECTIVA 1ºESCALÃO	PORTA ESTANQUE 2-98-2
12/04/2020 00:00:00	1681225100	C1 - MATERIAL PARA PORTAS E ESCOTILHAS	13	MANUTENÇÃO CORRECTIVA 1ºESCALÃO	PORTA ESTANQUE 2-98-2
01/10/2022 16:10:48	2330000000	REVISÃO GERAL DO MÓDULO DOS MOTORES PP - W6	31	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 3ºESCALÃO	MÁQUINAS DE COMBUSTÃO INTERNA
01/11/2022 12:08:43	2330000000	REVISÃO GERAL DO MÓDULO DOS MOTORES PP - W6	31	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 3ºESCALÃO	MÁQUINAS DE COMBUSTÃO INTERNA
03/09/2022 00:00:00	2330000000	REVISÃO GERAL DO MÓDULO DOS MOTORES PP - W6	31	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 3ºESCALÃO	MÁQUINAS DE COMBUSTÃO INTERNA
04/28/2022 00:00:00	2330000000	REVISÃO GERAL DO MÓDULO DOS MOTORES PP - W6	31	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 3ºESCALÃO	MÁQUINAS DE COMBUSTÃO INTERNA
01/11/2022 11:45:05	2330000000	REVISÃO PERIÓDICA DO MÓDULO - W5	31	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 3ºESCALÃO	MÁQUINAS DE COMBUSTÃO INTERNA
07/19/2018 00:00:00	2331000000	BLOCOS DE FILTROS PRIMÁRIOS	33	MANUTENÇÃO CORRECTIVA 3ºESCALÃO	MOTORES DIESEL PRINCIPAIS
10/17/2018 00:00:00	2331000000	BOMBAS ACOPLADAS DE ÁGUA SALGADA DOS MOTORES PRINCIPAIS	33	MANUTENÇÃO CORRECTIVA 3ºESCALÃO	MOTORES DIESEL PRINCIPAIS
04/05/2021 00:00:00	2331000000	C1 - COMPOSTO P/LAVAGEM CIRCUITO ÁGUA DOCE REFRIGERAÇÃO	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	MOTORES DIESEL PRINCIPAIS
01/10/2019 00:00:00	2331000000	C1 - JUNTA MOTORES	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	MOTORES DIESEL PRINCIPAIS
07/27/2018 00:00:00	2331000000	C1 - JUNTA TORICA (FRAREAL)	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	MOTORES DIESEL PRINCIPAIS
10/24/2019 00:00:00	2331000000	C1- LIQUIDO DE LAVAGEM PARA CIRCUITO DE REFRIGERAÇÂO	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	MOTORES DIESEL PRINCIPAIS
03/23/2016 00:00:00	2331000000	C1 - POST16 - SUBSTITUIÇÃO LIQUIDO DO CIRCUITO REFRIGERAÇÃO	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	MOTORES DIESEL PRINCIPAIS
11/27/2017 00:00:00	2331000000	C1 - PURGA COMBUSTÍVEL	13	MANUTENÇÃO CORRECTIVA 1ºESCALÃO	MOTORES DIESEL PRINCIPAIS

10/24/2019 00:00:00	2331000000	C1 - SUBSTITUIÇÃO LIQUIDO DO CIRCUITO REFRIGERAÇÃO	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	MOTORES DIESEL PRINCIPAIS
10/30/2016 00:00:00	2331000000	COMPENSADORES DE AR DE ADMISSÃO	13	MANUTENÇÃO CORRECTIVA 1ºESCALÃO	MOTORES DIESEL PRINCIPAIS
05/02/2022 00:00:00	2331000000	FILTROS DE OLEO EUROPAFILTER EF500HY	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	MOTORES DIESEL PRINCIPAIS
10/19/2020 00:00:00	2331000000	INSTALAÇÃO DE FILTROS DE BY-PASS DE ÓLEO DE LUBRIFICAÇÃO	42	ALTERAÇÕES	MOTORES DIESEL PRINCIPAIS
05/14/2018 00:00:00	2331000000	LIMPEZA BLOCOS FILTROS ÓLEO MOTORES PRINCIPAIS	33	MANUTENÇÃO CORRECTIVA 3ºESCALÃO	MOTORES DIESEL PRINCIPAIS
08/28/2021 00:00:00	2331000000	LIMPEZA DE MOTORES PP´S	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	MOTORES DIESEL PRINCIPAIS
10/24/2018 00:00:00	2331000000	LIMPEZA DO ARREFECEDOR DO MÓDULO	33	MANUTENÇÃO CORRECTIVA 3ºESCALÃO	MOTORES DIESEL PRINCIPAIS
08/10/2017 00:00:00	2331000000	MANUTENÇÃO MISSÃO FRONTEX	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	MOTORES DIESEL PRINCIPAIS
08/07/2018 00:00:00	2331000000	MANUTENÇÃO W3	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	MOTORES DIESEL PRINCIPAIS
08/29/2018 00:00:00	2331000000	MANUTENÇÃO W3	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	MOTORES DIESEL PRINCIPAIS
01/11/2022 12:08:44	2331000000	MÓDULO - LIMPEZA E INSPEÇÃO DO EXTRATOR E FLAP - W5/W6	31	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 3ºESCALÃO	MOTORES DIESEL PRINCIPAIS
03/09/2022 00:00:00	2331000000	MÓDULO - LIMPEZA E INSPEÇÃO DO EXTRATOR E FLAP - W5/W6	31	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 3ºESCALÃO	MOTORES DIESEL PRINCIPAIS
11/25/2019 00:00:00	2331000000	REPARAÇÃO DE 2 BOMBAS ACOPLADAS DE ÁGUA SALGADA	33	MANUTENÇÃO CORRECTIVA 3ºESCALÃO	MOTORES DIESEL PRINCIPAIS
02/10/2022 00:00:00	2331000000	SUBSTITUIÇÃO DOS MDPP	33	MANUTENÇÃO CORRECTIVA 3ºESCALÃO	MOTORES DIESEL PRINCIPAIS
10/11/2016 00:00:00	2331000000	SUSTENTAÇÃO 2017 W3	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	MOTORES DIESEL PRINCIPAIS
10/19/2018 00:00:00	2331000000	SUSTENTAÇÃO MANUTENÇÃO MAR ABERTO 19	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	MOTORES DIESEL PRINCIPAIS
06/08/2021 00:00:00	2331200000	SUBSTITUIÇÃO DAS JUNTAS DE VEDAÇÃO GASES SAÍDA DAS CABEÇAS BANCA A	33	MANUTENÇÃO CORRECTIVA 3ºESCALÃO	MOTOR DIESEL PRINCIPAL BB
10/31/2018 00:00:00	2331200000	VERIFICAÇÃO DO ALINHAMENTO E DISTRIBUIÇÃO DE CARGAS DE APOIO	32	MANUTENÇÃO PREVENTIVA CONDICIONADA 3ºESCALÃO	MOTOR DIESEL PRINCIPAL BB
08/13/2018 00:00:00	2331200000	W3 MOTOR DE BB	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	MOTOR DIESEL PRINCIPAL BB
06/02/2019 00:00:00	2331213000	KIT REPARAÇÃO DE VÁLVULA AR DE ARRANQUE MOTOR BB	13	MANUTENÇÃO CORRECTIVA 1ºESCALÃO	VALVULAS DE AR DE ARRANQUE

02/15/2016 00:00:00	2331225000	C2 -REPARAÇÃO DISTRIBUIDOR AR MOTOR BB	33	MANUTENÇÃO CORRECTIVA 3ºESCALÃO	DISTRIBUIDOR
10/14/2019 00:00:00	2331244000	SUBSTITUIÇÃO SENSOR DE PRESSÃO 0-16BAR 10-36V 4-20MA TIPO 8213.79	99	NÃO APLICÁVEL	PAINEL DE CONTROLO LOCAL (M.D.PP.BB)
05/10/2016 00:00:00	2341100000	C2- INSPECIONAR ESTATOR E AS PÁS DA TURBINA	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	TURBINA A GÁS PRINCIPAL EB
05/04/2017 00:00:00	2341100000	CIT SUBSTITUIÇÃO	13	MANUTENÇÃO CORRECTIVA 1ºESCALÃO	TURBINA A GÁS PRINCIPAL EB
01/10/2022 16:01:48	2452240000	TANQUE DE OLEO DE COMPENSAÇAO/EXPANSAO DO CPP BB	31	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 3ºESCALÃO	TANQUE DE OLEO DE COMPENSACAO/EXPANSAO BB
08/22/2017 00:00:00	2611120000	COLMATAÇÃO FILTROS FAUDI	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	FILTROS
06/28/2021 00:00:00	2611120000	SUBSTITUIÇÃO FILTROS COMPRESSÃO BOMBA ELEVADORA COMBUSTIVEL TG	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	FILTROS
01/12/2017 00:00:00	2611124000	FILTRO FAUDI SEDIMENTOS	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	FILTRO DE COMBUTIVEL PARA TURBINA GAS EB
04/18/2018 00:00:00	2613100000	C1 - VÁLVULA NÃO RETORNO CENTRIFUGADOR	13	MANUTENÇÃO CORRECTIVA 1ºESCALÃO	CENTRIFUGADORES DE COMBUSTÍVEL
07/14/2017 00:00:00	2613121000	CENTRIFUGADOR DE COMBUSTÍVEL.	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	CENTRIFUGADOR DE COMBUSTIVEL Nº2
01/06/2022 00:00:00	2613121000	DESMONTAR, LIMPAR, INSPECIONAR, LUBRIFICAR, MONTAR E TESTAR.	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	CENTRIFUGADOR DE COMBUSTIVEL Nº2
06/22/2018 00:00:00	2613121000	SOLDADURA/MANUFATURA DO TUBO DA ASPIRAÇÃO DO CENTRIFUGADOR.	23	MANUTENÇÃO CORRECTIVA 2ºESCALÃO	CENTRIFUGADOR DE COMBUSTIVEL Nº2
06/15/2018 00:00:00	2613122000	PRESSOSTATO CENTRIFUGADOR	13	MANUTENÇÃO CORRECTIVA 1ºESCALÃO	MOTOR ELECTRICO DO CENTRIFUGADOR DE COMBUSTIVEL Nº2
09/07/2017 00:00:00	2613124000	C1-COMUTADOR 1 PÓLO 2 POS C/MANIPULO E ESPELHO 48X48MM	13	MANUTENÇÃO CORRECTIVA 1ºESCALÃO	QUADRO DE COMANDO DO CENTRIFUGADOR DE COMBUSTIVEL Nº2
11/17/2016 00:00:00	5312110000	SUSTENTAÇÃO 2017 - PRODUTO GOI	99	NÃO APLICÁVEL	GERADOR DE AGUA DOCE (OSMOSE INVERSA)
09/12/2018 00:00:00	5312110000	ACOPLAMENTO BOMBA ELEVADORA	41	ASSISTÊNCIA TÉCNICA (CONTRATOS DE MANUTENÇÃO)	GERADOR DE AGUA DOCE (OSMOSE INVERSA)
03/29/2022 00:00:00	5515121000	REVISÃO GERAL COMPRESSOR ALTA PRESSÃO CASA MOTORES	33	MANUTENÇÃO CORRECTIVA 3ºESCALÃO	COMPRESSOR DE AR AP CASA DOS MOTORES PP
06/14/2019 00:00:00	5515300000	BUJÃO FUSIVEL DE 9MM EM AÇO	11	MANUTENÇÃO PREVENTIVA SISTEMÁTICA 1ºESCALÃO	COMPRESSORES DE AR DE B.P.
10/26/2020 00:00:00	5515300000	C1 - FUGA DE ÓLEO E PASSAGEM CÁRTER COMPRESSOR BP MOTORES	13	MANUTENÇÃO CORRECTIVA 1ºESCALÃO	COMPRESSORES DE AR DE B.P.

06/05/2020 00:00:00	5515300000	C1 - MATERIAL PARA INTERVENÇÃO FUGA ÓLEO COMPRESSOR BP DE´S	13	MANUTENÇÃO CORRECTIVA 1ºESCALÃO	COMPRESSORES DE AR DE B.P.
08/02/2018 00:00:00	5515300000	C1- BUJÃO FUSÍVEL COMPRESSOR BAIXA	13	MANUTENÇÃO CORRECTIVA 1ºESCALÃO	COMPRESSORES DE AR DE B.P.

Note: Unit Code (UC), Necessity Date (DatN), Functional Number (FuN), Intervention Description (ID), Maintenance Type (MT), Description of Maintenance Type (Mtdesc) and Description of nr functional.

Appendix C - FMECA, FMECA-H-CM and FMECA-H-CM

For the next FMECA-H-CM was considered the current threat state, considering Portugal Geographic place for ships missions, and a level two of threat. On the first column of the tables “Act Nr” are the activity number.

Table 70 - FMECA-H-CM MD with real data

Act Nr	Maintenance Activity	SS	SE	Seq	SP	SO	O	D	FMECA	FMECA-H	CMV	CMP	CMTex	TS	FMECA-H-CM
1	Navigating, check the color of the evacuation gases, condensation, obstructions, etc.	2,0	4,0	3,8	1,8	1,6	3,0	4,2	28,0	33,4	5	1	5	2	66,6
2	Navigating, check the color of the evacuation gases, condensation, obstructions, etc.	1,8	3,6	3,8	1,4	1,8	2,8	4,4	17,0	30,7	5	1	5	2	61,2
3	Navigating, check the color of the evacuation gases, condensation, obstructions, etc.	2,0	4,0	3,0	2,0	1,8	2,8	4,0	19,0	28,8	5	1	5	2	57,4
4	Navigating, check the color of the evacuation gases, condensation, obstructions, etc.	2,6	4,2	3,0	1,4	2,2	2,8	4,4	17,0	33,2	5	1	5	2	66,1
5	Inspect supercharging system, perform overspeed test	1,8	2,8	3,4	1,8	2,8	3,2	3,2	12,8	26,0	5	1	5	2	51,8
6	Inspect supercharging system, perform overspeed test	1,2	1,6	3,0	1,1	1,8	3,2	3,0	16,8	16,7	5	1	5	2	33,4
7	Inspect supercharging system, perform overspeed test	0,8	2,2	2,6	1,2	2,2	3,4	3,0	8,8	18,6	5	1	5	2	37,0
8	Inspect supercharging system, perform overspeed test	2,0	1,6	3,4	0,9	1,8	3,4	2,8	16,8	18,6	5	1	5	2	37,0
9	Inspect supercharging system, perform overspeed test	1,2	2,2	3,2	0,9	2,0	3,0	3,8	6,0	21,7	5	1	5	2	43,2
10	Check the sequential system of the supercharging groups	2,0	2,8	2,0	1,2	2,2	2,8	2,4	12,0	13,9	5	1	5	2	27,6
11	Check the sequential system of the supercharging groups	1,8	2,6	2,2	1,5	1,6	2,4	3,4	22,4	15,9	5	1	5	2	31,6
12	Check the sequential system of the supercharging groups	1,0	3,6	2,6	1,0	1,6	1,8	4,0	22,4	14,4	5	1	5	2	28,7
13	Oil sample collection and analysis	1,8	2,6	4,2	0,7	2,4	3,0	3,4	15,6	23,9	5	1	5	2	47,7
14	Oil sample collection and analysis	2,6	2,8	3,4	2,8	2,4	2,8	3,6	20,8	28,5	5	1	5	2	56,9
15	Oil sample collection and analysis	1,8	2,6	3,2	1,7	1,8	3,2	3,8	14,4	27,0	5	1	5	2	53,9
16	Oil sample collection and analysis	1,6	1,8	4,0	1,3	1,8	2,2	2,6	18,0	12,2	5	1	5	2	24,2
17	Change lubrication oil	1,4	2,4	3,8	0,7	2,2	3,4	2,8	11,2	20,0	5	1	5	2	39,9
18	Change lubrication oil	1,6	2,2	4,0	1,8	2,0	2,6	3,0	8,0	18,2	5	1	5	2	36,3

19	Change lubrication oil	2,0	2,2	4,2	1,2	1,8	2,4	3,4	10,4	18,9	5	1	5	2	37,7
20	Change lubrication oil	0,9	2,0	3,4	1,3	1,2	3,0	2,6	8,9	13,7	5	1	5	2	27,3
21	Change oil filters	1,4	1,2	3,2	1,6	2,2	2,8	3,4	10,5	18,5	5	1	5	2	36,9
22	Change oil filters	1,2	1,4	2,6	1,6	2,2	2,8	1,8	7,2	9,2	5	1	5	2	18,4
23	Change oil filters	1,2	1,6	3,2	2,2	1,8	2,6	1,6	10,4	8,5	5	1	5	2	16,9
24	Change oil filters	1,4	1,2	3,8	1,6	2,2	3,4	1,6	9,6	11,4	5	1	5	2	22,7
25	Check/Adjust valves	1,8	3,2	3,4	2,0	2,2	3,0	1,8	10,4	13,8	5	1	5	2	27,5
26	Check/Adjust valves	2,2	1,6	3,2	1,6	3,2	3,0	1,8	4,4	12,8	5	1	5	2	25,6
27	Check/Adjust valves	1,2	2,8	4,0	1,8	3,2	2,2	3,0	12,8	17,2	5	1	5	2	34,3
28	Check exhaust gas system	1,6	2,8	4,0	3,0	3,0	3,0	2,4	18,0	20,8	5	1	5	2	41,4
29	Check exhaust gas system	1,8	1,6	2,8	1,4	2,2	3,0	2,6	18,0	15,4	5	1	5	2	30,8
30	Check exhaust gas system	2,0	2,0	2,2	2,0	3,2	2,4	2,4	12,0	13,4	5	1	5	2	26,7
31	Check exhaust gas system	0,9	1,8	3,2	2,0	3,0	3,2	2,8	24,0	19,5	5	1	5	2	38,8
32	Change fuel filters	1,6	1,2	3,0	1,8	2,2	2,4	2,2	12,0	10,5	5	1	5	2	20,8
33	Change fuel filters	1,6	2,0	3,6	1,2	1,6	3,0	2,4	12,0	14,5	5	1	5	2	28,9
34	Change fuel filters	1,6	2,2	2,4	1,8	2,2	2,2	1,8	5,2	8,2	5	1	5	2	16,4
35	Change fuel filters	1,4	2,4	2,8	1,1	2,4	3,4	3,0	5,2	20,6	5	1	5	2	41,1
36	Cleaning Sea Filters	1,6	2,0	2,4	2,0	2,6	3,2	3,2	11,2	22,0	5	1	5	2	43,7
37	Cleaning Sea Filters	2,2	2,4	3,0	2,4	3,2	2,6	3,0	4,8	20,9	5	1	5	2	41,6
38	Lubrication of lubricating grease point	1,6	2,0	3,0	1,8	2,2	2,4	3,4	9,7	17,6	5	1	5	2	35,1
39	Lubrication of lubricating grease point	1,2	1,6	3,2	2,4	2,0	3,0	2,4	4,8	15,1	5	1	5	2	30,1
40	Lubrication of lubricating grease point	1,6	2,0	2,4	0,9	2,2	2,6	2,2	10,4	10,6	5	1	5	2	21,1
41	Check operation of the expansion tank level valve	2,2	2,2	3,6	1,8	1,6	3,2	3,6	8,8	26,4	5	1	5	2	52,7
42	Check operation of the expansion tank level valve	1,4	2,2	3,6	1,4	2,0	3,4	3,4	5,2	24,7	5	1	5	2	49,3
43	Check operation of the expansion tank level valve	1,4	2,0	3,6	0,9	1,4	2,6	3,6	14,4	17,4	5	1	5	2	34,7
44	Check coupling state	1,6	2,2	3,4	1,2	1,4	3,0	2,6	10,4	15,6	5	1	5	2	31,0
45	Check coupling state	1,6	1,4	3,8	1,7	1,4	3,2	3,6	5,2	22,9	5	1	5	2	45,6
46	Verify distribution components. Send feedback, side panels, history saved.	0,9	2,4	2,6	0,9	2,4	3,2	3,6	8,8	21,1	5	1	5	2	42,0

47	Verify distribution components. Send feedback, side panels, history saved.	1,6	3,2	3,2	1,5	2,0	2,8	2,8	4,8	18,0	5	1	5	2	35,9
48	Verify distribution components. Send feedback, side panels, history saved.	1,1	2,8	3,8	1,1	2,0	3,4	2,4	5,2	17,5	5	1	5	2	34,9
49	Checking the charge air system (or at 1500 hours)	2,0	2,0	2,4	0,9	2,0	3,6	2,4	8,8	16,1	5	1	5	2	32,1
50	Checking the charge air system (or at 1500 hours)	1,4	2,6	2,6	0,9	2,2	2,6	2,0	5,6	10,1	5	1	5	2	20,2
51	Checking the charge air system (or at 1500 hours)	1,2	2,0	3,6	2,0	2,4	2,6	3,4	13,2	20,0	5	1	5	2	39,8
52	Inspect and calibrate the injectors	1,6	2,2	3,8	1,8	2,0	3,0	2,6	5,2	17,9	5	1	5	2	35,7
53	Inspect and calibrate the injectors	2,0	2,0	3,4	1,4	2,0	2,8	2,8	10,4	17,1	5	1	5	2	34,1
54	Inspect and calibrate the injectors	1,0	2,4	3,2	1,4	1,4	2,2	2,8	10,4	11,7	5	1	5	2	23,3
55	Inspect and calibrate the injectors	1,4	2,2	3,8	1,4	1,6	2,6	3,6	5,2	19,7	5	1	5	2	39,2
56	Inspect and calibrate the injectors	1,4	2,4	4,2	2,0	1,2	2,8	3,0	5,2	19,0	5	1	5	2	37,8
57	Inspect and calibrate the injectors	0,9	2,2	4,0	1,8	2,0	3,0	2,6	5,2	17,2	5	1	5	2	34,2
58	Inspect and calibrate the injectors	1,6	2,0	3,8	1,6	2,2	2,8	2,4	10,4	15,3	5	1	5	2	30,5
59	Cooling freshwater change and treatment	1,4	2,2	3,0	1,8	1,6	2,2	2,6	5,2	11,6	5	1	5	2	23,0
60	Cooling freshwater change and treatment	1,6	1,8	3,6	2,2	1,2	2,8	2,6	5,2	15,3	5	1	5	2	30,4
61	Checking the engine mounts	1,6	1,8	3,4	2,2	3,0	3,6	2,0	5,2	17,6	5	1	5	2	35,1
62	Checking the engine mounts	1,2	1,8	4,0	1,3	3,2	3,4	2,0	5,2	15,7	5	1	5	2	31,3
63	Checking the engine mounts	1,8	2,0	3,0	2,2	2,4	2,6	1,6	5,2	9,6	5	1	5	2	19,1
64	Checking the engine mounts	1,0	2,2	3,2	1,8	3,0	3,2	2,2	5,2	15,9	5	1	5	2	31,7
65	Checking the engine mounts	2,6	2,2	3,5	2,6	3,0	3,4	2,0	5,2	19,2	5	1	5	2	38,2
66	Checking the engine mounts	1,0	2,0	4,0	2,4	2,6	3,2	2,4	5,2	18,6	5	1	5	2	37,0
67	Decarbonization	1,2	1,4	3,0	2,6	2,6	2,8	2,0	5,2	12,4	5	1	5	2	24,6
68	Decarbonization	1,0	2,4	3,8	2,0	2,4	2,8	2,2	5,2	14,4	5	1	5	2	28,7
69	Decarbonization	1,4	2,6	3,6	1,2	2,6	3,0	2,2	10,4	15,2	5	1	5	2	30,2
70	Decarbonization	1,4	1,6	3,8	2,2	2,0	3,0	2,4	5,2	15,9	5	1	5	2	31,7
71	General Overhaul	1,6	2,8	3,8	2,0	1,6	2,8	2,0	5,2	13,3	5	1	5	2	26,5
72	General Overhaul	2,0	1,8	3,2	1,6	2,2	3,0	2,0	5,2	13,1	5	1	5	2	26,0
73	General Overhaul	1,8	2,0	2,8	2,0	2,4	2,6	3,0	15,6	17,3	5	1	5	2	34,4
74	General Overhaul	0,9	2,4	3,8	1,8	2,4	3,0	1,6	5,6	10,8	5	1	5	2	21,6

75	General Overhaul	1,4	3,0	2,4	1,6	2,6	3,8	3,4	8,0	28,6	5	1	5	2	56,9
76	General Overhaul	1,0	1,2	3,2	2,2	2,2	2,6	2,6	5,2	13,4	5	1	5	2	26,7
77	General Overhaul	1,4	2,2	3,8	2,2	2,4	3,8	2,6	5,2	23,9	5	1	5	2	47,6

Table 71 - FMECA-H-CM MD with anomaly simulation 1

Nr Act	Maintenance Activity	SS	SE	Seq	SP	SO	O	D	FMECA	FMECA-H	CMV	CMP	CMTex	TS	FMECA-H-CM
1	Navigating, check the color of the evacuation gases, condensation, obstructions, etc.	2,0	4,0	3,8	1,8	1,6	3,0	4,2	28,0	33,4	2	3	5	4	86,6
2	Navigating, check the color of the evacuation gases, condensation, obstructions, etc.	1,8	3,6	3,8	1,4	1,8	2,8	4,4	17,0	30,7	2	3	5	2	58,2
3	Navigating, check the color of the evacuation gases, condensation, obstructions, etc.	2,0	4,0	3,0	2,0	1,8	2,8	4,0	19,0	28,8	2	3	5	2	54,6
4	Navigating, check the color of the evacuation gases, condensation, obstructions, etc.	2,6	4,2	3,0	1,4	2,2	2,8	4,4	17,0	33,2	2	3	5	2	62,9
5	Inspect supercharging system, perform overspeed test	1,8	2,8	3,4	1,8	2,8	3,2	3,2	12,8	26,0	2	3	5	2	49,3
6	Inspect supercharging system, perform overspeed test	1,2	1,6	3,0	1,1	1,8	3,2	3,0	16,8	16,7	2	3	5	2	31,8
7	Inspect supercharging system, perform overspeed test	0,8	2,2	2,6	1,2	2,2	3,4	3,0	8,8	18,6	2	3	5	2	35,2
8	Inspect supercharging system, perform overspeed test	2,0	1,6	3,4	0,9	1,8	3,4	2,8	16,8	18,6	2	3	5	2	35,3
9	Inspect supercharging system, perform overspeed test	1,2	2,2	3,2	0,9	2,0	3,0	3,8	6,0	21,7	2	3	5	2	41,2
10	Check the sequential system of the supercharging groups	2,0	2,8	2,0	1,2	2,2	2,8	2,4	12,0	13,9	2	3	5	2	26,3
11	Check the sequential system of the supercharging groups	1,8	2,6	2,2	1,5	1,6	2,4	3,4	22,4	15,9	2	3	5	2	30,1
12	Check the sequential system of the supercharging groups	1,0	3,6	2,6	1,0	1,6	1,8	4,0	22,4	14,4	2	3	5	2	27,3
13	Oil sample collection and analysis	1,8	2,6	4,2	0,7	2,4	3,0	3,4	15,6	23,9	2	3	5	2	45,4
14	Oil sample collection and analysis	2,6	2,8	3,4	2,8	2,4	2,8	3,6	20,8	28,5	2	3	5	2	54,2
15	Oil sample collection and analysis	1,8	2,6	3,2	1,7	1,8	3,2	3,8	14,4	27,0	2	3	5	2	51,3
16	Oil sample collection and analysis	1,6	1,8	4,0	1,3	1,8	2,2	2,6	18,0	12,2	2	3	5	2	23,1
17	Change lubrication oil	1,4	2,4	3,8	0,7	2,2	3,4	2,8	11,2	20,0	2	3	5	2	38,0
18	Change lubrication oil	1,6	2,2	4,0	1,8	2,0	2,6	3,0	8,0	18,2	2	3	5	2	34,6
19	Change lubrication oil	2,0	2,2	4,2	1,2	1,8	2,4	3,4	10,4	18,9	2	3	5	2	35,9
20	Change lubrication oil	0,9	2,0	3,4	1,3	1,2	3,0	2,6	8,9	13,7	2	3	5	2	26,0

21	Change oil filters	1,4	1,2	3,2	1,6	2,2	2,8	3,4	10,5	18,5	2	3	5	2	35,2
22	Change oil filters	1,2	1,4	2,6	1,6	2,2	2,8	1,8	7,2	9,2	2	3	5	2	17,5
23	Change oil filters	1,2	1,6	3,2	2,2	1,8	2,6	1,6	10,4	8,5	2	3	5	2	16,1
24	Change oil filters	1,4	1,2	3,8	1,6	2,2	3,4	1,6	9,6	11,4	2	3	5	2	21,6
25	Check/Adjust valves	1,8	3,2	3,4	2,0	2,2	3,0	1,8	10,4	13,8	2	3	5	2	26,2
26	Check/Adjust valves	2,2	1,6	3,2	1,6	3,2	3,0	1,8	4,4	12,8	2	3	5	2	24,3
27	Check/Adjust valves	1,2	2,8	4,0	1,8	3,2	2,2	3,0	12,8	17,2	2	3	5	2	32,7
28	Check exhaust gas system	1,6	2,8	4,0	3,0	3,0	3,0	2,4	18,0	20,8	2	3	5	2	39,4
29	Check exhaust gas system	1,8	1,6	2,8	1,4	2,2	3,0	2,6	18,0	15,4	2	3	5	2	29,3
30	Check exhaust gas system	2,0	2,0	2,2	2,0	3,2	2,4	2,4	12,0	13,4	2	3	5	2	25,4
31	Check exhaust gas system	0,9	1,8	3,2	2,0	3,0	3,2	2,8	24,0	19,5	2	3	5	2	37,0
32	Change fuel filters	1,6	1,2	3,0	1,8	2,2	2,4	2,2	12,0	10,5	2	3	5	2	19,8
33	Change fuel filters	1,6	2,0	3,6	1,2	1,6	3,0	2,4	12,0	14,5	2	3	5	2	27,5
34	Change fuel filters	1,6	2,2	2,4	1,8	2,2	2,2	1,8	5,2	8,2	2	3	5	2	15,6
35	Change fuel filters	1,4	2,4	2,8	1,1	2,4	3,4	3,0	5,2	20,6	2	3	5	2	39,1
36	Cleaning Sea Filters	1,6	2,0	2,4	2,0	2,6	3,2	3,2	11,2	22,0	2	3	5	2	41,7
37	Cleaning Sea Filters	2,2	2,4	3,0	2,4	3,2	2,6	3,0	4,8	20,9	2	3	5	2	39,6
38	Lubrication of lubricating grease point	1,6	2,0	3,0	1,8	2,2	2,4	3,4	9,7	17,6	2	3	5	2	33,5
39	Lubrication of lubricating grease point	1,2	1,6	3,2	2,4	2,0	3,0	2,4	4,8	15,1	2	3	5	2	28,7
40	Lubrication of lubricating grease point	1,6	2,0	2,4	0,9	2,2	2,6	2,2	10,4	10,6	2	3	5	2	20,1
41	Check operation of the expansion tank level valve	2,2	2,2	3,6	1,8	1,6	3,2	3,6	8,8	26,4	2	3	5	2	50,2
42	Check operation of the expansion tank level valve	1,4	2,2	3,6	1,4	2,0	3,4	3,4	5,2	24,7	2	3	5	2	46,9
43	Check operation of the expansion tank level valve	1,4	2,0	3,6	0,9	1,4	2,6	3,6	14,4	17,4	2	3	5	2	33,0
44	Check coupling state	1,6	2,2	3,4	1,2	1,4	3,0	2,6	10,4	15,6	2	3	5	2	29,5
45	Check coupling state	1,6	1,4	3,8	1,7	1,4	3,2	3,6	5,2	22,9	2	3	5	2	43,4
46	Verify distribution components. Send feedback, side panels, history saved.	0,9	2,4	2,6	0,9	2,4	3,2	3,6	8,8	21,1	2	3	5	2	40,0
47	Verify distribution components. Send feedback, side panels, history saved.	1,6	3,2	3,2	1,5	2,0	2,8	2,8	4,8	18,0	2	3	5	2	34,2
48	Verify distribution components. Send feedback, side panels, history saved.	1,1	2,8	3,8	1,1	2,0	3,4	2,4	5,2	17,5	2	3	5	2	33,2

49	Checking the charge air system (or at 1500 hours)	2,0	2,0	2,4	0,9	2,0	3,6	2,4	8,8	16,1	2	3	5	2	30,6
50	Checking the charge air system (or at 1500 hours)	1,4	2,6	2,6	0,9	2,2	2,6	2,0	5,6	10,1	2	3	5	2	19,2
51	Checking the charge air system (or at 1500 hours)	1,2	2,0	3,6	2,0	2,4	2,6	3,4	13,2	20,0	2	3	5	2	37,9
52	Inspect and calibrate the injectors	1,6	2,2	3,8	1,8	2,0	3,0	2,6	5,2	17,9	2	3	5	2	34,0
53	Inspect and calibrate the injectors	2,0	2,0	3,4	1,4	2,0	2,8	2,8	10,4	17,1	2	3	5	2	32,4
54	Inspect and calibrate the injectors	1,0	2,4	3,2	1,4	1,4	2,2	2,8	10,4	11,7	2	3	5	2	22,2
55	Inspect and calibrate the injectors	1,4	2,2	3,8	1,4	1,6	2,6	3,6	5,2	19,7	2	3	5	2	37,3
56	Inspect and calibrate the injectors	1,4	2,4	4,2	2,0	1,2	2,8	3,0	5,2	19,0	2	3	5	2	36,0
57	Inspect and calibrate the injectors	0,9	2,2	4,0	1,8	2,0	3,0	2,6	5,2	17,2	2	3	5	2	32,6
58	Inspect and calibrate the injectors	1,6	2,0	3,8	1,6	2,2	2,8	2,4	10,4	15,3	2	3	5	2	29,0
59	Cooling freshwater change and treatment	1,4	2,2	3,0	1,8	1,6	2,2	2,6	5,2	11,6	2	3	5	2	21,9
60	Cooling freshwater change and treatment	1,6	1,8	3,6	2,2	1,2	2,8	2,6	5,2	15,3	2	3	5	2	28,9
61	Checking the engine mounts	1,6	1,8	3,4	2,2	3,0	3,6	2,0	5,2	17,6	2	3	5	2	33,4
62	Checking the engine mounts	1,2	1,8	4,0	1,3	3,2	3,4	2,0	5,2	15,7	2	3	5	2	29,8
63	Checking the engine mounts	1,8	2,0	3,0	2,2	2,4	2,6	1,6	5,2	9,6	2	3	5	2	18,2
64	Checking the engine mounts	1,0	2,2	3,2	1,8	3,0	3,2	2,2	5,2	15,9	2	3	5	2	30,2
65	Checking the engine mounts	2,6	2,2	3,5	2,6	3,0	3,4	2,0	5,2	19,2	2	3	5	2	36,4
66	Checking the engine mounts	1,0	2,0	4,0	2,4	2,6	3,2	2,4	5,2	18,6	2	3	5	2	35,3
67	Decarbonization	1,2	1,4	3,0	2,6	2,6	2,8	2,0	5,2	12,4	2	3	5	2	23,4
68	Decarbonization	1,0	2,4	3,8	2,0	2,4	2,8	2,2	5,2	14,4	2	3	5	2	27,3
69	Decarbonization	1,4	2,6	3,6	1,2	2,6	3,0	2,2	10,4	15,2	2	3	5	2	28,7
70	Decarbonization	1,4	1,6	3,8	2,2	2,0	3,0	2,4	5,2	15,9	2	3	5	2	30,2
71	General Overhaul	1,6	2,8	3,8	2,0	1,6	2,8	2,0	5,2	13,3	2	3	5	2	25,2
72	General Overhaul	2,0	1,8	3,2	1,6	2,2	3,0	2,0	5,2	13,1	2	3	5	2	24,8
73	General Overhaul	1,8	2,0	2,8	2,0	2,4	2,6	3,0	15,6	17,3	2	3	5	2	32,7
74	General Overhaul	0,9	2,4	3,8	1,8	2,4	3,0	1,6	5,6	10,8	2	3	5	2	20,6
75	General Overhaul	1,4	3,0	2,4	1,6	2,6	3,8	3,4	8,0	28,6	2	3	5	2	54,2
76	General Overhaul	1,0	1,2	3,2	2,2	2,2	2,6	2,6	5,2	13,4	2	3	5	2	25,4
77	General Overhaul	1,4	2,2	3,8	2,2	2,4	3,8	2,6	5,2	23,9	2	3	5	2	45,3

Table 72 - FMECA-H-CM MD with anomaly simulation 2

Nr Act	Maintenance Activity	SS	SE	Seq	SP	SO	O	D	FMECA	FMECA-H	CMV	CMP	CMTex	TS	FMECA-H-CM
1	Navigating, check the color of the evacuation gases, condensation, obstructions, etc.	2,0	4,0	3,8	1,8	1,6	3,0	4,2	28,0	33,4	3	5	5	5	102,8
2	Navigating, check the color of the evacuation gases, condensation, obstructions, etc.	1,8	3,6	3,8	1,4	1,8	2,8	4,4	17,0	30,7	3	5	5	5	94,4
3	Navigating, check the color of the evacuation gases, condensation, obstructions, etc.	2,0	4,0	3,0	2,0	1,8	2,8	4,0	19,0	28,8	3	5	5	5	88,6
4	Navigating, check the color of the evacuation gases, condensation, obstructions, etc.	2,6	4,2	3,0	1,4	2,2	2,8	4,4	17,0	33,2	3	5	5	5	102,0
5	Inspect supercharging system, perform overspeed test	1,8	2,8	3,4	1,8	2,8	3,2	3,2	12,8	26,0	3	5	5	5	80,0
6	Inspect supercharging system, perform overspeed test	1,2	1,6	3,0	1,1	1,8	3,2	3,0	16,8	16,7	3	5	5	5	51,5
7	Inspect supercharging system, perform overspeed test	0,8	2,2	2,6	1,2	2,2	3,4	3,0	8,8	18,6	3	5	5	5	57,1
8	Inspect supercharging system, perform overspeed test	2,0	1,6	3,4	0,9	1,8	3,4	2,8	16,8	18,6	3	5	5	5	57,2
9	Inspect supercharging system, perform overspeed test	1,2	2,2	3,2	0,9	2,0	3,0	3,8	6,0	21,7	3	5	5	5	66,8
10	Check the sequential system of the supercharging groups	2,0	2,8	2,0	1,2	2,2	2,8	2,4	12,0	13,9	3	5	5	5	42,7
11	Check the sequential system of the supercharging groups	1,8	2,6	2,2	1,5	1,6	2,4	3,4	22,4	15,9	3	5	5	5	48,8
12	Check the sequential system of the supercharging groups	1,0	3,6	2,6	1,0	1,6	1,8	4,0	22,4	14,4	3	5	5	5	44,2
13	Oil sample collection and analysis	1,8	2,6	4,2	0,7	2,4	3,0	3,4	15,6	23,9	3	5	5	5	73,7
14	Oil sample collection and analysis	2,6	2,8	3,4	2,8	2,4	2,8	3,6	20,8	28,5	3	5	5	5	87,8
15	Oil sample collection and analysis	1,8	2,6	3,2	1,7	1,8	3,2	3,8	14,4	27,0	3	5	5	5	83,2
16	Oil sample collection and analysis	1,6	1,8	4,0	1,3	1,8	2,2	2,6	18,0	12,2	3	5	5	5	37,4
17	Change lubrication oil	1,4	2,4	3,8	0,7	2,2	3,4	2,8	11,2	20,0	3	5	5	5	61,6
18	Change lubrication oil	1,6	2,2	4,0	1,8	2,0	2,6	3,0	8,0	18,2	3	5	5	5	56,0
19	Change lubrication oil	2,0	2,2	4,2	1,2	1,8	2,4	3,4	10,4	18,9	3	5	5	5	58,2
20	Change lubrication oil	0,9	2,0	3,4	1,3	1,2	3,0	2,6	8,9	13,7	3	5	5	5	42,1
21	Change oil filters	1,4	1,2	3,2	1,6	2,2	2,8	3,4	10,5	18,5	3	5	5	5	57,0
22	Change oil filters	1,2	1,4	2,6	1,6	2,2	2,8	1,8	7,2	9,2	3	5	5	5	28,3
23	Change oil filters	1,2	1,6	3,2	2,2	1,8	2,6	1,6	10,4	8,5	3	5	5	5	26,1
24	Change oil filters	1,4	1,2	3,8	1,6	2,2	3,4	1,6	9,6	11,4	3	5	5	5	35,0

25	Check/Adjust valves	1,8	3,2	3,4	2,0	2,2	3,0	1,8	10,4	13,8	3	5	5	5	42,5
26	Check/Adjust valves	2,2	1,6	3,2	1,6	3,2	3,0	1,8	4,4	12,8	3	5	5	5	39,5
27	Check/Adjust valves	1,2	2,8	4,0	1,8	3,2	2,2	3,0	12,8	17,2	3	5	5	5	52,9
28	Check exhaust gas system	1,6	2,8	4,0	3,0	3,0	3,0	2,4	18,0	20,8	3	5	5	5	63,9
29	Check exhaust gas system	1,8	1,6	2,8	1,4	2,2	3,0	2,6	18,0	15,4	3	5	5	5	47,5
30	Check exhaust gas system	2,0	2,0	2,2	2,0	3,2	2,4	2,4	12,0	13,4	3	5	5	5	41,2
31	Check exhaust gas system	0,9	1,8	3,2	2,0	3,0	3,2	2,8	24,0	19,5	3	5	5	5	60,0
32	Change fuel filters	1,6	1,2	3,0	1,8	2,2	2,4	2,2	12,0	10,5	3	5	5	5	32,2
33	Change fuel filters	1,6	2,0	3,6	1,2	1,6	3,0	2,4	12,0	14,5	3	5	5	5	44,6
34	Change fuel filters	1,6	2,2	2,4	1,8	2,2	2,2	1,8	5,2	8,2	3	5	5	5	25,3
35	Change fuel filters	1,4	2,4	2,8	1,1	2,4	3,4	3,0	5,2	20,6	3	5	5	5	63,4
36	Cleaning Sea Filters	1,6	2,0	2,4	2,0	2,6	3,2	3,2	11,2	22,0	3	5	5	5	67,5
37	Cleaning Sea Filters	2,2	2,4	3,0	2,4	3,2	2,6	3,0	4,8	20,9	3	5	5	5	64,2
38	Lubrication of lubricating grease point	1,6	2,0	3,0	1,8	2,2	2,4	3,4	9,7	17,6	3	5	5	5	54,3
39	Lubrication of lubricating grease point	1,2	1,6	3,2	2,4	2,0	3,0	2,4	4,8	15,1	3	5	5	5	46,5
40	Lubrication of lubricating grease point	1,6	2,0	2,4	0,9	2,2	2,6	2,2	10,4	10,6	3	5	5	5	32,5
41	Check operation of the expansion tank level valve	2,2	2,2	3,6	1,8	1,6	3,2	3,6	8,8	26,4	3	5	5	5	81,4
42	Check operation of the expansion tank level valve	1,4	2,2	3,6	1,4	2,0	3,4	3,4	5,2	24,7	3	5	5	5	76,1
43	Check operation of the expansion tank level valve	1,4	2,0	3,6	0,9	1,4	2,6	3,6	14,4	17,4	3	5	5	5	53,5
44	Check coupling state	1,6	2,2	3,4	1,2	1,4	3,0	2,6	10,4	15,6	3	5	5	5	47,9
45	Check coupling state	1,6	1,4	3,8	1,7	1,4	3,2	3,6	5,2	22,9	3	5	5	5	70,4
46	Verify distribution components. Send feedback, side panels, history saved.	0,9	2,4	2,6	0,9	2,4	3,2	3,6	8,8	21,1	3	5	5	5	64,9
47	Verify distribution components. Send feedback, side panels, history saved.	1,6	3,2	3,2	1,5	2,0	2,8	2,8	4,8	18,0	3	5	5	5	55,5
48	Verify distribution components. Send feedback, side panels, history saved.	1,1	2,8	3,8	1,1	2,0	3,4	2,4	5,2	17,5	3	5	5	5	53,8
49	Checking the charge air system (or at 1500 hours)	2,0	2,0	2,4	0,9	2,0	3,6	2,4	8,8	16,1	3	5	5	5	49,5
50	Checking the charge air system (or at 1500 hours)	1,4	2,6	2,6	0,9	2,2	2,6	2,0	5,6	10,1	3	5	5	5	31,2
51	Checking the charge air system (or at 1500 hours)	1,2	2,0	3,6	2,0	2,4	2,6	3,4	13,2	20,0	3	5	5	5	61,4
52	Inspect and calibrate the injectors	1,6	2,2	3,8	1,8	2,0	3,0	2,6	5,2	17,9	3	5	5	5	55,2

53	Inspect and calibrate the injectors	2,0	2,0	3,4	1,4	2,0	2,8	2,8	10,4	17,1	3	5	5	5	52,6
54	Inspect and calibrate the injectors	1,0	2,4	3,2	1,4	1,4	2,2	2,8	10,4	11,7	3	5	5	5	36,0
55	Inspect and calibrate the injectors	1,4	2,2	3,8	1,4	1,6	2,6	3,6	5,2	19,7	3	5	5	5	60,5
56	Inspect and calibrate the injectors	1,4	2,4	4,2	2,0	1,2	2,8	3,0	5,2	19,0	3	5	5	5	58,3
57	Inspect and calibrate the injectors	0,9	2,2	4,0	1,8	2,0	3,0	2,6	5,2	17,2	3	5	5	5	52,8
58	Inspect and calibrate the injectors	1,6	2,0	3,8	1,6	2,2	2,8	2,4	10,4	15,3	3	5	5	5	47,0
59	Cooling freshwater change and treatment	1,4	2,2	3,0	1,8	1,6	2,2	2,6	5,2	11,6	3	5	5	5	35,5
60	Cooling freshwater change and treatment	1,6	1,8	3,6	2,2	1,2	2,8	2,6	5,2	15,3	3	5	5	5	46,9
61	Checking the engine mounts	1,6	1,8	3,4	2,2	3,0	3,6	2,0	5,2	17,6	3	5	5	5	54,1
62	Checking the engine mounts	1,2	1,8	4,0	1,3	3,2	3,4	2,0	5,2	15,7	3	5	5	5	48,3
63	Checking the engine mounts	1,8	2,0	3,0	2,2	2,4	2,6	1,6	5,2	9,6	3	5	5	5	29,5
64	Checking the engine mounts	1,0	2,2	3,2	1,8	3,0	3,2	2,2	5,2	15,9	3	5	5	5	48,9
65	Checking the engine mounts	2,6	2,2	3,5	2,6	3,0	3,4	2,0	5,2	19,2	3	5	5	5	59,0
66	Checking the engine mounts	1,0	2,0	4,0	2,4	2,6	3,2	2,4	5,2	18,6	3	5	5	5	57,2
67	Decarbonization	1,2	1,4	3,0	2,6	2,6	2,8	2,0	5,2	12,4	3	5	5	5	38,0
68	Decarbonization	1,0	2,4	3,8	2,0	2,4	2,8	2,2	5,2	14,4	3	5	5	5	44,3
69	Decarbonization	1,4	2,6	3,6	1,2	2,6	3,0	2,2	10,4	15,2	3	5	5	5	46,6
70	Decarbonization	1,4	1,6	3,8	2,2	2,0	3,0	2,4	5,2	15,9	3	5	5	5	48,9
71	General Overhaul	1,6	2,8	3,8	2,0	1,6	2,8	2,0	5,2	13,3	3	5	5	5	40,9
72	General Overhaul	2,0	1,8	3,2	1,6	2,2	3,0	2,0	5,2	13,1	3	5	5	5	40,2
73	General Overhaul	1,8	2,0	2,8	2,0	2,4	2,6	3,0	15,6	17,3	3	5	5	5	53,1
74	General Overhaul	0,9	2,4	3,8	1,8	2,4	3,0	1,6	5,6	10,8	3	5	5	5	33,4
75	General Overhaul	1,4	3,0	2,4	1,6	2,6	3,8	3,4	8,0	28,6	3	5	5	5	87,9
76	General Overhaul	1,0	1,2	3,2	2,2	2,2	2,6	2,6	5,2	13,4	3	5	5	5	41,2
77	General Overhaul	1,4	2,2	3,8	2,2	2,4	3,8	2,6	5,2	23,9	3	5	5	5	73,4

Table 73 - FMECA-H-CM sea water filters

Act Nr	Maintenance Activity	SS	SE	Seq	SP	SO	O	D	FMECA	FMECA-H	CMP	CMTex	TS	FMECA-H-CM
1	Cleaning seawater suction filters	2,0	2,6	3,4	1,8	2,6	3,4	2,8	4,4	23,7	1	1	2	16,4
2	Cleaning seawater suction filters	1,2	2,8	3,6	1,4	2,8	3,4	2,8	4,4	22,6	1	1	2	15,7
3	Cleaning seawater suction filters	1,6	2,4	3,6	1,6	2,0	3,2	3,2	4,8	23,1	1	1	2	16,0
4	Cleaning seawater suction filters	2,0	1,6	2,8	1,2	1,8	2,2	3,0	4,0	12,7	1	1	2	8,8
5	Cleaning seawater suction filters	2,2	2,0	3,6	1,6	2,6	2,8	2,0	4,8	13,5	1	1	2	9,4
6	Cleaning seawater suction filters	1,4	1,8	2,8	2,0	2,0	2,2	2,2	4,8	9,8	1	1	2	6,8

Table 74 - FMECA-H-CM air filters

Act Nr	Maintenance Activity	SS	SE	Seq	SP	SO	O	D	FMECA	FMECA-H	CMP	CMTex	TS	FMECA-H-CM
1	Washing the intake air filter panels	2,4	2,2	3,2	1,8	1,6	1,8	2,0	5,2	8,2	1	1	2	5,7
2	Washing the intake air filter panels	1,5	1,4	3,6	2,6	1,8	2,8	1,8	5,2	11,0	1	1	2	7,6
3	Washing the intake air filter panels	1,2	1,4	4,4	2,4	1,6	2,4	2,2	5,2	11,9	1	1	2	8,3
4	Washing the intake air filter panels	1,6	1,4	3,6	1,4	1,8	2,4	2,2	5,2	10,5	1	1	2	7,2

Table 75 - FMECA-H-CM low pressure air compressor

Act Nr	Maintenance Activity	SS	SE	Seq	SP	SO	O	D	FMECA	FMECA-H	CMTex	TS	FMECA-H-CM
1	Clean air filter - Perform every 1000 hours of operation	1,9	2,2	3,4	2,8	3,0	4,2	3,2	120,0	35,9	3	2	64,2
2	Clean air filter - Perform every 1000 hours of operation	2,6	2,2	2,8	2,6	3,0	3,0	2,6	125,0	20,9	3	2	37,4
3	Clean air filter - Perform every 1000 hours of operation	2,0	2,1	3,8	3,0	3,2	3,4	3,2	125,0	30,7	3	2	55,1
4	Clean air filter - Perform every 1000 hours of operation	2,4	2,0	3,0	3,4	3,2	4,2	3,6	125,0	42,6	3	2	76,3
5	Clean air filter - Perform every 1000 hours of operation	2,0	3,0	4,0	2,0	3,4	3,2	3,2	110,0	29,9	3	2	53,5
6	Cleaning the filters of 40/6 bar reducing stations	1,8	3,0	3,0	2,6	3,2	2,0	2,0	100,0	11,2	3	2	20,0
7	Cleaning the filters of 40/6 bar reducing stations	1,3	1,7	3,6	2,8	3,2	3,4	3,4	125,0	29,0	3	2	52,0
8	Cleaning the filters of 40/6 bar reducing stations	1,3	2,2	2,8	2,6	1,8	2,4	3,2	125,0	16,6	3	2	29,7
9	Cleaning the filter between the compressor and the charging reservoir	3,0	2,6	3,8	2,6	2,0	3,2	2,8	110,0	25,4	3	2	45,6

10	Cleaning the filter between the compressor and the charging reservoir	1,8	2,4	3,0	2,6	1,6	2,8	3,4	110,0	22,1	3	2	39,7
11	Cleaning the filter between the compressor and the charging reservoir	1,8	2,2	3,6	1,3	2,2	3,2	4,4	75,0	31,3	3	2	56,1
12	Check the charging time of the 63lt/40 bar reservoir	1,7	3,2	4,0	3,0	4,0	4,2	3,0	125,0	40,3	3	2	72,3
13	Oil change	2,0	2,4	4,0	1,5	1,6	3,4	3,6	85,5	28,5	3	2	51,0
14	Oil change	2,4	2,6	3,4	2,8	1,8	2,8	4,2	125,0	30,9	3	2	55,3
15	Oil change	2,4	3,6	3,0	2,6	2,6	2,8	3,4	110,0	27,4	3	2	49,1
16	Oil change	1,8	1,5	2,6	2,2	3,4	3,0	3,6	125,0	25,0	3	2	44,7

Table 76 - FMECA-H-CM marine gasoil purifier

Act Nr	Maintenance Activity	SS	SE	Seq	SP	SO	O	D	FMECA	FMECA-H	CMTex	TS	FMECA-H-CM
1	Check oil level.	2,2	2,8	2,8	1,6	3,4	4,0	3,6	120,0	37,2	2	2	51,5
2	Check oil level.	1,1	3,4	3,4	0,6	2,0	3,0	4,2	26,4	26,6	2	2	36,9
3	Check oil level.	1,7	2,0	3,8	2,0	2,0	3,4	3,8	18,0	29,8	2	2	41,3
4	Check the automatic program	1,7	1,5	3,6	2,4	2,8	3,8	3,4	120,0	30,9	2	2	42,8
5	Check the automatic program	1,8	2,8	3,2	1,8	3,0	2,8	3,4	28,8	24,1	2	2	33,5
6	Clean and putty the dome locking ring	1,6	2,4	3,4	1,6	1,6	2,8	2,0	30,6	12,0	2	2	16,7
7	Clean and putty the dome locking ring	2,2	2,0	3,6	2,0	2,0	2,4	2,0	16,8	11,4	2	2	15,8
8	Check flow detector adjustment; check pressure switch operation and adjustment	1,5	3,0	2,8	1,2	2,2	3,8	2,4	20,8	19,7	2	2	27,3
9	Every six months or every 750 hours, change the oil and clean the crankcase	1,4	0,9	2,4	1,4	3,0	4,0	3,4	14,4	24,9	2	2	34,5
10	Every six months or every 750 hours, change the oil and clean the crankcase	2,8	3,6	4,4	2,2	2,6	3,2	3,4	125,0	34,4	2	2	47,6
11	Dismantle the dome, clean and inspect all components; lubricate, assemble and test	2,2	3,2	2,8	1,2	2,4	4,0	3,6	120,0	34,4	2	2	47,7
12	Dismantle the dome, clean and inspect all components; lubricate, assemble and test	1,2	3,2	3,2	2,0	1,4	2,2	3,2	26,4	15,7	2	2	21,7
13	Clean dirty oil filter	1,8	2,4	3,0	1,6	1,6	2,4	3,0	18,0	15,2	2	2	21,1
14	Clean dirty oil filter	1,6	1,1	3,2	2,8	3,2	3,8	4,4	120,0	39,9	2	2	55,3
15	Check clutch and brake condition	1,5	2,2	3,4	1,6	2,8	2,4	3,2	28,8	17,8	2	2	24,7
16	Check clutch and brake condition	1,4	2,0	4,0	2,6	2,8	3,8	2,8	30,6	27,5	2	2	38,1

17	Remove the dome; inspect the rubber/metal bushing; check the starting time	1,8	1,4	2,4	2,4	1,8	2,8	2,8	16,8	15,7	2	2	21,7
18	Remove the dome; inspect the rubber/metal bushing; check the starting time	2,4	2,8	2,8	3,2	3,0	3,0	1,8	20,8	15,5	2	2	21,5
19	Check fastening screws for tightness, check condition of supports and vibration damperste	2,0	3,0	3,2	2,4	3,2	3,2	2,4	14,4	21,4	2	2	29,7
20	Check fastening screws for tightness, check condition of supports and vibration damperste	2,2	2,8	4,4	2,0	3,0	3,4	3,6	100,0	35,4	2	2	49,1
21	Check fastening screws for tightness, check condition of supports and vibration damperste	2,4	3,0	3,6	3,0	3,6	3,0	3,2	120,0	30,0	2	2	41,6
22	Check fastening screws for tightness, check condition of supports and vibration damperste	1,2	1,6	2,2	1,8	2,8	2,0	2,6	26,4	10,2	2	2	14,2
23	Check fastening screws for tightness, check condition of supports and vibration damperste	1,6	1,8	2,6	2,8	2,4	2,2	2,4	18,0	11,9	2	2	16,5
24	Check fastening screws for tightness, check condition of supports and vibration damperste	1,1	2,8	3,8	2,6	3,0	2,8	2,2	120,0	16,5	2	2	22,9
25	Clean hot water system filter and water pressure reducer	1,6	2,0	2,6	2,2	3,2	2,8	3,6	28,8	23,5	2	2	32,6
26	Clean hot water system filter and water pressure reducer	1,8	3,4	3,6	2,4	1,4	3,0	2,6	30,6	20,0	2	2	27,7
27	Clean hot water system filter and water pressure reducer	1,6	2,0	2,2	1,2	2,0	3,6	3,0	16,8	19,8	2	2	27,4
28	Clean hot water system filter and water pressure reducer	1,4	2,0	3,0	0,7	2,0	2,8	3,0	20,8	15,5	2	2	21,5
29	Inspect air and water solenoid valve. Inspect 3-way diaphragm valve operation	1,4	2,2	2,6	2,2	1,8	2,0	3,4	14,4	14,1	2	2	19,6

Table 77 - FMECA-H-CM oil purifier

Act Nr	Maintenance Activity	SS	SE	Seq	SP	SO	O	D	FMECA	FMECA-H	CMTex	TS	FMECA-H-CM
1	Check oil level	1,6	2,6	3,0	2,0	2,0	2,8	3,2	34,0	20,3	1	2	14,1
2	Check oil level	1,6	1,8	3,2	2,2	2,8	2,8	2,6	13,2	17,1	1	2	11,9
3	Check oil level	2,8	3,0	4,2	2,8	3,2	2,6	3,0	30,4	25,0	1	2	17,3
4	Check the automatic program	2,4	2,4	3,6	1,8	2,4	3,2	2,8	72,0	22,8	1	2	15,8
5	Check the automatic program	1,8	2,8	3,6	2,6	4,0	2,6	3,0	25,2	23,2	1	2	16,1
6	Clean and putty the dome locking ring	2,2	1,8	3,0	3,0	2,2	1,8	2,2	6,6	9,8	1	2	6,8
7	Clean and putty the dome locking ring	1,4	1,4	2,8	3,2	2,2	3,0	3,2	40,8	21,3	1	2	14,8
8	Check flow detector adjustment; check pressure switch operation and adjustment	1,2	2,8	4,0	2,8	2,2	2,2	2,6	22,4	15,1	1	2	10,4
9	Oil change and crankcase cleaning	1,8	2,0	3,2	1,3	2,0	2,0	1,6	19,2	6,7	1	2	4,7
10	Oil change and crankcase cleaning	1,0	2,6	2,6	2,6	2,0	3,4	3,0	48,0	22,6	1	2	15,6

11	Disassemble the dome, clean and inspect all components; lubricate, assemble and test	2,4	4,0	3,0	1,6	2,2	3,6	3,4	60,0	32,6	1	2	22,6
12	Disassemble the dome, clean and inspect all components; lubricate, assemble and test	1,5	2,0	3,8	2,2	3,0	3,6	3,6	72,0	32,5	1	2	22,5
13	Clean dirty oil filter	0,9	2,4	2,8	2,4	2,2	3,4	2,6	33,3	19,1	1	2	13,3
14	Clean dirty oil filter	2,0	1,4	2,6	2,4	3,6	3,2	2,6	23,4	20,1	1	2	14,0
15	Check clutch and brake condition	1,8	2,0	3,4	2,6	2,4	3,6	2,6	39,0	23,1	1	2	16,0
16	Check clutch and brake condition	2,0	1,6	3,2	1,8	4,2	3,6	1,8	21,6	16,9	1	2	11,7
17	Remove the dome; inspect the rubber/metal bushing; check the starting time.	2,4	3,0	2,8	2,6	3,6	2,6	3,6	7,2	27,3	1	2	18,9
18	Remove the dome; inspect the rubber/metal bushing; check the starting time.	1,6	2,2	2,8	2,6	2,6	3,2	4,6	33,6	35,0	1	2	24,2
19	Check the tightness of the fixing screws, check the condition of the supports and vibration dampers.	2,2	2,2	3,2	2,2	2,2	3,6	2,6	18,0	22,8	1	2	15,8
20	Check the tightness of the fixing screws, check the condition of the supports and vibration dampers.	1,8	2,8	3,2	2,4	1,2	3,2	3,6	10,4	26,8	1	2	18,5
21	Check the tightness of the fixing screws, check the condition of the supports and vibration dampers.	2,2	4,0	4,0	1,8	2,0	2,2	3,2	25,2	20,0	1	2	13,9
22	Check the tightness of the fixing screws, check the condition of the supports and vibration dampers.	1,8	3,4	3,0	3,0	2,2	3,4	3,8	76,0	35,1	1	2	24,4
23	Check the tightness of the fixing screws, check the condition of the supports and vibration dampers.	2,0	1,8	3,2	2,0	2,2	3,8	3,6	55,2	31,0	1	2	21,5
24	Check the tightness of the fixing screws, check the condition of the supports and vibration dampers.	1,6	2,6	3,2	2,2	2,8	3,6	3,4	40,0	30,6	1	2	21,2
25	Clean hot water system filter and water pressure reducer	0,8	2,6	2,6	2,8	1,6	2,8	3,0	85,0	17,6	1	2	12,2
26	Clean hot water system filter and water pressure reducer	1,5	2,0	3,2	2,2	3,6	3,2	3,2	60,0	25,8	1	2	17,9
27	Clean hot water system filter and water pressure reducer	1,8	1,7	2,6	1,7	1,8	2,0	3,8	80,0	14,9	1	2	10,3
28	Inspect air and water solenoid valve. Inspect 3-way diaphragm valve operation.	1,2	2,2	3,0	3,0	3,2	3,0	3,6	51,0	27,4	1	2	19,0
29	Inspect air and water solenoid valve. Inspect 3-way diaphragm valve operation.	1,6	2,8	3,6	2,8	3,2	2,6	3,0	51,0	22,0	1	2	15,2