

Dynamic Maintenance Based on Fuzzy Logic

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Abstract: - Currently, certain maritime assets are confronted with the challenge of optimizing their performance, even when resources are limited. They strive to minimize intervention actions on equipment while upholding safety standards and acceptable performance levels. Ships, which are not yet autonomous, serve as maritime assets responsible for transporting personnel and systems. Maintaining these ships with high performance is imperative to ensuring the safety of both material and personnel. This not only prevents damage to the ships themselves but also mitigates the potential for personnel injuries and sea pollution. Organizations, scientific community, and stakeholders have been actively developing advanced systems to monitor data from ship equipment within the scope of maintenance management. This helps in preventing breakdowns and ensures real-time knowledge about the equipment's condition. These systems employ various techniques for condition control using algorithms, statistical equations, and other methodologies on the collected data. In this investigation Fuzzy Logic will be applied to data from a selected equipment. For the case study, an air compressor from an ocean patrol vessel has been selected. This air compressor plays a crucial role on Navy ships and has been chosen by the Organization's Maintenance Management Centre for monitoring working hours and operational status.

Key-Words: - Fuzzy logic; maintenance management; decision process; air compressor.

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1 Introduction

The significance of maintenance to support production activity stem from its extensive contributions to the operability and enhancement of physical assets. In this context, the concept of maintenance management has been meticulously developed and defined by IPQ (NP, 2007) as follows: 'Maintenance management encompasses all managerial activities that delineate objectives, strategies, and responsibilities pertaining to maintenance and subsequently implement them through various means such as planning, monitoring, and supervising maintenance operations while also improving organizational methods, including economic considerations. Maintenance planning, in turn, encompasses all activities associated with the formulation of a systematically scheduled work program aimed at ensuring the

seamless operation of equipment and averting potentially severe issues." (Dhillon, 2002). Conversely, maintenance control and supervision encompass the diverse facets that require vigilant monitoring to ensure the proper execution of maintenance management." (Manzini et al., 2010). Morvay & Gvozdenac (2008), the concept posits that any management system comprises an organizational structure grounded in three fundamental aspects: procedures, personnel, and technology. These elements are harnessed to oversee and optimize resource utilization while ensuring the realization of the company's objectives. In pursuit of this goal, maintenance planning and execution processes are bolstered by an information system. This system facilitates the management of worklists and inventory, standard procedures and technical specifications, scheduling and resource allocation,

transmission of intervention requests, monitoring, parts management, spare parts inventory, reporting, and cost control. In this context, technology plays a crucial role, not only as a necessity for an information system seamlessly integrated with all relevant company assets but also as a valuable tool for operators to ensure more reliable interventions (Silvestri et al., 2020).

However, effective management is rarely straightforward, and the maintenance of maritime assets presents inherent complexities due to uncertainties and constraints, such as climatic conditions (Abbas & Shafiee, 2020). When objectives encompass reducing accidents, cultivating a versatile and adaptable organizational structure, enhancing production efficiency, and creating a more accessible and user-friendly system for all stakeholders, it can be asserted that the fundamental objectives of maintenance management namely, maximizing profit and conferring competitive advantage to the organization are also being realized. This multifaceted array of considerations has prompted the pursuit and implementation of an adequate model to evolve from a nebulous concept into a recurrent research focus and an indispensable question in the quest for effectiveness and efficiency in maintenance management (Campos & Marquez, 2008).

Within the realm of maintenance management, and with the aim of minimizing unforeseen breakdowns, the Fuzzy Logic methodology was selected for the development of a decision support model specific to the maintenance of an air compressor (AComp) aboard a ship (Mestre, 2021).

2. Maintenance Management

2.1 Maintenance Support Systems

Many factors contribute for supporting systems, not only mathematical methodologies, or high evolute technology but also the maintenance operators' skills (Tortora, Pasquale, Franciosi, Miranda, & Iannone, 2021)(Tortora et al, 2021). The Systems Maintenance is a topic that has been increasing of interest for reasons of equipment operation performance, reducing costs, enhance companies' economic

performance and even environmental with the aim of reducing residues and pollution.

Applying a "constraint programming" methodology can be the answer for maintenance in companies with limit budgets, it can combine various information's and data and contribute for reducing costs and optimize the systems operationally (Liu, Utami, Budiwirawan, Arifin, & Perdana, 2023)(Liu et al, 2023).

Augmented Reality in maintenance may allow the usage of various collected data and relate the data to obtain an answer for decision support (Malta, Farinha, Farinha, & Mendes, 2023)(Malta et al, 2023).

Considering the need of reducing maintenance costs and enhance the systems availability, implementing "an element-grouping preventive strategy" concept, where "three maintenance methods" exists as effects directly in the reliability enhance in the systems elements. (Pei, Liu, Xu, Qi, & Cheng, 2022)(Pei et al, 2022).

The data collected from a machine may allow its reliability calculation, and characterizing its failure mode and effect, and implementing mathematical methods allows the results understanding and knowing its state, determining the intervention and when to do it (Florea, Ionică, Florea, Itu, & Stelea, 2022)(Florea, 2022).

For improving maintenance activities in complex systems if the equipment maintenance is made in lots, for example using rotatable equipment concept. Where if the maintenance is preventive, when the opportunity came, various equipment can be maintained, for that an optimization model may be applied with an "algorithm based on Non-Dominated Sorting Genetic Algorithms" (Zhou, Ye, Wang, Cao, & Gao, 2023)(Zhou et al, 2023).

Many approaches can be made to maintenance, Big Data approach, data mining approaches, algorithm approaches, empirical approaches, risk analysis approach, etc. The use or selection and adaptation of

some of these approaches may allow enhancing maintenance management and the act of maintenance itself.

2.2 Maintenance in the Organization

Given the organization necessities of optimizing material and persons, several years ago, Portuguese Navy had implemented Maintenance Management System (SGM - *Sistema de Gestão da Manutenção*). The SGM is divided in two subsystems: the Data Collection and Treatment System (SRTD - *Sistema de Recolha e Tratamento de Dados*) and the Planned Maintenance System (SMP – *Sistema de Manutenção Planeada*)

The SGM, which aims to ensure the availability of all assets and materials, as well as the definition of responsibilities, the introduction of procedures and the collection and effective use of information conceived during maintenance activities. For this to be possible, it is important that all the following parameters are considered simultaneously (Oliveira, 2020)(Oliveira, 2020):

- Obtaining acceptable degrees of material reliability;
- Obtaining high assets availability coefficients;
- Obtaining the lowest maintenance costs.

Regarding the maintenance of maritime assets be they war ships or any type of vessel, the SGM was adapted to its procedures and techniques so that the following objectives were fulfilled (Marques, 2020) (Marques, 2020):

- Definition of standardized criteria and procedures for maintenance;
- Ensuring the effective use of available resources;
- Documentation of maintenance information;

- Improvement of material maintainability and reliability through analysis and exploitation of available information;
- Identification and reduction of the respective maintenance costs.

In SRTD, more succinctly, maintenance planning should include the following aspects:

- Type of Maintenance;
- Equipment;
- Procedure;
- Period of time;
- Current condition of the equipment;
- Team or person who will carry out the work.

Through the analysis of these points, it is possible to state that maintenance planning is one of the most complex and important tasks for the proper functioning of assets and, consequently, of organizations, hence being one of the areas that has most deserved to be highlighted over time.

The SRTD is processed by the SICALN, this system feed an Integrated Logistic System (SLI - *Sistema Logístico Integrado*) from the organization.

To refer that 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/Naval Base local technical support workshop, which has the ships Operational Command). And the third stage, is under the responsibility of the Navy Maintenance Management Center (DN - *Direção de Navios*), that give technical advice and support, and also determines what work should be done, and if it will be carried out by the navy local shipyard or another company.

2.3 Maintenance Applications of Fuzzy Methodology

Fuzzy logic emerged to address the challenge of dealing with data that falls within the grey area between being entirely false and entirely true. This form of logic provides a framework for constructing decision-making systems that operate on inputs represented as linguistic variables (Ierace & Cavalieri, 2008). It is used to clear boundary between a set of information (Maletič et al., 2014).

In the realm of maintenance, Fuzzy Logic methodology finds applicability as it aligns with the view that many maintenance objectives are inherently intangible and contingent upon the experiential knowledge of the workers (Ierace & Cavalieri, 2008). However, it is important to note that, according to the same authors, this method may be perceived as somewhat subjective from a mathematical perspective. This subjectivity can pose challenges when attempting relative importance of each objective and the effectiveness of various maintenance policies in achieving it. Nevertheless, when this methodology is employed by a specialized team well-versed not only in fuzzy methodology but also in ship equipment and systems, it becomes a credible and viable approach."

Numerous applications of Fuzzy Systems have been explored in the literature. Khan et al. (2004) examined the utilization of an RBIM (Risk-Based Inspection Maintenance) system for risk management within the gas and oil industry. Meng Tay and Peng Lim (2006) applied Fuzzy FMEA (Failure Mode and Effects Analysis) to the realm of semiconductor manufacturing. Yang and Bai (2009) employed Fuzzy FMEA for assessing boiler tube risks. Additionally, Abdelgawad and Fayek (2010) incorporated Fuzzy AHP (Analytic Hierarchy Process) and the Fuzzy FMEA methodology in the

field of risk management within the construction industry.

3. Pure Fuzzy Logic Methodology

This methodology is indicated to deal with imprecise human thinking because it takes into account "experience and knowledge; it also provides a mathematical structure to model the uncertainty of human cognitive processes that can be controlled by a computer" (Moreno-Cabezali & Fernandez-Crehuet, 2020).

The process inherent to Fuzzy Logic can be described by the following 7 stage (Jaderi et al., 2019; Kumru & Kumru, 2013):

- Define variables and linguistic terms;
- Build the membership functions;
- Build the rule base;
- Convert crisp input data to fuzzy values (Fuzzification);
- Evaluate rules created against the rule base;
- Combine results considering the rules;
- Transform fuzzy output data to crisp values.

Fuzzification is a transformation of the text input data into numerical data based on Fuzzy methodology using its membership functions. It is at this phase that the degrees of belonging functions are determined. In addition, as it is a relevant phase in the process, the contribution of specialists in the phenomenon under investigation is imperative to modelled it, so it can be built on a justified and consolidated base (Silva, 2018).

Inference is the process aimed at enabling system action by evaluating the compatibility of input data with established rules. The number of output fuzzy sets must correspond to the number of established rules (Paixão, 2010). In the literature, various inference methods exist. For instance, the Mamdani

model and Larsen model utilize fuzzy propositions for both antecedent and consequent. In contrast, Tsukamoto's model differs as it employs a function of monotonic membership. Lastly, the Takagi-Sugeno model relies on a polynomial function (Ross, 2010).

Defuzzification is the stage where output values are computed based on the inference process and the membership functions of linguistic variables (Cox, 1994). The number of rules determines the number of outputs. For instance, if five rules are established, there will be five output values. However, there can only be one final response value, determined on a case-by-case basis to best represent the obtained region through the output values (Cox, 1994). Several defuzzification methods exist, including the Center of Gravity (COG), Center of Area (COA), and Average Maxima (MOM). Given its prevalence, this study opts for the COG (Cox, 1994).

The COG identifies the point where a vertical line bisects the fuzzy set, essentially finding the center of gravity of set A within an interval [A;B], the COG can be calculated for example in two ways, as described in equation X, which accurately reflects this concept (Kumru & Kumru, 2013).

$$COG = \frac{\int_a^b \mu_A(x)xdx}{\int_a^b \mu_A(x)dx} \quad (1)$$

By the second present form, in equation nr 3.4, o COG is calculated by a estimation obtained by a data sample (Jaderi et al., 2019).

$$COG = \frac{\sum_{x=a}^b \mu_A(x)x}{\sum_{x=a}^b \mu_A(x)} \quad (2)$$

One important aspect of using Fuzzy Logic is the fact that it is possible to convert common language, such

as words or phrases, into numerical data so that computer can process them. Normally, when referring to the temperature of the water, it is said if it is cold, warm, or hot, instead of saying that it is a certain degree of Celsius. Or when it is intended to allude to someone's age, it is recurrent to say that a certain individual is young, or is in middle age or is old (Silva, 2018)

According to Melo (2009), this phenomenon occurs primarily because humans typically communicate using words rather than numerical values. For instance, when discussing the linguistic variable "age," individuals often use terms like "young," "middle-aged," or "old." These linguistic terms can be effectively represented using fuzzy sets, which are defined by membership functions.

3.1 Fuzzy Sets

A fuzzy set A, belonging to a U universe, is defined by a membership function:

$$\mu_A(x) : U \rightarrow [0,1] \quad (3)$$

This membership function represents a fuzzy set through a set of ordered pairs given by:

$$A = \{(x, \mu_A(x)) \mid x \in U\} \quad (4)$$

For it only one correspondence may exist, a real number from the range [0,1], for each presented element x.

The nearest μ_A is from 1, the bigger is the probability of the x element belong to A set. This degree of belonging of the elements allows the occurrence transitions between true and false by (Silva, 2018). The transition is given by (Silva, 2018):

$$\mu_A(x) : x \rightarrow [0,1], \begin{cases} \mu_A(x) = 0 \\ 0 < \mu_A(x) < 1 \\ \mu_A(x) = 1 \end{cases} \quad (5)$$

The membership functions convert linguistic terms into numerical values, facilitating the generation of

output values during the fuzzification and defuzzification phases, respectively. These functions come in various types, including rectangular, triangular, trapezoidal, and others, with the latter two being the most used in the literature (Silva, 2018).

The equations for triangular and trapezoidal membership functions are as follows, respectively:

$$\mu_A = \begin{cases} 0, & \text{se } x < x_1 \\ \frac{x-x_1}{x_2-x_1}, & \text{se } x_1 < x \leq x_2 \\ \frac{x_3-x}{x_3-x_2}, & \text{se } x_2 < x \leq x_3 \\ 0, & \text{se } x > x_3 \end{cases} \quad (6)$$

$$\mu_A = \begin{cases} 0, & \text{se } x < x_1 \\ \frac{x-x_1}{x_2-x_1}, & \text{se } x_1 < x \leq x_2 \\ 1, & \text{se } x_2 < x \leq x_3 \\ \frac{x_3-x}{x_3-x_2}, & \text{se } x_3 < x \leq x_4 \\ 0, & \text{se } x > x_4 \end{cases} \quad (7)$$

In complex problems where this logic is applied (Díaz & González, 2023), for example in a customer service enhancement and for resolving urban problems (Habib & Shokoohi, 2009)

3.2 Advantages and Disadvantages of Fuzzy Logic in Maintenance

The advantages of logic over other types of logic are as follows (Zanette et al., 2006):

- Improves handling of untreated data;
- Easier process of specifying the rules of a system;
- Intuitive due to the use of words instead of numbers;
- Easier the resolution of complex problems;
- Provides faster development of system prototypes.

The following disadvantages can be presented (Sousa, 2014):

- Difficult to analyze aspects (ex.: optimization);
- Precision of the fuzzy system is limited by the specialist's experience and knowledge;
- System is influenced by all its variables (ex.: chosen method for fuzzification, number of rules, etc.).

4. Fuzzy Methodology Applied to an AComp Maintenance

4.1 Fuzzy-RBM methodology structure

In accordance with the objective of this investigation, of determining the level of risk and from this establish a maintenance plan, a relationship was established that allows determining this level of risk based on the interaction between two variables that are the frequency of failure and the consequence of the failure. This relationship is established from the equation 8.

$$FxC(OI + ESI + MC) = R \quad (8)$$

Where F is de Frequency, C de Consequence, OI the Operational Impact, ESI the Environment and Safety Impact and the maintenance Cost, and R the Risk.

Fuzzy methodology applied to an AComp risk - based maintenance philosophy will allow quantified in harmonization not only predicted maintenance for the AComp, or condition control like vibration measure, but also the human cognitive registering in the SRTD from the Navy. The equipment's condition states perceptions with criteria levels can be quantified using a quantifying system and algorithms.

In the present study, we centred the risk-based maintenance in the existent SMP for the Air Compressor.

The fuzzy logic methodology proposed is to assess the risk of failure of an air compressor in a Navy Patrol vessel. The methodology will support the decision for the type of maintenance that suits the equipment considering the risk evaluation. Therefore, the integration of this methodology in the context of risk-based maintenance is exposed.

To define this methodology was considered four sequential stages in the Fuzzy-RBM specifically. The four stages are:

1. Equipment definition;
2. Parametrization;
3. Risk level analysis;
4. Maintenance plan.

Corresponding to the four sequential stages the methodology was defined, where: the first step for the implementation of the Fuzzy logic methodology was the equipment selection, and the second step was the evaluation and study the existent data. If the data was not adequate more data were be acquired, when it was the data structure were defined, then more data and storage in the database are collected, the Fuzzy Logic was designed and variable for study and inference were selected. Proceeding there were the data and results comparison. Then for further and continuous work the continuous application and improvement of the methodology, alongside with the model validation Fig.1.

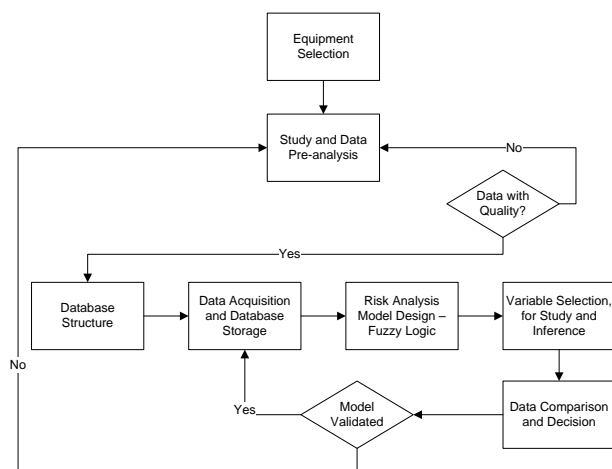


Fig. 1 - Fuzzy methodology for a ship equipment

To plan interventions, four stage in the Fuzzy-RBM, according to the results that were obtained in the case study, a Risk Matrix was considered for a Fuzzy-RBM methodology so that, it serves as an indicator for the type of maintenance to be chosen for compressors in accordance with the risk assessment.

4.1 Methodology Fuzzy-RBM Structure

To calculate the risk level, it was established an algorithm to calculate the risk using three variables which are the frequency, the failure consequence and the combined impact and maintenance costs, equation nr 9.

$$FxC(I * IES * MC) = R \quad (9)$$

Where F, (Frequency) represents the equipment failures number, C (Consequence), IO (Impact Operational), ESI (Environment and safety Impact), MC (Maintenance costs), and R (Risk) the global risk of equipment failure.

5. Air Compressor Case study - A Fuzzy Logic for risk-based maintenance

An equipment failure, not only because it is considered a risk factor for personal incidents, may represent losses for the responsible entities. In the case of Portuguese Navy ships, it may represent, for example, the impossibility of a ship carrying out a rescue mission at sea or putting the ship and the people on its crew at risk. It is always therefore important for those responsible for the equipment to know the state of the equipment, and for that to have decision support tools. Hence, the application of a decision support methodology based on the Fuzzy is of greater importance in naval environments.

The selected equipment for the present study was eight air compressors from four Oceanic Patrol Vessel from Portuguese Navy (Systems 1 to 8). These ships have two air compressors. In addition, these are these air compressors fall under the category of

selected equipment, signifying that their operating hours are meticulously tracked for the purpose of effective maintenance management. Furthermore, they are deemed essential components for ensuring the vessel's operational functionality. Because these are vital equipment's for the functioning and command and control of other selected equipment like the propulsion diesel engines or the diesel generators.

5.1 Air compressor maintenance plan

Air compressor general characteristics:

- Type: WP 81 L;
- Nr Cylinders: 3;
- Maximum speed: 1800 rpm;
- 3 Compression stages;
- Maximum pressure: 40 bar.

The previewed maintenance plan in this air compressor is (Marinha, 2010), figure 2:

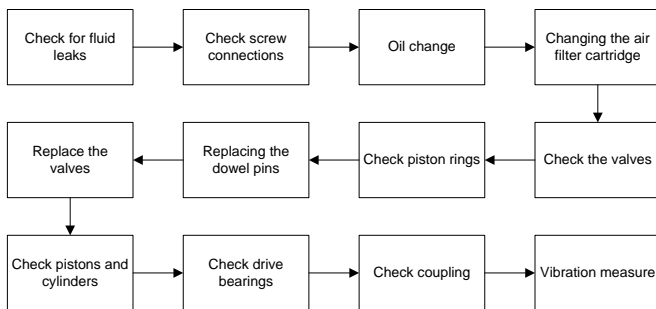


Fig. 2 – Air compressor base maintenance

(Adapted from Lampreia et al, 2022)

5.2 Air Compressor Fuzzy Logic Parameterization

Tables 1 to 8 illustrate the categorizations of failure frequency and the consequence.

Table 1 is the occurrence frequency which has a range from 0 to 4, and it is divided in four levels, the remote, less frequent, frequent and very frequent.

Table 1 – Classification for frequency of the occurrence

Failure frequency	Abbreviation	Description	Range (Failure per year)
Remote	Re	Less than 4 occurrences per year.	[0, 4]
Less frequent	Lf	5 to 8 occurrences per year.	[5, 8]
Frequent	Fr	9 to 14 occurrences per year.	[9, 13]
Very frequent	Vf	More than 15 occurrences per year	[14, 15]

The consequence includes and had integrate the categorization and valorization of the operational, the environment, the safety impact, and the maintenance costs consequence, table 2.

Table 2 – Classification of consequence factor (C)

Consequence	Abbreviation	Description	Range
Low	L	Consequence	[0, 4]
Moderate	Mo	considering the	[5, 8]
High	H	Operational	[9, 12]
Very high	Vh	impact,	[13, 16]
Extremely high	Eh	environmental and safety impact, and maintenance costs	[17, 20]

The Operational Impact has a range between 0 to 10 because it was considered that the operation mission and its accomplishment is normally one of the most important variables for evaluate the risk in a military ship.

Table 3 - Classification of consequence factor - Operational Impact

Operational Impact	Abbreviation	Description	Range
Low	L	Both air compressors are regularly maintained. No impact on ship's equipment and operations.	[0, 1]
Moderate	Mo	One air compressor exceeded operation hours for sealing elements.	[2, 3]
High	H	Two air compressors exceeded operation hours for sealing elements. Air compressor increased risk of anomaly.	[4, 5]
Very high	Vh	One air compressor is inoperational and the other has many functioning hours without maintenance. Possible unexpected anomaly, unavailable in case of the need for start diesel engines or generator groups	[6, 7]
Extremely high	Eh	Both air compressor on board fail. Mission commitment. Diesel engines and generating groups with start limitations.	[8, 10]

For the environment and safety, the range is from 0 to 5 considering 3 levels of impact in these matters.

Table 4 – Consequence factor classification –Environment and Safety Impact

Environmental and Safety Impact	Abbreviation	Description	Classification
Low	L	It causes some effects on the environment, however, there is no violation of associated laws.	[0, 1]
Moderate	M	Occurrence of some accidents and incidents	[2, 3]

		causing minor damage to surrounding equipment, to sailors and the environment.	
High	H	Occurrence of accidents and serious incidents for equipment, equipment, and the environment, such as air and lubrication oil leaks, risk of fire.	[4, 5]

And finally, the maintenance costs consequence the range are from 0 to 5, also considering 3 levels.

Table 5 – Classification of consequence factor – maintenance costs

Maintenance Costs	Description	Description	Classification
Low	L	Low maintenance costs	[0, 1]
Moderate	Mo	Medium maintenance costs	[2, 3]
High	H	High maintenance costs	[4, 5]

The product of Frequency and the consequence result on the risk calculation and levels. Considering the applied inference rules and the outcomes pertaining to the equipment's state based on the considered inferences.

Table 6 - Linguistic terms and range for variable risk (R)

Linguistic term (Risk level)	Abbreviation	Description	Classification
Not critical	Nc	Risk is totally controlled	[0, 39]
Less critical	Lc	Risk is controlled	[40, 87]
Semicritical	Sc	There is a little preoccupation about the equipment and system state	[88, 125]
Critical	C	There are some preoccupations	[126, 210]

		about the critic equipment/system situation	
Very critical	Vc	The equipment/system are in a very critical situation	[211, 300]

To build the inference rules it was considered the interval in frequency and consequence table, and it was considered the combination that in the end highlighted the representatives' values of the various risk levels.

Table 7 – Inference rule

Rule nr	Rule
1	If (F is Vf) and (C is Eh) then (R is Vc if Re[211, 300])
2	If (F is Vf) and (C is Vh) then (R is Vc if Re[211, 300])
3	If (F is Fr) and (C is Vh) then (R is C if Re[126, 210])
4	If (F is Lf) and (C is H) then (R is Sc if Re[88, 125])
5	If (F is Lf) and (C is Mo) then (R is Lc if Re[40, 87])
6	If (F is Re) and (C is Mo) then (R is Nc if Re[0, 39])
7	If (F is Re) and (C is L) then (R is Nc if Re[0, 39])
8	If (F is Vf) and (C is Vh) then (R is C if Re[126, 210])
9	If (F is Fr) and (C is H) then (R is Sc if Re[88, 125])
10	If (F is Lf) and (C is Vh) then (R is Lc if Re[40, 87])
11	If (F is Lf) and (C is Vh) then (R is H if Re[40, 87])
12	If (F is Lf) and (C is H) then (R is Lc if Re[40, 87])
13	If (F is Lf) and (C is H) then (R is Sc if Re[88, 125])
14	If (F is Fr) and (C is Mo) then (R is Lc if Re[40, 87])
15	If (F is Lf) and (C is Mo) then (R is Nc if Re[0, 39])

For the defined attributes and for the situations presented in table 7, it was calculated the risk level

for the next systems: SIS-1, SIS-2, SIS-3, SIS-4, SIS-5, SIS-6, SIS-7, and SIS-8, table 8.

Table 8 – Classic Risk and Fuzzy-RBM (Adapted from Mestre, 2021)

Nr - compressor number, ID Compressor - name specification, F - frequency, OI - operational impact, ESI - environment and safety impact, C – Consequence, R – Risk, Comp-compressor, class-classification, P - Priorization.

Nr	ID Comp	F	OI	ESI	MC	C	R	Fuzzy-RBM Class	P
1	SIS-1	15	10	5	5	20	300	Vc	1º
2	SIS-2	6	5	4	4	16	96	Sc	4º
3	SIS-3	9	6	4	4	14	126	C	3º
4	SIS-4	8	5	3	3	11	88	Sc	5º
5	SIS-5	5	4	4	2	10	50	Lc	6º
6	SIS-6	4	3	2	2	7	28	NC	7º
7	SIS-7	2	2	2	1	5	10	NC	8º
8	SIS-8	13	8	5	2	15	195	C	2º

The membership functions are used to convert frequency input values into linguistic terms and are used to convert linguistic terms into output numerical values, Fig.5.

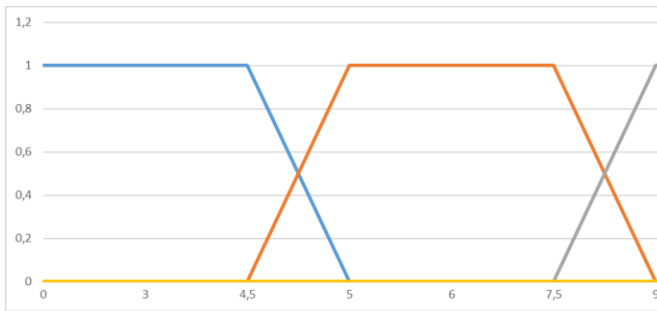


Figure 5: Membership function trapezoidal

5.3 Maintenance plan step

Then a maintenance risk matrix based on Jamshidi et al (2015) and Ratnayake & Antosz (2017) was developed to make a bridge between the Fuzzy-RBM system and the maintenance activities plan. This matrix must be intuitive and expeditiously to support decisions, for it was selected four maintenance types that can be applied on the selected equipment: systematic maintenance, RBM detailed, Corrective Maintenance and Condition Based Maintenance, Fig. 6.

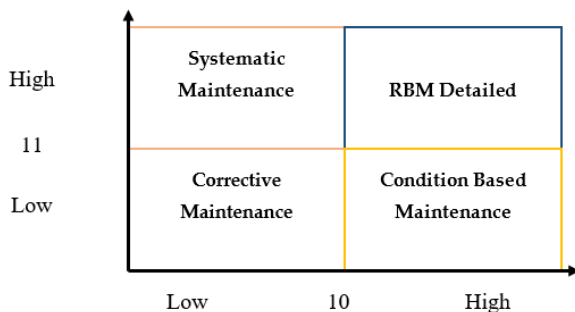


Figure 6: Risk matrix created for Fuzzy-RBM methodology.

In the first quadrant of Fig. 6, it may be found the systematic maintenance, because if any failure occurs the frequency is denominated as high, and the consequence is low.

To define the maintenance type, we considered risk and the operability of the ship:

- Systematic maintenance – Risk level 0 to 125: If operations allow corrective intervention;

- RBM Detailed – Risk level 211 to 300: If operations doesn't allow intervention;
- Corrective maintenance – Risk level 126 to 300: If operations allow corrective intervention;
- Condition based maintenance – Risk level 0 to 211: If operations doesn't allow intervention;

5.4 Air Compressor Fuzzy Logic - Results Analysis

During the application of Fuzzy Logic, it was observed that the obtained results were not highly critical. The case study focused on a ship's compressed air system, and the attribute levels forming the foundation of the methodology were defined. Based on the developed inference, the results were presented within a spectrum ranging from non-critical to critical.

To validate the methodology, it is essential to implement the developed system in practice, allowing for potential adjustments as needed. While the inference rules are generally well-defined, the absence of highly critical results suggests the necessity of closely monitoring equipment operation by applying the current rules and adjusting when required.

In the context of the trapezoidal membership function, there was no overlap in results, indicating that the model has been adequately calibrated.

With the result of risk level and the needed maintenance, it connected the different risk level to the needed task for the compressors.

Moreover, the general maintenance plan for the different systems, accordingly the results are, Tab. 9:

Tab. 9 – Intervention prioritization

Fuzzy-RBM Class	Priorization
Vc1	1º
Sc2	4º
C3	3º
Sc4	5º
Lc5	6º
NC6	7º
NC7	8º
C8	2º

Table 10 – Applied maintenance accordingly the risk analysis

ID	Maintenance Type
Compressor	
SIS-1	RBM Detailed or Corrective maintenance – depending on the operability
SIS-2	Systematic maintenance or Condition based maintenance – depending on the operability
SIS-3	RBM Detailed or Condition based maintenance – depending on the operability
SIS-4	Systematic maintenance or Condition based maintenance – depending on the operability
SIS-5	Systematic maintenance or Condition based maintenance – depending on the operability
SIS-6	Systematic maintenance or Condition based maintenance – depending on the operability
SIS-7	Systematic maintenance or Condition based maintenance – depending on the operability
SIS-8	Corrective maintenance or Condition based maintenance – depending on the operability

6. Conclusions

Fuzzy logic is a methodology that allows quantifying the human thinking. So in the presence of registered equipment's condition states perceptions from the maintenance responsible, defining the criteria and quantifying it considering various levels implementation, and using a defined algorithm, it is possible to quantify the risk associated to equipment maintenance.

Fuzzy logic allows converting text data into fuzzy values using membership functions. The application of Fuzzy Logic in ship equipment can

be useful in supporting the development of a decision support system in the maintenance management of ships in the Portuguese Navy. The result of the algorithm can be a level of risk that allows prioritizing maintenance actions on equipment.

The developed Fuzzy methodology was applied to an air compressor onboard a ship, and it serves as a decision support system for the equipment maintenance. The trapezoidal membership function did not result in overlapping results since the chosen variables and criteria.

It was used the Fuzzy methodology for risk analysis, it was defined the maintenance prioritization and the applied maintenance.

The developed methodology and method were theoretically validated, in future work it will be subject to a practical application with online observation of the systems by supervisors and for the responsible of implementing the system.

Abbreviations

AComp	- Air compressor
RBM	- Risk Based-Maintenance
C	- Consequence
COA	- Center of Area
COG	- Center of Gravity
ESI	- Environment and Safety Impact
F	- Frequency
MC	- Maintenance Costs
MMTC	- Maintenance Management Technical Center
MOM	- Average Maxima
OI	- Operational Impact
R	- Risk
SGM	- Maintenance Management System (Sistema de Gestão da Manutenção).
SMP	- Planned Maintenance System (Sistema de Manutenção Planeada)
SRTD	- Data Collection and Treatment System (Sistema de Recolha e Tratamento de Dados)

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Contribution of individual authors to the creation of a scientific article (ghostwriting policy)

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