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Study of the Condition of Forest Fire Fighting Vehicles

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Abstract: The Forest Fire Fighting Vehicle (FFFV) is one of the most important pieces of equipment in direct firefighting; therefore, its maintenance is strategic to guarantee high levels of reliability. The history of interventions is essential to support the increase in the quality of maintenance, namely with regard to the specificity of each equipment, in its actual operating conditions. In the absence of previous information, it is important to resort to complementary tools that allow for overcoming this gap where usually the knowledge of maintenance held by professionals and users is structuring and very helpful. In this perspective, data were collected from several fire brigades. The analysis and decisions were possible using fuzzy logic, following the Mamdani model and the centroid method for the defuzzification phase. Subsequently, a Failure Modes, Effects and Criticality Analysis (FMECA) was carried out to identify which would be the most severe failures, the possible cause of each failure and the respective maintenance action. Through the results obtained, it was possible to identify a set of elements of the FFFV where maintenance should pay additional attention so that the vehicle guarantees the desired levels of reliability and propose a maintenance program with added value compared to what is currently practised.

Keywords: forest fires; Forest Fire Fighting Vehicle; decision analysis; maintenance

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1. Introduction

1.1. Motivation

Forest fires are considered natural disasters, which does not mean that they are caused by natural phenomena. Human intervention in fires plays a decisive role, not only in their origin due to accidents or arson, but also in fighting them, limiting their development.

To transport the necessary human and material resources, firefighters are equipped with fire-fighting vehicles that, due to the need for speed in responding to events, are driven in a more aggressive way than would be ideal. The use of vehicles before and during a forest fire is widespread and inevitable. However, in many fires where civilians or operational people die, often some of the fatalities involve the use of vehicles [1].

Data provided by the Portuguese Firefighters League state that between 1980 and 2020, 231 firefighters died, of which 94 died while travelling in combat vehicles, in contrast to 24 who died in direct combat to fires, thus concluding that road accidents are the main cause of death of firefighters in Portugal.

In the specific case of fighting forest fires, operators have to move vehicles along degraded paths, mountain roads, steep hills and slopes, sometimes even having to use the vehicle to create its own path [2]. This type of stress leads to greater wear and tear on the vehicle's components, so it is necessary that they have an adequate maintenance program in order to ensure the best possible conditions.

1.2. Objectives

The purpose of this study is to better understand the average state of forest firefighting vehicles in Portugal, know what is executed to keep them in the best condition, identify the most serious failures that could lead to accidents and define possible improvements to be applied in the future, to generalise to any emergency vehicle in any geographic location.

Since there are several vehicles for fighting forest fires and they have different equipment and systems, it was necessary to select only one vehicle, having chosen the Forest Fire Fighting Vehicle (FFFV) for its competence in fighting fires.

Once the vehicle to be studied was defined, several visits were made to fire brigades (FB) in Portugal to understand what checks have been carried out, the level of maintenance performed and the frequency of service. Then, a Failure Modes, Effects and Criticality Analysis (FMECA) was performed to identify the risk associated with each failure.

Due to the type of data analysed not being totally reliable, that is, being subjective, imprecise, uncertain or incomplete, fuzzy logic was later used to determine which are the critical elements of each system and thus to be able to implement corrective measures to reduce risks.

1.3. Firefighting Engines

One of the many rescue missions entrusted to firefighters is the fight against fires, whose intervention implies the displacement of human and material resources [2]. For this, the fire brigades (FB) are equipped with different vehicles that are optimised for different tasks and different areas of action.

Standard NP EN 1846:2012 [3] classifies firefighting vehicles according to their Gross Vehicle Mass (GVM) and also in terms of the preferential area of use, as can be seen in Table 1.

Upon contacting several fire brigades, it became clear that one of the most important types of vehicles in the fight against forest fires is the FFFV due to its equipment and versatility. It is a vehicle that combines mobility with water transport capacity, being the one used as first intervention when a fire alert arises. For these reasons, this was the vehicle chosen as the target of study, and an example of a FFFV can be seen in Figure 1.

Figure 1. Portuguese Forest Fire Fighting Vehicle (source: Fátima’s FB).

Table 1. Vehicle Classification [2].

Class	L Light	M Medium	S Super
	>3 t MTC ≤7.5 t	>7.5 t MTC <16 t	≥16 t
Type	1	2	3
	Urban	Rural	All-Terrain

According to Order No. 7316/2016 of the Portuguese National Emergency and Civil Protection Authority (ANEPC) [4], FFFVs must be of class M and type 3. They are described as motor vehicles capable of using all types of public roads, as well as rough terrain, equipped with an off-road chassis, a service pump and a tank with a minimum capacity of 3000 litres and intended primarily for forest or rural firefighting.

1.4. General Overview of Maintenance

To ensure that a vehicle is in good condition, several tasks must be carried out throughout its life, designated as maintenance, which correspond to a set of management, technical and economic actions that, when applied to an asset, allow optimising its life cycle. This optimisation implies the need to maintain or restore a specific state that guarantees the fulfilment of the function [5].

According to the standard NP EN 13306:2007 [6], there are several types of maintenance, such as:

- Preventive maintenance

Maintenance carried out at pre-defined time intervals with the aim of reducing the probability of damage or degradation of an asset.

This is divided into scheduled maintenance if it is carried out according to a pre-established schedule or a certain number of uses, or, if there is no prior control of the state of the asset, this is called systematic maintenance.

It can be conditional maintenance if it is based on monitoring the operation of the asset and/or the significant parameters of its functioning. If extrapolated forecasts are made from the analysis and evaluation of these parameters, it is called predictive maintenance.

- Corrective maintenance

Corrective maintenance is unplanned maintenance. It occurs after the detection of a fault in order to restore the state in which the asset can perform its function.

This can be classified as deferred maintenance if the repair is not carried out when the failure is detected, or it can be emergency maintenance if it is carried out immediately after the failure was found and thus avoid aggravated consequences.

Maintenance can also be classified according to the execution strategy and, in this particular case, can be maintenance in operation if it is carried out while the FFFV is being operated, on-site maintenance if it is not necessary to go to a workshop or maintenance by the operator if it is carried out by a firefighter. Standard [6] also mentions, among others, five important concepts for this work:

- Reliability: ability of a good to fulfil a required function under certain conditions, during a given time interval;
- Availability: aptitude of a good to fulfil a required function under certain conditions, at a given moment;
- Durability: aptitude of a good to fulfil a required function, until a limit state is reached, whether technical or economic;
- Condition control: activity performed manually or automatically in order to observe the current state of an asset;
- Conformity test: test intended to prove whether a characteristic or property of a good is, or is not, in accordance with the nominal specifications.

1.4.1. International Normative Literature, an International Legal Regulations and Technical Standards, Guidance for Emergency Vehicles

The ISO55002:2018 is a good sources as guidelines for the management of assets and can be applied in any sector [7]. There are several different programs that may be used based on the maintenance and certification of emergency equipment For fire activities, they are based on the type of activity and geographic location. In the USA, the Standard NFPA 1911 is in use, which is a standard for the Inspection, Maintenance, Testing, and Retirement of In-Service Fire Apparatus. This standard is applicable to any public or private organisation that uses fire apparatus and helps ensure in-service fire apparatus are serviced and maintained to keep them in safe operating condition and ready for response at all times [8].

In Australia, the AS 5062-2016 specifies the minimum requirements for the design, installation, commissioning and maintenance of vehicle fire suppression systems. It is intended to be applied to new equipment and can also be applied to existing equipment for maintenance activities [9].

European countries use the EN-1846-2:2009+A1:2013 which is a standard that deals with the technical requirements to minimise the hazards which can arise during operational use, and that define routine checking and maintenance of firefighting and rescue service vehicles, carried out in accordance with the specifications given by the manufacturer or their authorised representative [10].

Despite the presented normatives or standards, the level of maintenance and assessment of the tools specified are of very low development and application in the general firefighting brigades.

1.4.2. Maintenance Plan

In order for maintenance to be carried out properly, the set of activities to be performed must be documented. This document must also include the procedures, means and the time required to carry out the tasks, thus improving the organisation, which is reflected in an increased efficiency and a reduction in costs.

Thus, a preventive maintenance program (PMP) plays a vital role in saving lives and protecting property. All PMPs depend directly on the vehicle operators, as they are the ones who maintain contact with the equipment. Daily inspections of oil, fuel and coolant levels combined with the monitoring of the vehicle's condition (wear, abuse or neglect) form a routine of checks that are absolutely necessary [11].

Ref. [12] highlights the importance of maintenance being combined with training. Performing preventive maintenance also increases the ability of vehicle operators and firefighters in general. For example, conducting a water pump test run not only tests the equipment and possibly detects faults, but also trains operators to use the pump more efficiently and dexterously. In this way, the competence of the Fire brigade is improved.

If vehicles are properly maintained, the costs associated with them will be lower and their lifespan will increase. In the words of Craven [13] the useful life of a vehicle depends on the amount of use, the local environment, the conditions of use and workload and can be divided into three categories, namely: useful life, technological life and economic life. Useful life is the period of time that the vehicle is expected to operate normally and reliably, technological lifetime is the duration of the vehicle before it becomes obsolete, and economic life is the period of time during which repair is economically viable and the vehicle can be maintained.

The importance of structuring a PMP is recognised since it not only increases reliability and durability, but also the availability of the vehicle, which is absolutely necessary for emergency response. As for its operators, there will also be an increase in dexterity and aptitude in dealing with the vehicle and its systems, which will translate into a more careful and conscious use, avoiding failures by neglect.

2. Methodology

In order to carry out this work, it was necessary in the first phase to do research on the different firefighting vehicles and what their equipment and specifications are. During the research it was found that there were several types of vehicles with different systems, and it would be impossible to address all of them in this work, being necessary to choose only one vehicle.

This was followed by visits to fire brigades to establish a closer contact with firefighters and firefighting vehicles. After a tour and presentation of Fátima's fire department headquarters and fleet, it became evident that the vehicle to address in this work would be the FFFV due to its ability to progress in a forest environment while transporting firefighters and a reasonable amount of water. All of the visited fire departments elected this vehicle as the most relevant in fighting fires outside urban environments.

Having now defined the FFFV as the subject of study, it was essential to deepen our knowledge about it. Fire brigades of Coimbra, Alcanena, Minde and Miranda do Corvo were also visited in order to allow the author to get in touch with FFFV of different brands and manufacturers. Together with these corporations, it was investigated what care each one had in the maintenance of their vehicles, the frequency of inspections and service, which failures or breakdowns they have already experienced and whether any of these were recurrent.

Although some fire departments keep a record of the failure accompanied by the date and the number of kilometres the vehicle had at the moment, this data did not prove to be relevant due to inaccuracy and reduced extent. A document was then created containing information about the main mechanical systems and the failure modes of a FFFV, having assigned a degree of severity, probability of occurrence and detectability to each failure, in order to multiply them and obtain its failure risk, so as to elaborate the FMECA approach.

Taking advantage of the greater experience of the FFFV operators, a blank FMECA was delivered to the fire brigades of Fátima, Minde and Alcanena and their collaboration was requested to complete it, assigning the grades they thought were correct, according to tables also provided. When analysing the data, it was found that some of them were not only quite far from the assumptions, but also differed between corporations; therefore, it was decided to use the average of the collected data and discard the presupposed values in order to reduce the imprecision.

Finally, the FMECA data was used to make an approach through fuzzy logic using MATLAB, since, through this strategy it is possible to find the best solution to the problem even using imprecise, vague, uncertain or incomplete information, such as the information mostly used in this work, which was acquired through contact and direct conversation with the firefighters.

2.1. Methodology Used in the Vehicles Maintenance

When visiting different FBs, it was possible to verify that there are great differences regarding the maintenance performed, since the lack of imposed rules makes the person in charge of each fleet adopt different measures. In this way, there are corporations that neglect certain maintenance tasks or do them between excessively long intervals of time; these practises will impact the condition of the vehicle.

Checking firefighting vehicles should be executed on a daily basis. By carefully inspecting and maintaining vehicles, you will not only prolong their lifespan, but also increase the safety of firefighters and the entire community. To perform good maintenance, an inspection is recommended every morning, recording the vehicle's condition, paying attention to details, testing all resources, checking all functionalities after an incident, normalising the procedures and carrying out the necessary interventions, consequently becoming an expert in your own vehicle [14].

Following Robertson's ideology, inspections should be made every day, as follows:

- Check fluid levels: engine oil; steering oil; brake fluid; oil from the built-in pump; coolant; windshield washer fluid; fuel (and AdBlue if applicable); tank water.

- Examine: the presence of leaks or spills; the pressure and condition of the tyres (pulls, cuts, punctures, etc.); the condition of timing belts; the functioning of electrical components; the existence and fastening of all vehicle equipment; the condition of the cab and bodywork.
- Execute: purge of air tanks; vehicle washing; the built-in pump test; the SAROCA dynamic tests (Evaluation and Review of the Operability of Auto Kinematics).

The purpose of the latter is to check the operability of the vehicle's traction systems, and the tasks performed are: engaging the differential locks (front and rear), switching the gear ratio of the transfer case (transfer case reduction) and locking the transfer case differential (if the vehicle is a permanent 4×4) or coupling the front axle mechanism (if it is a non-permanent 4×4). Due to their extent, SAROCA tests may be excluded from daily inspections, and must be carried out at least once a month and after firefighting where any of these systems have been used.

Well-functioning drive trains are crucial when travelling off-road and it is extremely important to ensure they are working correctly, as they can be the difference between progressing on the terrain or getting stuck. When running the tests, knowledge about the systems in question and the correct way to activate and use them is also developed.

When an anomaly is found, it must be recorded and rectified immediately, if possible, thus avoiding worsening the fault. If the fault cannot be corrected on the spot, information about the problem should be reported and appropriate means for repair should be put in place.

After an event (firefighting), all these tasks must be repeated, with special emphasis on cleaning the vehicle, cleaning the air and cabin filters and filling the fuel and water tanks.

In order to carry out all these procedures without forgetting any of them, the FBs use different methods: For example, Fátima's fire brigade use a checklist, as partially exemplified in Figure 2; firefighters from Minde a mobile phone application.

<table>
<tr><td colspan="2">Date: dd/mm/yyyy</td><td colspan="2">Time: hh:mm</td></tr>
<tr><td colspan="4">1 - Vehicle Data</td></tr>
<tr><td>Make:</td><td rowspan="2">Kilometres:</td><td colspan="2" rowspan="2">Insured until:</td></tr>
<tr><td rowspan="2">Model:</td></tr>
<tr><td rowspan="2">Pump Hours:</td><td colspan="2" rowspan="2">Safety inspection date:</td></tr>
<tr><td>Number Plate:</td></tr>
<tr><td colspan="4">2 - Fluid levels</td></tr>
<tr><td>Engine oil:</td><td></td><td>Fuel:</td><td></td></tr>
<tr><td>Steering oil:</td><td></td><td>Ad Blue:</td><td></td></tr>
<tr><td>Brake fluid:</td><td></td><td>Pump Fuel:</td><td></td></tr>
<tr><td>Transfer case oil:</td><td></td><td>Engine coolant:</td><td></td></tr>
</table>

Figure 2. Excerpt of Technical checklist of a FFFV (source (given directly to the author): Fátima's FB).

To ensure attention to detail, checks are carried out by different operatives the following day, enabling the latter to discover something that the former might have missed.

When servicing, the manufacturer's specifications must be followed, which advise oil and filter replacements depending on the number of kilometres travelled or the amount of time elapsed. These values vary depending on the make of the vehicle; however, almost all FBs have their vehicles overhauled every one or two years (the first year they only check and clean the filters and restore the correct oil levels, and the following year they replace them, and so on), as they never reach the minimum mileage for replacements. It is also important to mention that firefighting vehicles with coupled pumps are kept running during the firefight, so, despite the fact that the kilometres do not increase, there is degradation of the oils, so the pump's operating hours must also be taken into account, if the vehicle has been used extensively.

FFFVs are emergency response vehicles, and it is necessary that they are in the best possible condition, always available for any occurrence, since not only the safety of firefighters, but also of the remaining population, is dependent on their proper functioning. The cost of these vehicles and the repair of their equipment is also quite high, so a good maintenance plan can result in long-term cost reduction by preventing long periods of inoperability due to catastrophic failures that result from continuous wear and tear and negligence on the part of those responsible. If vehicles are not properly cared for, the likelihood of failure increases, which compromises the ability of the FBs to act, not only in direct fire-fighting but also in assisting the population, sometimes even putting their own safety at risk.

2.2. Failure Modes, Effects and Criticality Analysis (FMECA)

Standard IEC 60812:2018 [15] classifies the Failure Modes and Effects Analysis (FMEA) as a systematic method of evaluating an asset (or process) that aims to identify what the potential failure modes are and the potential effects of that failure on the performance of the asset, its operators and the surrounding environment.

When failure modes are prioritised to support treatment decisions, the process is called Failure Modes, Effects and Criticality Analysis (FMECA); in this case, the severity of the failure is taken into account to classify which are the most dangerous failures, which is the analysis developed in this work.

A FMECA can be carried out several times during the asset's lifetime, i.e., as more information becomes available, subsequent, more detailed analyses can be carried out in order to discover solutions and adopt decisions that further reduce the likelihood of failure and its effects, thus contributing to maintaining the vehicle in good condition [15].

Therefore, since FMECA is based on finding, prioritising and minimising the failures, it has been widely used in numerous projects, in the development phase or even during the operational life, in order to increase the reliability of an asset.

To apply a FMECA to a FFFV, it was first necessary to break down the vehicle into its most important mechanical systems and then divide these systems into their main components, describing what role each one plays. Having divided the vehicle into subsystems and their components, it is necessary to identify which are the most probable failure modes of each and what will be their effects on the vehicle. Next, a potential cause of this effect is presented, as well as a possible treatment action that should be taken in order to restore the vehicle to working order.

To carry out the FMECA itself, degrees of severity (S), probability of occurrence (O) and detectability (D) will be assigned, which are related to the effect, the potential cause and the treatment action, respectively. These factors will be multiplied to obtain the risk of failure [16].

Severity rates the gravity of the effect on a scale of 1 to 10, where S = 1 classifies as insignificant and S = 10 is catastrophic, as can be seen at Table 2. The probability of occurrence estimates the chance of that failure occurring in that component and is also measured from 1 to 10, where O = 10 is a persistent failure and O = 1 is an unlikely failure, according to Table 3. Each failure also has a probability of being detected or not, so that the appropriate treatment actions can be applied, the scale also varies from 1 to 10, and as shown in Table 4, when detectability is certain, D = 1 is given and when detectability is practically impossible, D = 10 is assigned [17].

Table 2. Severity Classification (S).

Severity (S)	
Description/Definition	**Rating**
Very insignificant effect. Corrected immediately by the operator	1
Insignificant effect. Corrected by maintenance.	2
Very minor effect. Gradual wear. Repair is required	3
Minor effect. Component does not perform correctly. Needs maintenance	4
Slight effect. Noise and vibration. Repair necessary	5
Moderate effect, vehicle still operable. Performance compromised. Replacement required	6
Severe effect. Impaired performance. Needs extensive repair work	7
Serious effect. Vehicle is inoperable. Overhaul required	8
Dangerous. Poorly maintained vehicle. Needs complete overhaul	9
Catastrophic. Endangers the operator	10

Table 3. Occurrence Classification (O).

Probability of Occurrence (O)		
Probability of Failure	**Possible Failure Rate**	**Rating**
Very high:	>100 per 1000 vehicles/components	10
Persistent failures	±50 per 1000 vehicles/components	9
High:	±20 per 1000 vehicles/components	8
Frequent failures	±10 per 1000 vehicles/components	7
Moderate: Occasional failures	±5 per 1000 vehicles/components	6
	±2 per 1000 vehicles/components	5
	±1 per 1000 vehicles/components	4
Low: Rare failures	±0.5 per 1000 vehicles/components	3
	±0.1 per 1000 vehicles/components	2
Remote: Unlikely failures	±0.01 per 1000 vehicles/components	1

After assigning grades for S, O and D, the R is calculated by multiplying the three factors. The component with the highest R value will be the one that represents the greatest risk to the proper functioning of the vehicle, this being a component to be taken into account during maintenance.

To prepare the FMECA, a first approach was made, which will be identified as "Assumption"; afterwards, the collaboration of Fátima's FB, Minde's FB and Alcanena's FB was requested in order to use data based on the experience of the firefighters that integrate these corporations. Finally, it was decided to use the average resulting from the data acquired in the three fire brigades to obtain a more reliable R and also to compare this average with the assumed values. The results presented are highlighted with four different colours, which classify the risk of failure as follows:

(i) Green: values below 50, components with low failure frequency and low severity, corrective maintenance can be performed;
(ii) Yellow: values of [50; 100], components with some risk of failure, but minor severity, need condition control;
(iii) Orange: values of [100; 150], components to be taken into account during inspection and maintenance, must be regularly reviewed;
(iv) Red: values greater than 150, critical components that require greater attention during inspection and a high level of preventive maintenance to avoid failures.

Table 4. Detectability Classification (D).

Detectability (D)		
Detection	**Description/Definition**	**Rating**
Certain	Detection is certain	1
Very high	Detection is very probable	2
High	Probable detection	3
Moderate high	Fair probability of detection	4
Moderate	Moderate probability of detection	5
Moderate low	Fault may be detected	6
Low	Detection is difficult	7
Very Low	Detection is very difficult	8
Remote	Detection is improbable	9
Impossible	Near zero chance of detection	10

2.3. *Fuzzy Logic*

Fuzzy logic is based on the fuzzy set theory developed by Lofti A. Zadeh. The main objective of this technique is to find the best possible solution with imprecise, vague, uncertain or incomplete information [18]. These uncertainties can lead to an increase in the difficulty of implementing improvements. These uncertainties may increase the difficulty of implementing improvements; however, they cannot be ignored as they would result in wrong decision-making [19].

The advantage of using fuzzy logic in risk assessment lies in the fact that it is possible to work with variables that were not described numerically, thus allowing the use of subjective linguistic data [20].

Using this tool, it is possible to determine which are the critical elements of a system because all factors will be evaluated simultaneously, with different influences to infer the operational risk and then implement the appropriate corrective measures [21].

To use this technique, the Fuzzy Logic Toolbox application was used, which is an add-on for MATLAB. The information provided by the FBs was used as input data, as previously in the FMECA.

Thus, firstly, the input parameters were defined: severity (S), occurrence (O) and detectability (D), and for each of them numerical values and respective linguistic terms were defined, thereby creating their fuzzy sets.

As in FMECA, severity was ranked from 0 to 10; however, in the fuzzy logic it is divided into 5 different sets, namely: Very Low Severity (VL), Low Severity (L), Moderate Severity (M), High Severity (H) and Very High Severity (VH), which represent the failure severity range where an insignificant failure is represented by VL and a catastrophic failure corresponds to VH. The relations between numerical values and linguistic terms are represented in Table 5 and the fuzzy sets of severity in Figure 3.

Table 5. Severity scenarios (S).

		Severity (S)			
Rate	**<1**	**3**	**5**	**7**	**>9**
Linguistic term	Insignificant	Slight	Moderate	Severe	Catastrophic
Fuzzy set	VL	L	M	H	VH

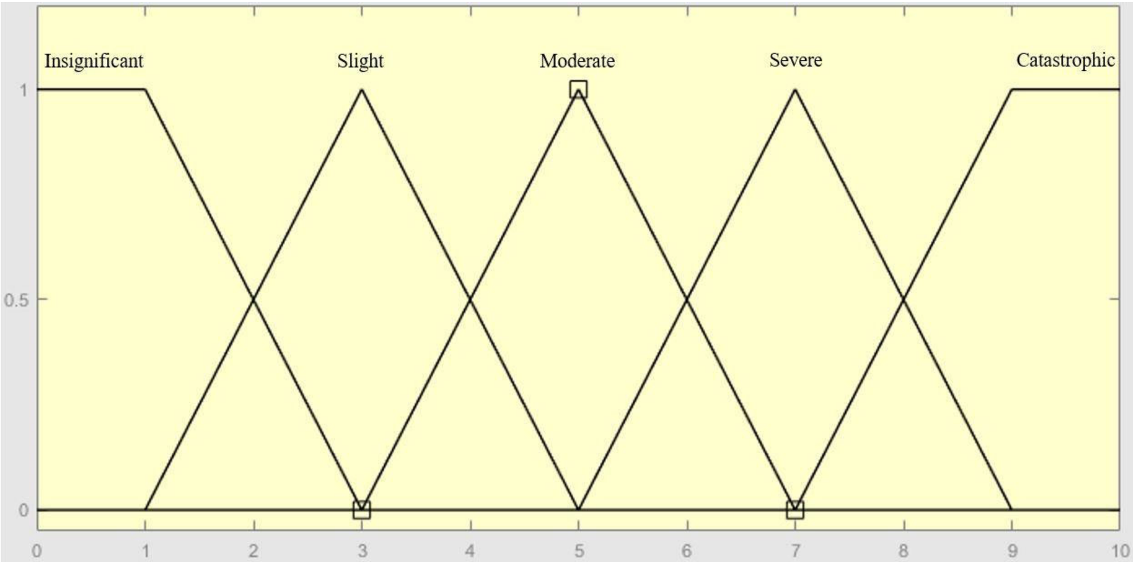

Figure 3. Fuzzy sets for Severity (S).

The occurrence was also divided into five sets: Very Low Occurrence (VL), Low Occurrence (L), Moderate Occurrence (M), High Occurrence (H) and Very High Occurrence (VH), with an unlikely failure being classified as VL and a persistent failure classified as VH. The remaining relations can be consulted in Table 6 and the respective fuzzy sets in Figure 4.

Table 6. Occurrence scenarios (O).

		Occurrence (O)			
Rate	**1**	**3**	**5**	**7**	**10**
Linguistic term	Unlikely	Rare	Occasional	Frequent	Persistent
Fuzzy set	MB	B	M	A	MA

The last input parameter is detectability; this was divided into four groups, namely: Very Low Detectability (VL), Low Detectability (L), High Detectability (H) and Very High Detectability (VH). When a failure can be easily detected by any firefighter, it is said that the detectability is certain and is classified as VH; if, on the other hand, someone specialised is needed to detect the fault, it is characterised as remote detectability, VL. The relations for detectability are shown in Table 7 and their fuzzy sets illustrated in Figure 5.

Next, it is necessary to define the inference rules. Since the criticality (RPN—Risk Priority Number) depends on the sets of Severity (five sets), Occurrence (five sets) and Detectability (four sets), there will be one hundred rules (5 × 5 × 4) that relate these three input parameters, in order to assign to each combination, the respective fuzzy set of the RPN.

According to the relations presented from Tables 8–11, the inference rules are inserted in the fuzzy logic application. For example, in a failure with Insignificant Severity (S = VL), Unlikely Occurrence (O = L) and Certain Detectability (D = H), its Criticality will be Very Low (RPN = VL), Figure 6.

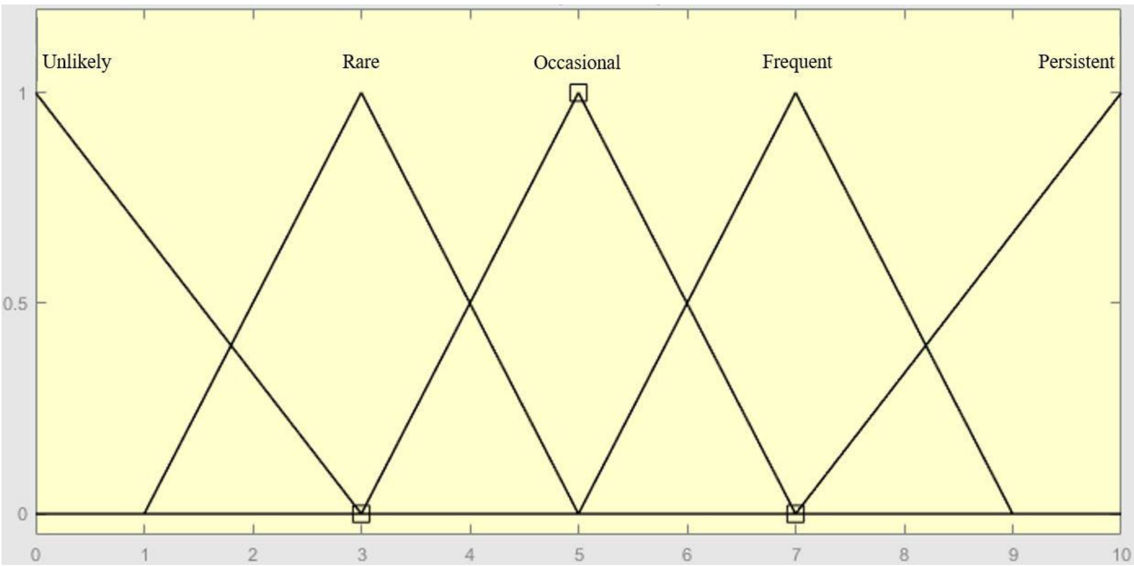

Figure 4. Fuzzy sets for Occurrence (O).

Table 7. Detectability scenarios (D).

	Detectability (D)			
Rate	**<1**	**3**	**5**	**>7**
Linguistic term	Certain	High	Low	Remote
Fuzzy set	VH	H	L	VL

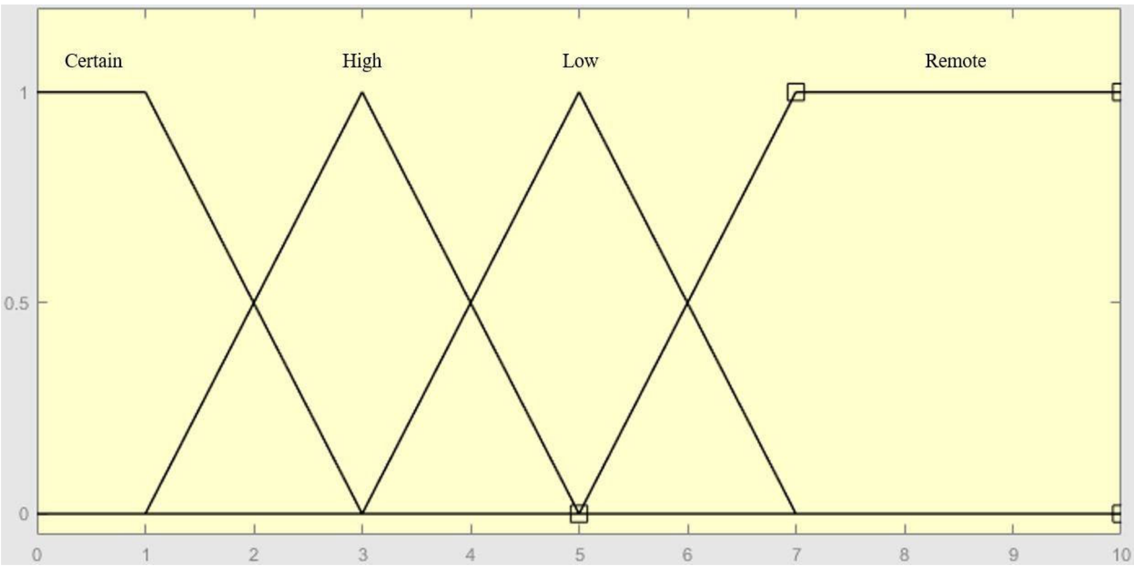

Figure 5. Fuzzy sets for Detectability (D).

The RPNs are the output results, which also have their fuzzy sets, as shown in Figure 7, dividing the criticality into: Very Low Criticality (RPN < 22.5), Low Criticality (22.5 < RPN < 37.5), Moderate Criticality (37.5 < RPN < 52.5), High Criticality (52.5 < RPN < 67.5) and Very High Criticality (67.5 < RPN).

Having all the variables and rules inserted in the program, the centroid method was chosen as the defuzzification method to obtain the numerical value of the RPN, leaving the program ready to be used to generate results, as shown in Figure 8.

Table 8. RPN outcomes when D = VH.

D = VH						
RPN		O				
		VL	L	M	H	VH
S	VL	VL	VL	VL	VL	VL
	L	VL	VL	VL	L	L
	M	VL	L	L	L	L
	H	L	L	L	M	M
	VH	L	L	M	M	H

Table 9. RPN outcomes when D = H.

D = H						
RPN		O				
		VL	L	M	H	VH
S	VL	VL	VL	L	L	L
	L	L	L	L	L	M
	M	L	L	L	M	M
	H	L	M	M	H	H
	VH	M	M	H	H	H

Table 10. RPN outcomes when D = L.

D = L						
RPN		O				
		VL	L	M	H	VH
S	VL	L	L	L	L	M
	L	L	L	M	M	M
	M	M	M	M	H	H
	H	M	M	H	H	VH
	VH	M	H	VH	VH	VH

Table 11. RPN outcomes when D = VL.

D = VL						
RPN		O				
		VL	L	M	H	VH
S	VL	L	L	M	M	M
	L	M	M	M	H	H
	M	M	M	H	H	VH
	H	M	H	VH	VH	VH
	VH	H	VH	VH	VH	VH

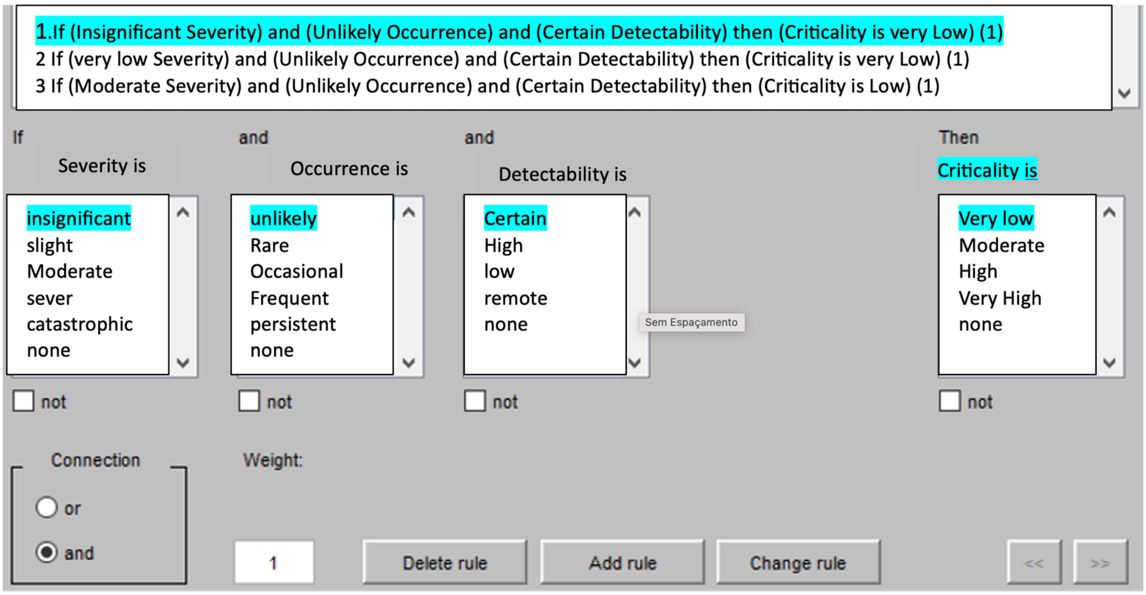

Figure 6. Inference rules.

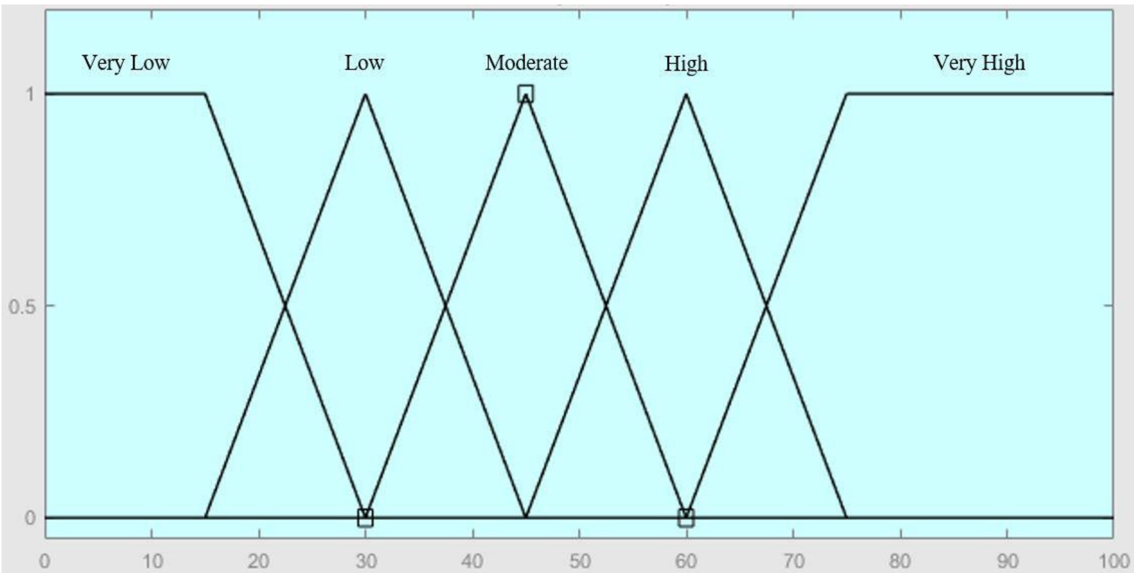

Figure 7. Fuzzy sets for Criticality (RPN).

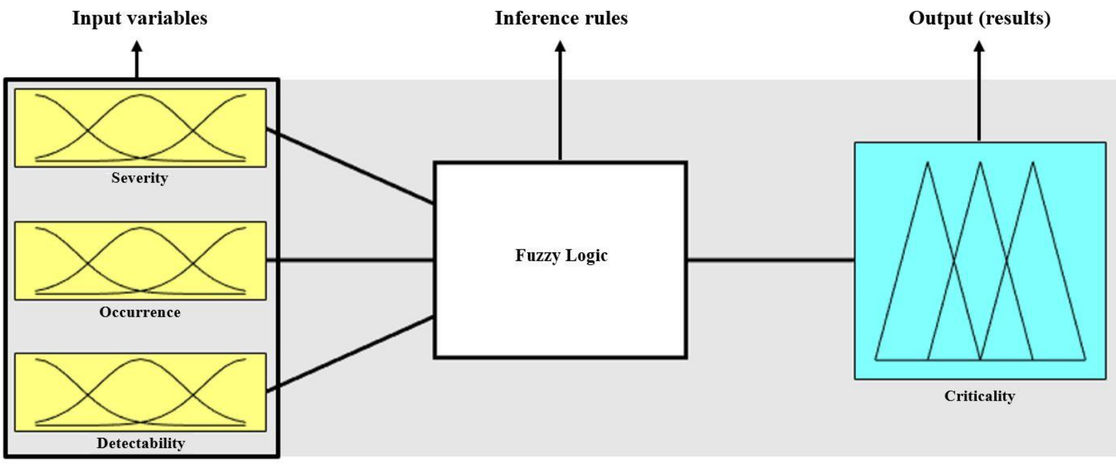

Figure 8. Fuzzy logic software in MATLAB—Version 8.2 (R2013b).

Using the same systems and components that were used for the FMECA (MATLAB—Version 8.2 (R2013b)), as well as the average grades of S, O and D of each fault, the respective RPNs will be calculated, according to the inference rules previously defined.

By entering the grades of S, O and D as input data, the program responds with a value for RPN. For example, a flat tyre has the following parameters: S = 6.3, O = 7 and D = 1 and, by placing these values in the Input text box, its criticality will be calculated by the fuzzy logic program, in this case, returning the value of RPN = 39.3, as exemplified in Figure 9.

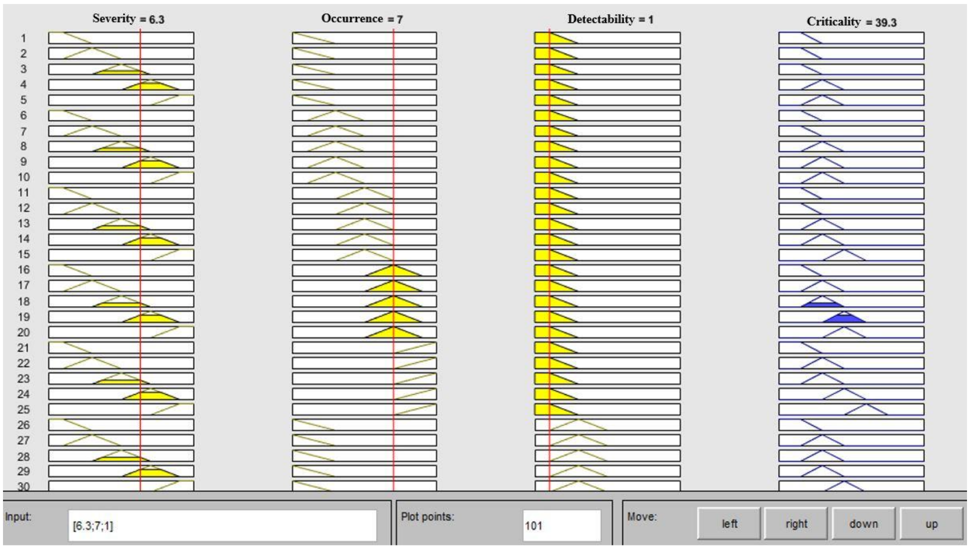

Figure 9. Calculation of RPN using fuzzy logic software.

The use of this method allows assigning different relevance to the input parameters and, as can be seen in the RPN results tables, greater relevance was attributed to severity and detectability, since a high degree of severity is dangerous and a low detectability leads to the aggravation of the failure as it is not identified or fixed. On the other hand, a high probability of occurrence means that the problem is already recurrent, its effects are already known and a solution to it should already exist, hence this is the input parameter with less importance.

In the analysis using fuzzy logic, the results presented are highlighted only in three colours, according to Figure 7, as follows:

(i) Green: values less than 37.5, low or very low criticality, components with low failure frequency and minor severity, corrective maintenance can be performed;
(ii) Yellow: values of [37.5; 52.5], moderate criticality, components with some risk of failure and moderate severity, need attention during inspection and maintenance, should be regularly reviewed;
(iii) Red: values greater than 52.5, high or very high criticality, critical components that require major attention during inspection and a high level of preventive maintenance to avoid failures.

3. Results

3.1. FMECA

This chapter will present the average results obtained through the collaboration of firefighters and also the results assumed in a first approach.

The complete FMECA that includes all systems with the function description and presents the grades awarded by each FB is found in greater dimension and detail in database link: https://drive.google.com/drive/folders/1ipMIRFznMHVi9-7IqJOt2XvHjiUNwazh?usp=share_link (accessed on 22 June 2023), with only the necessary, or analysis being presented here. The access should be requested in case it needs to be consulted.

Due to the large amount of data concerning the different systems and their components, only the Failure Modes, Effects and Criticality Analysis of the engine will be presented below. The remainder of the analysis is found in the database.

The propulsion unit, in this case, an internal combustion engine, converts chemical energy into thermal energy by combustion and directly applies force to the components of the engine generating mechanical work, responsible for the movement of the vehicle.

As can be observed in Figure 10, the malfunctions that can be considered more serious are fuel leaks due to the high danger and low detectability, and also problems with the intake that can result from clogged or degraded air filters due to the smoke and dust characteristic of fighting forest fires.

Major Components	Failure mode	Effect	Set value	average	Potential cause	Set value	average	Action	Set value	average	Set value	average
ignition	do not ignite the mixture	engine does not start	4	9.3	discharged battery/burned spark plugs	6	3.7	replace the battery/spark plugs.	1	1.3	24	46
	incorrectly ignites	underperforming engine	6	7.7	damage to the sail cables	4	2.3	replace the cables	4	1.7	96	30
Injection	fuel leak	waste of fuel	6	5.7	faulty injector	2	3.7	replace injector	2	8.3	24	173
	Low performance	affects engine performance	6	5.7	damaged centralina	2	2.0	check the ECU	4	9.3	48	106
	does not reach the maximum combustion pre	affects engine performance	6	5.7	damaged centralina	2	2.0	check the ECU	4	9.3	48	106
	incomplete combustion	pollution/decreases efficiency	3	5.0	faulty injector	3	3.3	replace injector	4	8.3	36	139
Lubrication	noise	damage to moving parts	5	5.0	oil leak	6	5.3	replace seals/gaskets	2	1.0	60	27
Valves	incorrect pressure in the combustion chambe	efficiency decreases	6	6.0	deterioration of the valve	2	2.7	replace valves	7	9.0	84	144
combustion chamber	fuel leak	accident risk	10	10.0	inner crack due to wear	1	2.0	check condition of combustion chamber	5	7.7	50	153
piston rods	noise	engine damage	8	8.0	inner crack due to wear	4	2,0	replace pistons/rods	2	3.7	64	59
Segments	fuel leak	power loss	6	6.3	segment wear	6	4.3	replace segments	2	6.3	72	174
Admission	low performance	low performance / efficiency	6	6.7	air filter wear	4	6.0	clean/replace filter	2	4.0	48	160
refrigeration	water leak	engine overheating	4	7.3	Broken tube	7	4.7	replace the tube	2	2.3	56	80
Crankshaft	noise	engine damage	7	7.3	bearing wear	2	2.7	replace the bearings	2	4.7	28	91

Figure 10. FMECA of the engine.

As can be seen in Figure 10, the malfunctions that can be considered as most serious are fuel leaks due to the high risk and low detectability, and also intake problems that may result from clogged or degraded air filters due to the smoke and dust, that are typically characteristic of fighting forest fires.

3.2. Fuzzy Logic

Similarly to the FMECA, the analysis using fuzzy logic will only include the most important data and respective results. The complete and detailed version can be consulted in the database link: https://docs.google.com/document/d/1gBAKl-OHt6Y0xiIK5E57AgH6P6ZEjazdErMD-6ZNxkY/edit?usp=share_link (accessed on 22 June 2023). The access should be requested in case it needs to be consulted.

For comparison purposes, the results obtained in the FMECA are also presented. Recalling that the input parameters have different relevance (greater importance for severity and detectability), the final results will also be different; therefore, failures that were considered minor can turn out to be critical and vice versa.

Furthermore, the four colours that highlight the FMECA's criticality levels become only three in the fuzzy logic, making failures previously displayed in orange evolve to red or yellow in case their criticality is more or less relevant, respectively.

Accordingly, the fuzzy analysis applied to the engine is presented as follows:

From Figure 11 it is concluded that the most serious engine failures are still fuel leaks. Additionally, problems arising from the admission are no longer considered serious, because the probability of occurrence is quite high, which causes the air filter to be checked and cleaned regularly, preventing total failure. On the other hand, the criticality of valve failures increased due to the low ability to detect such faults, and the criticality of ignition failures also increased, due to the high severity, since in case the vehicle's engine does not start, the fire brigade's ability to operate decreases.

			S		O		D	R	R
Major Components	Failure mode	Effect	Average	Potential cause	average	Action	average	Difuse Logic	FMECA
ignition	do not ignite the mixture	engine does not start	9.3	discharged battery/burned spark plugs	3.7	replace the battery/spark plugs.	1.3	39	46
	incorrectly ignites	underperforming engine	7.7	damage to the sail cables	2.3	replace the cables	1.7	36	30
Injection	fuel leak	waste of fuel	5.7	faulty injector	3.7	replace injector	8.3	63	173
	Low performance	affects engine performance	5.7	damaged centralina	2.0	check the ECU	9.3	51	106
	does not reach the maximum combustion pressure	affects engine performance	5.7	damaged centralina	2.0	check the ECU	9.3	51	106
	incomplete combustion	pollution/decreases efficiency	5.0	faulty injector	3.3	replace injector	8.3	48	139
Lubrication	noise	damage to moving parts	5.0	oil leak	5.3	replace seals/gaskets	1.0	30	27
Valves	incorrect pressure in the combustion chamber	efficiency decreases	6.0	deterioration of the valve	2.7	replace valves	9.0	53	144
combustion chamber	fuel leak	accident risk	10.0	inner crack due to wear	2.0	check condition of combustion chamber	7.7	76	153
piston rods	noise	engine damage	8.0	inner crack due to wear	2,0	replace pistons/rods	3.7	45	59
Segments	fuel leak	power loss	6.3	segment wear	4.3	replace segments	6.3	72	174
Admission	low performance	low performance / efficiency	6.7	air filter wear	6.0	clean/replace filter	4.0	49	160
refrigeration	water leak	engine overheating	7.3	Broken tube	4.7	replace the tube	2.3	42	80
Crankshaft	noise	engine damage	7.3	bearing wear	2.7	replace the bearings	4.7	46	91

Figure 11. Fuzzy analysis of the engine.

4. Discussion

As mentioned, to avoid lengthening the article, only important illustrative data and the respective results were presented, with the entirety, in greater dimension and detail, link.

We can observe by the exemplifying data that for comparison purposes the obtained results were presented as it can be verified the colours used to highlight the degrees of criticality. Four colours in FMECA become only three in fuzzy logic, causing the failures previously shown in orange to evolve into red or yellow if their criticality is more or less relevant, respectively. Thus, the most serious faults can be visually detected.

In order to obtain results, assumptions were used in the first stage. Later, three FBs were asked to formulate their own versions with the values they considered to be more accurate. To standardise the data, the average of the corporations was calculated, since the values differed significantly among them in some of the parameters. The average of the data provided by the firefighters was then assumed as real data due to their greater experience and contact with the FFFV.

As the assumptions were found to be very divergent from the actual data, the former was only used for comparison purposes. By relating the two, with the presupposed data, the failures would be underestimated in most cases, thus being discarded from the analyses performed.

The average data were then used to obtain the results of the risk of failure (R) in the FMECA. These results have been highlighted in four different colours as they have a fairly wide range of values from (19–191)in this case.

Subsequently, to perform the analysis using fuzzy logic, the same data as in the FMECA were used. Despite the data being the same, the final results will be different, as greater expression was attributed to severity and detectability, with reduced relevance for the occurrence.

For example, in the case of FMECA, failures with the same input values will obtain the same result for R, whereas in fuzzy logic, when the data is assigned to different parameters, different RPNs will be returned, thus making the analysis more meaningful, as can be verified by Table 12.

Table 12. Comparison between R (FMECA) and RPN (Fuzzy Logic).

Failure	S	O	D	R (FMECA)	RPN (Fuzzy Logic)
X	5	8	7	280	72.0
Y	8	7	5	280	74.6
Z	7	5	8	280	83.7

Despite the faults and their S, O and D values being merely hypothetical, it can be concluded that, through fuzzy logic, we were able to sort them in order of criticality, while the FMECA always returns the same value, thus strengthening the importance of fuzzy analysis in this work.

The results obtained from fuzzy logic range from [23–76], therefore, it was decided to group the low and very low criticality and high and very high criticality, highlighting the results with just three different colours: green for low criticality, yellow for moderate criticality and red for high criticality, as mentioned previously.

It can then be stated that the most serious faults are highlighted in red in the analysis using fuzzy logic. Thus, organised in ascending order of criticality, they are:

- Faults associated with engine valves which, due to deterioration, are no longer airtight and compromise engine performance. If the valve breaks completely, it will damage other engine components;
- Heavy tyre wear due to the conditions of the terrain in which the FFFV normally operates;

- Localised tearing, cracking or cuts in tyres which can be caused by driving on rough roads, skidding on gravel or stones, or manoeuvring when stationary in the woods;
- Fatigue or wear of the gearbox bearings, which can result from the high stresses that the gearbox undergoes or from inadequate lubrication;
- Failure of one or more injectors leading to increased fuel consumption, if they are continuously dripping diesel. If excessive fuel enters the combustion chamber black smoke will also come out of the exhaust pipe;
- Air leaks in the pneumatic suspension which, being a very critical system, is not commonly used in FFFVs;
- Damage to the gears of the gearbox, which makes it difficult to engage the different gear ratios and, in an extreme situation, may even lead to the inoperability of the vehicle;
- Wear of the piston compression rings, leading to a loss of engine sealing, resulting in oil passing into the combustion chamber and fuel passing into the oil, leading to increased oil consumption, emission of white smoke from the exhaust pipe and poor performance;
- Cracked combustion chamber or engine block as a result of continuous wear, and aggravation by overheating due to proximity to fires.

Once the problems are identified, the need for regular inspections to control the condition of the components is reinforced, as well as an increase in preventive maintenance, replacing critical elements before their failure. Although preventive maintenance does not take advantage of the component's full potential, it turns out to be a good strategy, since by replacing the part prematurely, the breakdowns that would arise due to the failure of the former are avoided, thus reducing costs in the long term.

To increase the effectiveness of this strategy, it is necessary to keep records of all interventions performed on the vehicle, thus forming a breakdown list. By keeping this log, as the life of the FFFV evolves, more data will be available to allow a more accurate estimate of the best time to replace a component, thus finding the optimum balance between the part's durability and failure prevention.

According to the data obtained in this study, preventive maintenance must be performed primarily on the replacement of valves, injectors and piston rings; great attention must be paid to fuel leaks in the engine and noise coming from the gearbox; and the tyres must be constantly and thoroughly checked, on the tread and both sidewalls, keeping in mind that some damage only becomes visible when it is close to contact with the ground.

The authors are aware that the scarcity of data is always a limitation that implies the use of more powerful and complex tools such as the one presented in this work. The adoption of maintenance policies that value the operator that reports and cooperates in the entity's maintenance strategy can be a facilitator of obtaining data. Together, the evolution of data acquisition with non-intrusive physical systems could greatly increase the amount of information available. Nowadays, variables such as temperature, vibrations, pressure and fuel consumption, among others, can be easily monitored with modular systems. Facilitating the early detection and prevention of failures, can be completed using machine learning algorithms that can generate alerts. Thus, it will be possible to improve security based on predictive maintenance systems.

That said, still it is advisable to have a mandatory and rigorous inspection plan and maintenance programme, accompanied by fault records in order to optimise preventive maintenance.

Despite the presented normatives or standards, the level of maintenance and assessment of the tools specified are unfortunately at this moment of very low development and application in the general firefighting brigades. The main reasons for this lacking are the high cost of certain types of maintenance programs and the absence of knowledge about effective maintenance plans and procedures which can pay back economic and safety profits. The development of easy and friendly maintenance procedures such as the ones presented in this work are needed for a better function of our emergency systems and for the safety of the workers of the referred systems.

5. Conclusions

Through direct contact with firefighters, it was possible to acquire knowledge about which would be the most relevant vehicle to fight forest fires. The selection was unanimous, and the target vehicle of study was the Forest Fire Fighting Vehicle (FFFV).

In order to study the general mechanical condition of the FFFVs, it was necessary to begin by deepening the knowledge about them, investigating their main equipment and the procedures used to maintain them in proper operating condition. It was quickly perceived that, although vehicles from different manufacturers and with different ages were being analysed, most of the main equipment was similar and the inspections and maintenance carried out on each vehicle were the same within the same fire brigade (FB).

Additionally, when contacting different FBs, it was found that there are no standardised inspection and maintenance programmes, leaving it up to each fleet manager to execute his own plan. This way, some of the tasks that should be performed to maintain the vehicle's competence end up being neglected (or performed in excessively long time intervals).

Research was then carried out on which failures could occur in the components of the different systems of these vehicles, what their potential causes were and what treatment action should be taken. Through the collaboration of firefighters from the different FBs, a degree of severity, probability of occurrence and detectability was assigned to each fault, thus forming a Failure Modes, Effects and Criticality Analysis (FMECA).

Next, it was essential to perform a new analysis with the same data, but this time using fuzzy logic since the data used was mostly linguistic, where information could be imprecise, vague, uncertain or incomplete.

Through the analyses carried out, it was found that many of the potential failures represent a risk, not only for the functioning of the FFFV, but also for the safety of its operators (firefighters). For these faults and for those that have a low detectability, which means that specialised personnel are needed to identify them, preventive maintenance should be carried out. On the opposite hand, when the severity of the fault is low and detectability is high, corrective maintenance can be executed.

Along this study, the importance of carrying out inspections, maintenance programmes and recording the interventions carried out was proven.

Hence, if the techniques presented here are implemented:

- Condition monitoring of components during inspections to assess the evolution of their state over time;
- Conformity tests, such as the SAROCA tests and the coupled pump operation test, to ensure that the various systems are working properly;
- Maintenance logbook, where a full record is made of all faults along with the date of the breakdown, the kilometres the vehicle had at the time, what repair was performed, the materials used, how long it took for the vehicle to be available again and what was the cost;

It will be possible to reduce serious failures and avoid long periods of inoperability because there is a strategy that not only prevents breakdowns through early replacement of end-of-life components, but also allows faults to be detected during systematic inspections providing the right approach to any failure that may actually occur.

In the future, thanks to the registration of data, a more systematic and comprehensive analysis can be carried out, with factual information, allowing the use of stochastic and other models, in order to achieve the required reliability.

In future works, it would be interesting to deepen the study and include systems that are not part of the main mechanics of the vehicle, such as the coupled pump and the vehicle fire protection systems (sprinklers). In addition, it would also be an advantage to carry out similar studies for other types of firefighting vehicles, or even for other emergency response units. The applicability of this type of research on emergency vehicles can be significant in developing international standards for emergency vehicle maintenance, ensuring consistent practises across different countries and organisations. This can facilitate interoperability and exchange of knowledge and best practises. Technology in future work can explore the use of predictive maintenance systems and remote diagnostics for emergency vehicles. These advancements can enhance maintenance practises by enabling real-time monitoring, early detection of issues, and proactive maintenance interventions.

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