Dynamic Maintenance based on Fuzzy Logic

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Abstract: - Currently, certain maritime assets face the challenge of optimizing their performance despite limited resources. They aim to minimize intervention actions on equipment while maintaining safety standards and acceptable performance levels. Ships, which are not yet autonomous, serve as maritime assets responsible for transporting personnel and systems. Keeping these ships operating at a high level of performance is crucial to ensuring the safety of both materials and personnel. This not only prevents damage to the ships but also reduces the risk of injuries to personnel and sea pollution. Organizations, the scientific community, and stakeholders have been actively developing advanced systems to monitor data from ship equipment within the scope of maintenance management. These efforts help prevent breakdowns and provide real-time information about the equipment's condition. These systems use various techniques for condition monitoring, including algorithms, statistical equations, and other methodologies applied to the collected data. In this study, Fuzzy Logic will be applied to data from selected equipment. Specifically, an air compressor from an ocean patrol vessel has been chosen for the case study. This air compressor is essential for Navy ships and has been selected by the Organization's Maintenance Management Centre to monitor working hours and operational status.

Key-Words: - Fuzzy logic; maintenance management; risk-based maintenance; decision process; air compressor, failure categorization.

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1 Introduction

The significance of maintenance in supporting production activities stems from its extensive contributions to the operability and optimization of physical assets, [1]. It subsequently implements them through various means such as planning, monitoring, and supervising maintenance operations while also improving organizational methods, including economic considerations. Maintenance planning, in turn, includes all activities associated with creating a systematically scheduled work program aimed at ensuring the seamless operation of equipment and preventing potentially severe issues", [2]. Conversely, maintenance control and supervision involve various aspects that require careful monitoring to ensure the proper execution of maintenance management, [3].

Any management system comprises an organizational structure grounded in three fundamental aspects: procedures, personnel, and technology, [4]. These elements are utilized to oversee and optimize resource utilization while ensuring the achievement of the company's objectives. To achieve this goal, maintenance planning and execution processes are supported 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 key component in enhancing the efficiency and effectiveness of maintenance operations. as a valuable tool for operators to ensure more reliable interventions, [5].

Effective management is rarely straightforward, and the maintenance of maritime assets involves inherent complexities due to uncertainties and constraints, such as varying climatic conditions, [6]. When the objectives include reducing accidents, fostering a versatile and adaptable organizational structure, improving production efficiency, and developing a more accessible and user-friendly system for all stakeholders, it can be argued that the core objectives of maintenance management, namely, maximizing profit and providing a competitive advantage to the organization—are also being achieved. This broad array of considerations has led to the development and implementation of appropriate models, transforming maintenance management from a vague concept into a prominent research area and a critical question in the pursuit of effectiveness and efficiency, [7].

Within the field of maintenance management, and with the goal of minimizing unforeseen breakdowns, the Fuzzy Logic methodology was chosen to develop a decision support model specifically for the maintenance of an air compressor (AComp) aboard a ship, [8].

2 Maintenance Management

2.1 Maintenance Support Systems

Many factors contribute to the effectiveness of maintenance support systems, including not only mathematical methodologies and advanced technology but also the skills of maintenance operators, [9]. The field of systems maintenance has garnered increasing interest due to its potential to improve equipment performance, reduce costs, enhance a company's economic performance, and minimize environmental impact by reducing waste and pollution.

Applying a "constraint programming" methodology can be an effective strategy for companies with limited budgets. This approach integrates various types of information and data, helping to reduce costs and optimize system operations, [10].

Augmented Reality (AR) in maintenance can leverage collected data to provide real-time, data-driven decision support, enhancing the efficiency and effectiveness of maintenance activities, [11].

To further reduce maintenance costs and increase system availability, implementing an "element-grouping preventive strategy" could be beneficial. This concept involves three maintenance methods that directly enhance the reliability of system components, [12].

Data collected from a machine can facilitate the calculation of its reliability, characterize its failure modes and effects, and, through the application of mathematical methods, provide insights into its condition, enabling the determination of the appropriate interventions and the optimal timing for those interventions, [13].

To improve maintenance activities in complex systems, equipment maintenance can be organized in batches, such as by using the concept of rotatable equipment. For instance, if maintenance is preventive, multiple pieces of equipment can be serviced when an opportunity arises. An optimization model, such as an algorithm based on Non-Dominated Sorting Genetic Algorithms, can be applied to achieve it, [14].

When data are collected without the guidance of a modeling expert, the data may lack significant information. Therefore, a methodology should be implemented to define which data is essential for monitoring, [15].

There are many approaches to maintenance, including Big Data, data mining, algorithmic methods, empirical approaches, and risk analysis. The selection, adaptation, and application of these approaches can significantly enhance both maintenance management and the maintenance process itself.

2.2 Maintenance in the Organization

To meet the organization's needs for optimizing both materials and personnel, the Portuguese Navy implemented a Maintenance Management System (SGM - Sistema de Gestão da Manutenção) several years ago. The SGM is structured into 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 is designed to ensure the availability of all assets and materials by clearly defining responsibilities, introducing standardized procedures, and facilitating the collection and effective use of data generated during maintenance activities. For the system to function effectively, it is crucial that all the following parameters are considered simultaneously, [16]:

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

For the maintenance of maritime assets, whether warships or any other type of vessel, the SGM was adapted to specific procedures and techniques to achieve the following objectives, [17]:

- 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 deserves to be highlighted over time.

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

To refer to 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 ship's Operational Command). The third stage, is under the responsibility of the Navy Maintenance Management Center (DN - *Direção de Navios*), which give technical advice and support, and 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

The original approach of maintenance, was preventive and took in account the time to proceed to maintenance action, for example, replace a component of an engine if it has been used for more than 5000 hours. With a Fuzzy Logic approach, the engine components are substitute if it is "quite old" and showing signs of "minor wear". In this sentence, "quite old" and "minor wear" are not strictly defined; instead, they allow for a range of interpretations based on expert judgment. A fuzzy set for the linguistic variable "pressure", rather than defining "under pressure" as anything above 7 bar, fuzzy logic might define #under pressure" as something starting at 6 bar with increasing membership (degree of truth) until 8 bar, where it is fully pressure.

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, [18]. It is used to clear boundaries between a set of information, [19].

In the realm of maintenance, the 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, [18]. 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. Fuzzy logic has been explored in the gas and oil industry for managing risks, [20]. Here, fuzzy logic, with the Risk-Based Inspection Maintenance helps evaluate the risk levels of different equipment and prioritize inspections based on risk, considering that the exact risk is often not a clear-cut number.

The Fuzzy Failure Mode and Effects Analysis (FMEA) has been applied in semiconductor manufacturing to assess potential failures and their effects. Fuzzy FMEA allows engineers to deal with uncertainties in the failure modes and consequences, [21].

The Fuzzy FMEA has been used to evaluate risks associated with boiler tubes, considering the complexity and uncertainty of potential failures in such systems, [22]. The Fuzzy Analytic Hierarchy Process (AHP) is combined with Fuzzy FMEA in the construction industry to improve risk management, [23]. This approach helps in making decisions where multiple criteria and their relative importance are not strictly quantifiable.

To design a fuzzy logic system for maintenance management, we can follow a structured approach. Below is a step-by-step outline along with a demonstrative example:

Step 1: Define the Problem Identify the maintenance management problem you want to address. For example, predicting equipment failure or optimizing maintenance schedules.

Step 2: Identify Input Variables Determine the input variables that will affect the maintenance decision. Common variables include: - Equipment Age - Operating Hours - Vibration Level - Temperature - Maintenance History

Step 3: Define Fuzzy Sets Create fuzzy sets for each input variable. For example:

- Equipment Age:- New (0-5 years) - Middle-aged (5-10 years) - Old (10+ years)
- Operating Hours: - Low (0-1000 hours) - Medium (1000-5000 hours) - High (5000+ hours)
- Vibration Level: - Normal (0-2 mm/s) - Warning (2-5 mm/s) - Critical (5+ mm/s)

Step 4: Define Output Variable Identify the output variable, such as: - Maintenance Priority (Low, Medium, High).

Step 5: Fuzzy Rules Create a set of fuzzy rules that will govern the decision-making process. For example:

- If the Equipment Age is Old and Operating Hours are High and the Vibration Level is Critical, then Maintenance Priority is High.
- If the Equipment Age is Young Operating Hours is Low and the Vibration Level is Normal, then Maintenance Priority is Low.

Step 6: Fuzzification Convert the input data into fuzzy values based on the defined fuzzy sets. This process involves determining the degree to which each input belongs to the fuzzy sets.

Step 7: Apply Fuzzy Inference System Use a fuzzy inference engine to evaluate the fuzzy rules and derive the output fuzzy set for Maintenance Priority.

Step 8: Defuzzification Convert the fuzzy output back into a crisp value. This could be done using methods like the centroid method or the mean of maxima.

By applying these steps in the fuzzy set and using the defined rules, the conditions of an equipment or system are evaluated, and it can be determined if the Maintenance Priority is High or not and maintenance can be prioritized. More detailed information about fuzzy further.

3 Pure Fuzzy Logic Methodology

This methodology was developed in the 1965 and is indicated to deal with imprecise human thinking because it considers "experience and knowledge" [24], it also provides a mathematical structure to model the uncertainty of human cognitive processes that can be controlled by a computer", [25].

The process inherent to Fuzzy Logic can be described by the following 7 stages, [26], [27],[28]:

- 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, [29], [30].

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, [31]. 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, [32].

Defuzzification is the stage where output values are computed based on the inference process and the membership functions of linguistic variables, [33]. 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, [33]. 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, [33].

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, [27].

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

By the second present form, in equation nr 3.4, o COG is calculated by a estimation obtained by a data sample, [26].

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

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, [29].

This phenomenon occurs primarily because humans typically communicate using words rather than numerical values, [34]. 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:

$$\mu_A(x) : U \to [0,1] \tag{3}$$

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

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

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 [29]. The transition is given by [29]:

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

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, [29].

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

$$\mu_A = \begin{cases} 0, \ se\ x < x_1 \\ \frac{x-x_1}{x_2-x_1}, \ se\ x_1 < x \le x_2 \\ \frac{x_3-x}{x_3-x_2}, \ se\ x_2 < x \le x_3 \\ 0, \ se\ x > x_3 \end{cases} \tag{6}$$

$$\mu_A = \begin{cases} 0, \ se\ x < x_1 \\ \frac{x-x_1}{x_2-x_1}, \ se\ x_1 < x \le x_2 \\ 1, \ se\ x_2 < x \le x_3 \\ \frac{x_3-x}{x_3-x_2}, \ se\ x_3 < x \le x_4 \\ 0, \ se\ x > x_4 \end{cases} \tag{7}$$

In complex problems where this logic is applied [35], for example in a customer service enhancement and for resolving urban problems, [36].

3.2 Advantages and Disadvantages of Fuzzy Logic in Maintenance

The advantages of logic over other types of logic are as follows, [37]:

- 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, [38]:

- 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 establishing 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 equation 8.

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

where F is de Frequency, C de Consequence, OI the Operational Impact, ESI is 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 centered 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.

The methodology for implementing Fuzzy Logic was defined through four sequential stages, each designed to ensure a comprehensive and systematic approach. The first stage involves the selection of equipment to be analyzed. This step is crucial as it determines the focus of the maintenance strategy and ensures relevance to the operational context. The second stage entails evaluating and studying the existing data to assess its adequacy for the Fuzzy Logic methodology. If the data is found inadequate, additional data is acquired to fill any gaps. Once sufficient and appropriate data is collected, the data structure is defined and stored in the database. Following this, the Fuzzy Logic model is designed, and the variables for study and inference are selected based on the specific requirements of the system under consideration. Subsequently, a comparison of data and results is conducted to validate the initial assumptions and refine the model. The final stage involves the continuous application and improvement of the methodology, ensuring ongoing refinement and validation of the model to maintain its accuracy and relevance over time, as depicted in Figure 1.

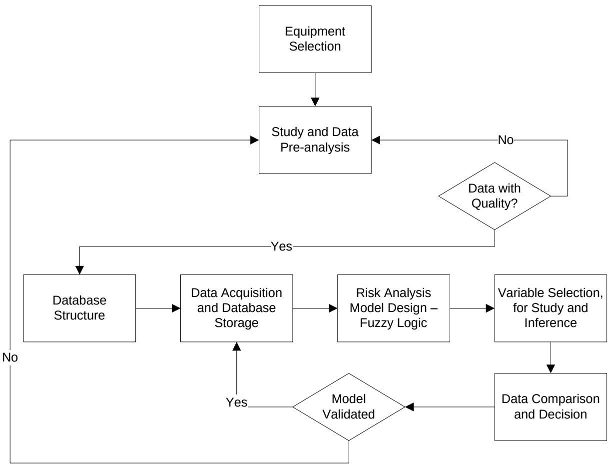

Fig. 1: Fuzzy methodology for ship equipment

To plan interventions, four stages 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. Detailed information about this case study is present in subject nr 5.

4.2 Methodology Fuzzy-RBM Structure

To calculate the risk level associated with an air compressor, an algorithm was established that utilizes three primary variables: frequency of failure, consequence of failure, and the combined impact along with maintenance costs. This approach is outlined in Equation 9:

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

where F represents the frequency, or the number of times the equipment fails over a specific period, and C denotes the consequence of these failures. I stand for the operational impact, ESI represents the environmental and safety impact, and MC refers to maintenance costs. The product of these variables provides a comprehensive assessment of R, which is the global risk of equipment failure.

In this fuzzy logic-based methodology, each variable is not simply a static value but rather a linguistic variable that can take on different degrees of truth based on the context. For example, the frequency can range from "rare" to "frequent," and consequences can be "minor" or "severe." By incorporating these fuzzy logic principles, the risk calculation becomes more flexible and reflective of real-world maintenance complexities, allowing for more nuanced risk assessments that can better inform maintenance decisions for the air compressor.

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 vessels from the Portuguese Navy (Systems 1 to 8). These ships have two air compressors. In addition, 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 equipments 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 [39]:

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

The previewed maintenance plan for this air compressor is [40], Figure 2:

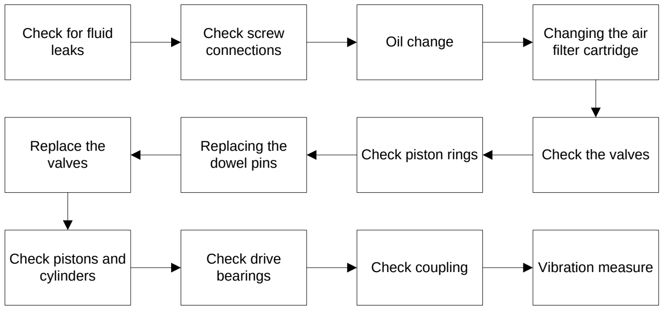

Fig. 2: Air compressor base maintenance (Adapted from [40])

5.2 Air Compressor Fuzzy Logic Parameterization

Table 1, Table 2, Table 3, Table 4, Table 5, Table 6, Table 7 and Table 8 illustrate the categorizations of failure frequency and the consequences.

Table 1 shows the occurrence frequency which has a range from 0 to 15, and it is divided into four levels, 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 integrates 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 considering the Operational impact, environmental and safety impact, and maintenance costs	[0, 4]
Moderate	Mo		[5, 8]
High	H		[9, 12]
Very high	Vh		[13, 16]
Extremely high	Eh		[17, 20]

The Operational Impact has a range between 0 to 10, Table 3, because it was considered that the operation mission and its accomplishment are normally one of the most important variables for evaluating the risk in a military ship.

Table 3. Classification of consequence factor - Operational Impact (Abr-abbreviation)

Operational Impact	Abbr	Description	Range
Low	L	Both air compressors are regularly maintained. No impact on the 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 to start diesel engines or generator groups	[6, 7]
Extremely high	Eh	Both air compressors on board fail. Mission commitment. Diesel engines and generating groups with start limitations.	[8, 10]

For the environment and safety Impact, Table 4, 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 causing minor damage to surrounding equipment, to sailors, and the environment.	[2, 3]
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.

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 risk levels, the product of Frequency and Consequence Factor, are present in Table 6.

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 about the critical equipment/system situation	[126, 210]
Very critical	Vc	The equipment/system is 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 Rϵ[211, 300])
2	If (F is Vf) and (C is Vh) then (R is Vc if Rϵ[211, 300])
3	If (F is Fr) and (C is Vh) then (R is C if Rϵ[126, 210])
4	If (F is Lf) and (C is H) then (R is Sc if Rϵ[88, 125])
5	If (F is Lf) and (C is Mo) then (R is Lc if Rϵ[40, 87])
6	If (F is Re) and (C is Mo) then (R is Nc if Rϵ[0, 39])
7	If (F is Re) and (C is L) then (R is Nc if Rϵ[0, 39])
8	If (F is Vf) and (C is Vh) then (R is C if Rϵ[126, 210])
9	If (F is Fr) and (C is H) then (R is Sc if Rϵ[88, 125])
10	If (F is Lf) and (C is Vh) then (R is Lc if Rϵ[40, 87])
11	If (F is Lf) and (C is Vh) then (R is H if Rϵ[40, 87])
12	If (F is Lf) and (C is H) then (R is Lc if Rϵ[40, 87])
13	If (F is Lf) and (C is H) then (R is Sc if Rϵ[88, 125])
14	If (F is Fr) and (C is Mo) then (R is Lc if Rϵ[40, 87])
15	If (F is Lf) and (C is Mo) then (R is Nc if Rϵ[0, 39])

Considering the applied inference rules and the outcomes pertaining to the equipment's state based on the considered inferences. 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 [8])
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, Figure 3.

Fig. 3: Membership function trapezoidal

5.3 Maintenance Plan Step

A maintenance risk matrix was developed to establish a link between the Fuzzy-RBM system and the maintenance activities plan, [41], [42]. This matrix needs to be intuitive and efficient to facilitate decision-making. Therefore, four types of maintenance were chosen for application to the selected equipment: systematic maintenance, detailed RBM, corrective maintenance, and condition-based maintenance, as shown in Figure 4.

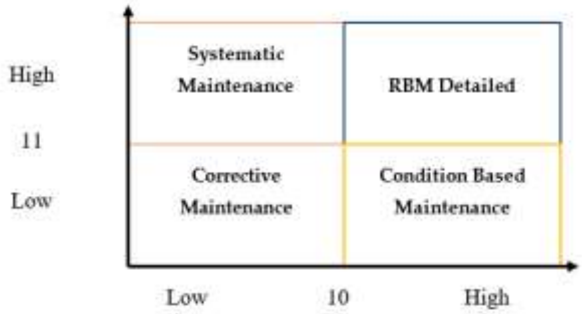

Fig. 4: Risk matrix created for Fuzzy-RBM methodology

In the first quadrant of Figure 4, it may be found 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 operationality of the ship:

- Systematic maintenance – Risk level 0 to 125: If operations allow corrective intervention;
- RBM Detailed – Risk level 211 to 300: If operations don´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 don´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 levels to the needed task for the compressors.

Accordingly, to the risk results in Table 8, the prioritization of maintenance is present in Table 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

Moreover, the general maintenance plan for the different systems, accordingly the results are Table 10.

Table 10. Applied maintenance according to the risk analysis

ID Compressor	Maintenance Type
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 for the quantification of human thinking. By using perceptions of equipment condition states recorded by maintenance personnel, it defines criteria and quantifies them at various levels of implementation through a specific algorithm, making it possible to quantify the risk associated with equipment maintenance.

Fuzzy logic enables the conversion of textual data into fuzzy values using membership functions. Applying fuzzy logic to ship equipment can be beneficial in developing a decision support system for maintenance management within the Portuguese Navy. The outcome of the algorithm can provide a risk level that helps prioritize maintenance actions for equipment.

The fuzzy methodology developed was applied to an air compressor onboard a ship, serving as a decision support system for equipment maintenance. The use of trapezoidal membership functions resulted in no overlapping outcomes, given the chosen variables and criteria.

The fuzzy methodology was employed for risk analysis, which defined maintenance prioritization and the maintenance actions to be applied. The developed methodology and method were theoretically validated.

This fuzzy logic design helps in making informed maintenance decisions based on uncertain and imprecise data. By implementing this system, maintenance managers can prioritize tasks more effectively, ultimately leading to reduced downtime and improved equipment reliability.

In future work, they will undergo practical application with real-time observation of the systems by supervisors and those responsible for 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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Declaration of Generative AI and AI-assisted Technologies in the Writing Process

During the preparation of this work the authors used Chat GPT Openai in order to enhance the English. After using this tool/service the authors reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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