RCM3 Methodology Application to Pandur II 8x8 Cooling System

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Abstract: The evolution of the maintenance paradigm over time has led to several changes, both in the maintenance tasks performed and in the objectives of maintenance and asset management, assuming itself as an area of fundamental interest for organizations. In the specific case of the Portuguese Army, the process of gradual modernization that it goes through, has resulted in the increase of the complexity of the equipment at its disposal, which brings new challenges to maintenance and to the ability of maintain (in an effective and efficient way) the operational readiness of the equipment, always with the aim of reach the appropriate cost level.

In this study, the RCM3 maintenance methodology was applied to the Pandur II 8x8 cooling system. This methodology focuses on the reliability of the equipment and allows to identify and evaluate the risks associated with the failure modes presented, as well as developing appropriate strategies to manage and minimize these risks.

The study starts with the review of the applied methodology principles, and some concepts used throughout this assignment. A functional analysis of the studied system is performed, followed by an analysis of failure modes and effects. After defining and quantifying the risk, the respective mitigation actions are proposed according to the RCM3 decision process. Finally, the proposed actions were compared with the existing maintenance plan and conclusions were drawn about its suitability, the robustness of the system studied, and the existing gaps in the Pandur II maintenance management process in the Portuguese Army.

Keywords: Maintenance, Reliability, RCM3, Pandur II, Portuguese Army.

1. Introduction

The demand associated with the Army's missions, whether in national territory, or abroad in detached national forces, combined with the degree of readiness that is required, demands a great availability by the human resources, and the equipment at their disposal. In this way, maintenance undoubtedly plays an essential role in the proper functioning and reliability of equipment, being responsible for ensuring that they fulfill their task when requested.

The Pandur II 8x8 weapon system is a modern, versatile equipment of major importance for the Portuguese Army and for the fulfillment of its mission. This acquisition marked a new phase in the modernization of the Portuguese Army, and it has been widely used both nationally and abroad, having participated in exercises in Lithuania and more recently employed In the Central African Republic theater of operations.

Once Pandur II is one of the most recent equipment at the service of the Portuguese Army and used by few countries in NATO (apart from Portugal only Austria and the Czech Republic use this Pandur version), makes it an equipment that is still a little unknown, in terms of maintenance needs and requirements (caused by its continued operational use). In this way, Portugal follows the manufacturer's indications and executes the maintenance plan proposed by the manufacturer, therefore there is room for a critical analysis and adaptation to the needs arising from the known use of the Pandur II, during the time it has been at Portuguese Army service.

The cooling system was chosen to be analyzed in this study because it is one of the systems with the highest incidence of failures, and improvement potential. Of the total of 2038 corrective work orders analyzed, 126 are related to the cooling system, which corresponds to about 6.2% of the failures recorded for the entire weapon system.

This paper describes the application of the RCM3 methodology to the Pandur II cooling system, to review the suitability of the current maintenance plan and propose possible improvements.

2. Literature review

There are currently several definitions of the concept of maintenance in the literature, two of which are presented below.

The European standard EN 13306:2017 defines maintenance as "the combination of all technical, administrative and management actions performed during the life cycle of an item with the intention of maintaining or restoring it to a state where it can perform the intended function" [1]. In turn, the definition proposed by John Moubray in his work "RCM II - Reliability Centered Maintenance" [2] (one of the reference works regarding the application of the RCM methodology) also adopted by Marius Basson in his work "RCM3: Risk-Based Reliability Centered Maintenance" [3] (a current review of Moubray's work) considers that maintenance corresponds "to ensure that physical assets continue to do what their users want them to do". In this way, it is easily perceived that maintenance serves to maintain the desired level of operability of a given system in service, to ensure that it can fulfill its function.

2.1. RCM3 Methodology

The RCM methodology origin is related with the commercial aviation industry and arose from the need to increase the reliability of the aircraft and decrease the costs associated with their maintenance actions.

In 1960 and drawing on the information available about the failure of the already large fleet of aircraft in the United States, the American aeronautics industry developed a comprehensive and exhaustive process to select the most appropriate maintenance actions to keep the aircraft in operating condition. Later in 1978,' Nowlan and Howard Heap from United Airlines, prepared a report for the U.S. Department of Defense [4] where the RCM designation was used for the first time, and which served as the basis for formulating the maintenance strategy called MSG-3 [5], which is still used today by much of the commercial aviation industry to develop and refine maintenance programs [2].

The RCM process quickly spread to other areas outside aviation, and since 1978 several versions of Nowlan and Heap's work appeared, which were also called RCM, however, and although some of these versions presented improvements and optimizations of the original process, many others appeared, less rigorous and with attempts to speed up some of the steps of the original procedure, which would turn out to be inaccurate and with different results from a "true" RCM methodology. In order to obtain a credible procedure that could be used without misunderstandings, the first standard related to this subject, the SAE JA1011 [6], was published along with the associated guide SAE JA1012 [7], in 1999. One of the most remarkable assignments in the area was, as previously mentioned, the methodology proposed by John Moubray (RCM 2) which would become a reference work even in the definition of the previous standards and widely used by several organizations in different areas of industry [8].

The RCM methodology allows to develop and optimize maintenance programs for physical systems, and when correctly applied allows to increase their reliability, which results in several other positive results such as reduced downtime, decreased associated costs, increased security, and productivity. It also allows to get maintenance programs with a much lower amount of programmed work than traditional methods and when used for the revision of existing maintenance programs it allows to obtain a decrease in the amount of programmed maintenance, usually in order of 40% to 70%.

The SAE JA1011 standard defines "RCM as a specific process used to identify the policies that must be implemented to manage the failure modes that can cause the functional failure of any physical asset in a given operational context" [6]. The European standard BS EN 60300-3-11 states, in turn, that "RCM is a method for identifying and selecting fault management policies in order to efficiently and effectively achieve the desired safety, availability and economy of operation" [9]. Finally, to define the RCM3 in concrete terms, its author, Marius Basson, assumes it as being "a process used to define the minimum necessary and safe number of maintenance actions, engineering and other risk management strategies to guarantee a tolerable level of safety, environmental integrity and profitable operational capacity, as specified by the asset management standards of the organization in which it is inserted" [3].

In general, the RCM process is divided into 5 stages, which represent in a generic way a synthesis of the logical sequence of work that must be performed during the implementation of this analysis [9]:

- Establishment and planning of the RCM;
- Functional failure analysis;
- Task selection;
- Implementation;
- Continuous improvement.

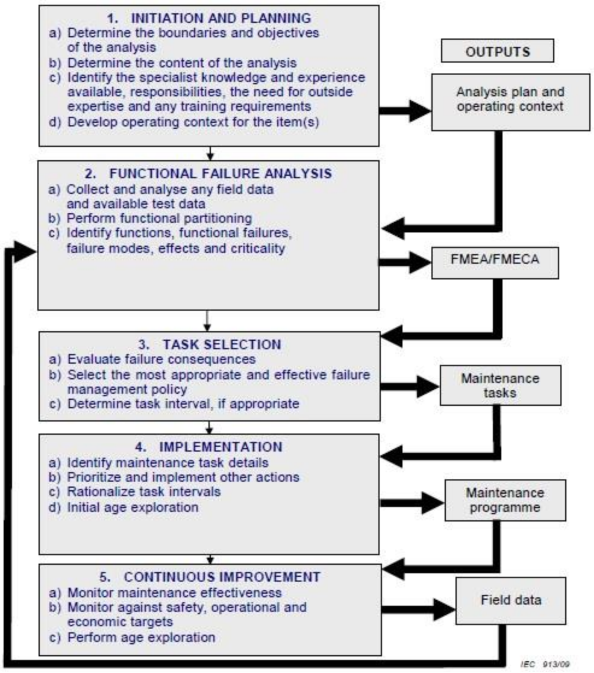

Figure 1: RCM Overview [9]

The RCM3 process, requires 8 questions to be answered throughout its application [3], [7]:

1. What are the operational conditions?
2. What are the functions and performance standards associated with the asset in its current operational context?
3. How does the asset fail to perform its functions?
4. What causes each failure state (failure modes)?
5. What happens when each failure occurs?
6. What are each failure associated risks (quantification of inherent risk)?
7. What should be done to reduce intolerable risks to a tolerable level (use of proactive risk management strategies)?
8. What can be done to reduce or manage the tolerable risks in an economically viable way?

2.2 Censored Data

When analyzing failure data, we are often confronted with poor quality (less relevant information or lack of data registration) or even incomplete information. Regarding existing data (whether from tests or actual operational context), it is practically impossible to obtain all the elements of a system, which requires estimates and approximations of the distribution parameters according to the available data. If all the systems/components are analyzed until the failure occurs (the failure time of all the components of the sample is known) the obtained data are complete. If in turn, there are components whose failure time is unknown (because it did not occur during the analysis period or because it is not possible to access the information) it is said that the data are censored [10].

Right Censored Data

A certain system failure time is said to be censored on the right, if its exact failure time is not known, and it is only known that it is going to fail after the final time of information recording (either the test completion time or the operational data collection limit time). In this case, we only know when the asset is put into service, but not when it will fail [11].

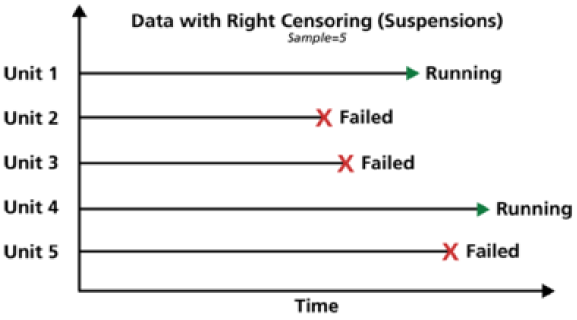

Figure 2: Right Censored Data [11]

Right censored data can also be divided into Type 1 and Type 2 data [11]:

- Type 1: Data collection ends after a pre-determined time. Observation time is fixed.
- Type 2: Data collection ends after a predetermined number of failures occurs (defined at the beginning of the analysis).

Weibull Distribution

There are currently available in the literature several probability distributions that can be used to model the useful life of an asset, despite the great variety of available mathematical models, this paper will address the Weibull distribution which due to its characteristics address the distribution of Weibull, which due to its characteristics becomes very versatile, constituting one of the most used models to represent assets life in reliability analysis [10], [12].

Weibull's distribution corresponds to a semi-empirical expression developed by the Swedish Ernest Weibull in 1939. It is a suitable distribution for assets with several components and for cases where the failure rate may or may not be constant, and where it is considered that the failure is caused by the most serious imperfection. This distribution can assume several shapes, and the standard model corresponds to the 2-parameter distribution [13]:

$$F(t,\eta,\beta) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (1)$$

The location parameter η, corresponds to the lower limit of the domain t considered, and represents the asset life without failure, which means, the time interval for which no failure occurs. The shape parameter β is a non-dimensional value, responsible for the shape of the distribution, and translates the mechanism of asset degradation, allowing to relate the distribution with the different asset life phases [14]:

- β=1: the probability density function of the Weibull distribution takes the form of the exponential distribution. In this case the failure rate is constant and given by λ= 1/η, which allows representing the useful life period;
- β<1: the probability density function takes the form of the gamma distribution. In this case the failure rate will be decreasing, which is suitable for the period of infant mortality;
- β>1: the probability density function takes the form of the normal distribution (if β=3.5) or the log-normal distribution (if β=2). In this case the failure rate is increasing, making it appropriate to represent the period of wear.

Once the reliability is the complement to the probability of failure, it is possible to write [13]:

$$R(t) = 1 - F(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (2)$$

The probability density function of this distribution is represented as:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (3)$$

Considering equations (2) and (3), the failure rate can then be defined, in terms of Weibull distribution, as follows:

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \qquad (4)$$

Another relevant reliability concept is Mean Time Between Failures (MTBF), which for the Weibull distribution is given by the average of the statistical distribution, which is described by the following equation (where Γ is the gamma function):

$$MTBF = \bar{T} = \eta\Gamma\left(\frac{1}{\beta} + 1\right) \qquad (5)$$

It is possible to find in the literature several methods that allow estimating the parameters of the Weibull distribution, η, β, in the case of the standard model of two parameters. These methods are essentially divided into two types: graphic methods and analytical (or statistical) methods [12].

Graphic methods:

The graphic methods allow to obtain in a simple way the parameters of the Weibull distribution through the graphical representation of the data corresponding to the failure times in analysis and are a good alternative to obtain a first approximation of the distribution parameters [12]. According to Abernethy [15] the "WPP" method - "Weibull Probability Plotting" is the most used graphic method to determine the Weibull distribution parameters, being widely used by most of the software currently available on the market. This method is based on the linearization of the accumulated probability function (equation (2)), which is obtained by performing twice the logarithm of that function, obtaining the following equations [12], [13], [15]:

$$\ln\big(R(t)\big) = -\left(\frac{t}{\eta}\right)^{\beta} \qquad (6)$$

$$\ln\big[-\ln\big(R(t)\big)\big] = \beta\ln(t) - \beta\ln(\eta) \qquad (7)$$

Considering:

$$Y(t) = \ln\big[-\ln\big(R(t)\big)\big] \qquad (8)$$

$$B = -\beta\ln(\eta) \qquad (9)$$

$$X = \ln(t) \qquad (10)$$

And simplifying:

$$Y(t) = \beta X + B \tag{11}$$

The equation (11) allows to dimension the Weibull probability plot which is represented by a straight line when it is verified that the distribution fits the sample data set. This equation is obtained by linear regression of the set of points made up on the X axis by the logarithm of the failure times (equation (10)) and on the Y axis by the logarithm value of the accumulated probability of failure (F(t)) for each of the failure times (equation (7)). Without the values of η and β, the value of F(t) is unknown and it is necessary to estimate it using the following estimators, where i represents the order number of the failure time and n represents the total number of data corresponding to failure times (incrementally ordered) of the sample [12]:

$$F(t) = \frac{i}{n} \tag{12}$$

$$F(t) = \frac{i}{n+1} \tag{13}$$

$$F(t) = \frac{i-0{,}5}{n} \tag{14}$$

$$F(t) = \frac{i-0{,}3}{n+0{,}4} \tag{15}$$

$$F(t) = \frac{i-\frac{3}{8}}{n+\frac{1}{4}} \tag{16}$$

Analytical Methods:

Analytical methods can be considered more complete, when compared with graphic methods, since they can be considered more general and applicable to all types of models and data sets, and whose underlying theory allows a good understanding of the asymptotic properties of estimators [12]. There are several estimators in the literature that can be used to determine the Weibull distribution parameters. This paper focuses the Maximum Likelihood Estimator (MLE) method, since it is one of the most widely used methods today due to its great versatility and capacity to produce reliable results. This estimator uses the maximization of the probability function of the statistical model in question (in this case the Weibull distribution) to obtain the parameters that characterize its distribution [16], [17].

In many cases, the probability function is very complex, and it is not possible to obtain an analytical solution which requires the use of numerical methods to obtain an approximate result [16], [17].. Resort to the literature it is possible to find the likelihood function for the distribution of Weibull [12], [18]:

$$L(\eta,\beta) = \prod_{i=1}^{n} \frac{\beta}{\eta} (\frac{t_i}{\eta})^{\beta-1} e^{-(\frac{t_i}{\eta})^{\beta}} \tag{18}$$

Since this is a monotonically increasing function, it is equivalent to maximizing the likelihood function or its logarithm, and in many cases, it is easier to maximize the logarithm than the likelihood function itself:

$$\ln\big(L(\eta,\beta)\big) = \sum_{i=1}^{n} \ln\left[\frac{\beta}{\eta}\left(\frac{t_i}{\eta}\right)^{\beta-1} e^{-\left(\frac{t_i}{\eta}\right)^{\beta}}\right] \tag{19}$$

As previously mentioned, the objective of this model applied to the Weibull distribution is to determine the values of η and β that maximize the previous function, which can be done using numerical methods. It is also possible to apply this estimator to censored data sets. We only present the equations corresponding to the application of the model for the Weibull distribution with Type 1 right censored data because is the used in this paper. For this case, the likelihood function is represented as follows [12], [18]:

$$L(\eta,\beta) = \prod_{i=1}^{n} [\frac{\beta}{\eta}\left(\frac{t_i}{\eta}\right)^{\beta-1} e^{-\left(\frac{t_i}{\eta}\right)^{\beta}}]^{\delta_i} \quad [e^{-\left(\frac{t_i}{\eta}\right)^{\beta}}]^{\delta_i} \tag{20}$$

All that remains is to apply the logarithm to this equation for convenience and use a numerical method to maximize it.

3. Case Study

The case study consists in the application of all the steps defined by the RCM3 methodology to the Pandur II cooling system, to obtain a proposed maintenance plan. The Portuguese Army as the branch of the Portuguese Armed Forces responsible for the ground component of military operations is equipped with several armored vehicles, which include the Pandur II 8x8. The Pandur II, manufactured by Steyr Daimler Puch Spezialfahrzeug GmbH, is classified as personnel transport armored vehicle (VBTP), have been at Portuguese Army´s service since 2009 and have been equipping the units of the Intervention Brigade and the FND (specifically the FND in the RCA theater of operations) since 2019.

The Portuguese Army possesses a fleet of 188 Pandur II, divided in 9 different types, which allows to have a great versatility in its tactical and operational use. Despite these 9 different types of vehicles, all of them possess the same cooling system.

According to the classification made by the "Operator's Manual", the cooling system is part of the vehicles “Power Pack”. This system is controlled by the water pump (which is mounted on the motor) and by a V-belt, and it is divided into 2 circuits, which are called large cooling circuit and small cooling circuit. The small circuit cools the motor and the hydraulic oil, transmission, and drive axels heat exchangers. In its turn, the large circuit cools the cooling fluid on the radiator [19]:

Operational Context

The first task to do after the definition of the system to be studied in RCM3 analysis is definition of the operational context [3]. Regiments equipped with Pandur II are predominantly distributed in the north of Portugal (in regions of Porto, Braga, Viseu and Vila Real). The climate in this region of Portugal is classified as temperate climate with rainy winter and dry and not very hot summer (in most of the region) and temperate climate with rainy winter and dry and hot summer (in Vila Real). In the last 10 years, between 2009 and 2019, the average annual temperature recorded for this region (data regarding the meteorological stations of Bragança, Porto and Viana do Castelo) was 14.5 ºC, the maximum temperature (on average, recorded for the warmest month of the year) was 27.5 ºC and a minimum temperature (on average, recorded for the coldest month of the year) of 3.1 ºC. This range of temperature values, allows the conclusion that the vehicles were used in mild weather conditions, without extreme temperatures [20]..

On national territory, the Pandur II are used in operational training, with the aim of maintaining the tactical capabilities and readiness of the forces they equip and are engaged in Portuguese Army exercises and brigade sectorial exercises. As they are vehicles for military use, it is assumed that they travel on paved roads, but also on all-terrain roads, and in Portugal it is possible to assume that they are used, generally, in terrain with good access and mobility.

Functional Analysis

To be able to perform a functional analysis of the refrigeration system, it was necessary to identify the boundaries of the system, which means to clearly identify which components are part of the refrigeration system and will be analyzed. After this, all the system component’s functions were identified and recorded in the proper sheets used to record all the RCM3 process information.

Failure Modes Analysis

After the functional analysis was carried out, the failure modes for each of the analyzed components were identified. This was done by recording all the failures that have occurred for this system, which corresponds to a total of 126 work orders relating to the cooling system in the period from January 2014 to April 2020. In addition to the failure modes that could be identified in the recorded failure occurrences, a critical analysis (engineering analysis) was also performed to complement the analysis with possible (and likely) failure modes for the components of the cooling system.

Failure Effects

The description of the failure effects is a very important phase, as it provides the necessary information for the risk analysis that is carried out for each failure mode identified. In this description, as the name indicates, the consequences resulting from the failure modes have been defined, both the operational consequences and the warning signs of the occurrences and their estimated frequency (used to define the probability of the failure mode when performing the risk analysis). Both the consequences and the warning signs of the occurrence have been evaluated considering the characteristics of the cooling system mentioned in the technical manuals. The frequency of occurrence of the failure modes, in turn, has been evaluated by estimating their Mean Time Between Failure (MTBF). For the failure modes with lack of failure information, it was considered that its probability of occurrence was low.

To estimate Weibull distribution parameters (to be able to estimate the MTBF values) was used the WPP method previously described in this paper, in section 2. The reliability estimator used in this method was the Herd-Johnson estimator, which corresponds to equation (13), because it was the estimator that allowed to obtained better results to this data sets (higher R^2).

Attending to the failure information in the analyzed work orders, was possible to estimate the MTBF for 4 failure modes. failure modes have the same MTBF and therefore the same Weibull distribution parameters.

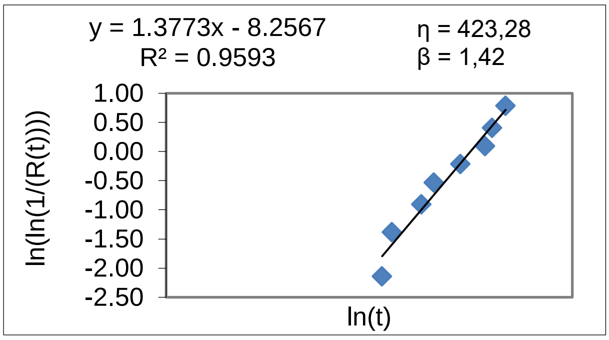

Figure 3: Weibull Probability Plot - Water Sensor

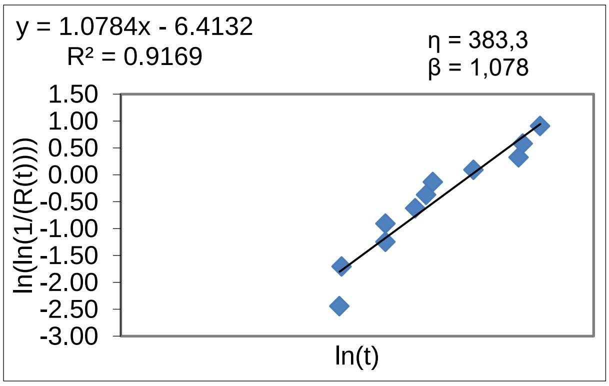

Figure 4:Weibull Probability Plot – Decompression Valve

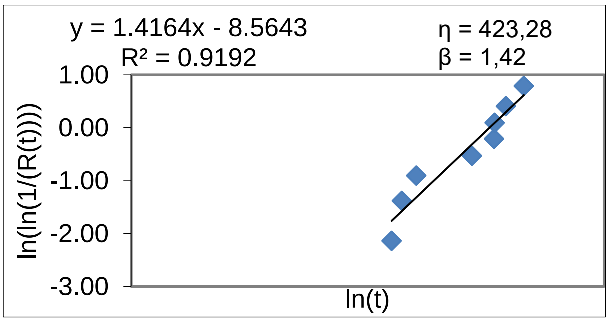

Figure 5: Weibull Probability Plot – Radiator Dirt

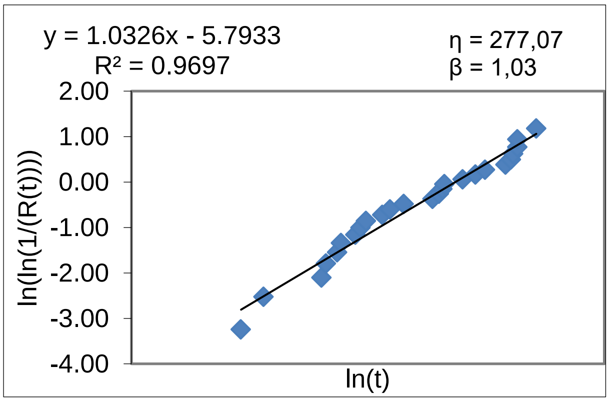

Figure 6:Weibull Probability Plot – Leaks

After this first estimation was applied to this results the Maximum Likelihood Estimator method, as was described previously in this paper section 2, in order to obtain a more accurate result for the Weibull distribution parameters, because the used failure data sets were a typical Type 1 right censored data sets. The application of this algorithm (it was used the Excell solver to maximize the maximum likelihood function) allowed to obtain the Weibull distribution and MTBF values:

Table 1: Right censored data results

	MTBF (Engine Hours)	**First Estimation**	**Obtained Parameters**
Water Sensor	4134,37	η = 401,97 β = 1,38	η = 4330,66 β = 1,14
Decompression Valve	3696,19	η = 382,30 β = 1,078	η = 3267,94 β = 0,8
Radiators Dirt	3478,83	η = 423,28 β = 1,42	η = 3742,36 β = 1,26
Leaks	1827,43	η = 277,07 β = 1,03	η = 1514,86 β = 0,74

Risk Analysis

The risk associated to each failure mode identified, was determined according to the proposed methodology by Marius Basson [3] which defines the risk as the combination of the failure mode severity and its probability of occurrence.

$$Risk = Severity \times Probability\ of\ Ocurrence \qquad (21)$$

For this RCM3 analysis was created a specific risk matrix with 5 levels of Severity and 5 levels of probability of occurrence. The severity was classified under 4 parameters of consequences: Security and Health, Environmental, Operational and Economical. The combination of both this parameter allows to rank the risk in 25 different levels divided into 4 categories (low, medium, severe, and high). If the risk ranking corresponds to a severe or high classification, then it is unacceptable, and something must be done to reduce the associated risk.

Risk Mitigation Strategies

After the risk analysis, risk mitigation strategies were defined based on RCM3 decision diagram.

4. Results

The new maintenance plan ads 4 new tasks and proposes to change 2 task time intervals. The proposed verification of warning systems, such as engine temperature indicator and fluid and transmission emergency lights, allows to ensure that potential vehicle overheating related to cooling system failures are detected in a timely manner to prevent serious consequences in terms of other associated failures that may result.

The decision to change the inspection time intervals of the water pump belt and coolant hoses from biennial to annual was due to water pump belt failures and hose related leaks with failure times of less than two years (or 500 equivalent engine hours). The inspection was planned to be performed every two years because the visual inspection requires the removal of the Powerpack from the vehicle to access the referred components. Thus, reducing the inspection periodicity to one year requires the acquisition of an optical system (inspection chamber) that allows visual checks to be made without the need to remove the Powerpack (to avoid overloading the work related to periodic maintenance and thus avoid accumulating work and revising be more time consuming). This is an equipment that can be valuable for Portuguese Army maintenance teams, since it allows inspections to be made in inaccessible places without the need to remove the Powerpack, which allied to the fact that it is a portable equipment, makes it available to be used both in workshops and by contact teams in campaign, and can also be used to inspect not only the cooling system, but all systems whose components are inaccessible to the naked eye, allowing greater ease and frequency in the inspections performed.

It has also been proposed to program the replacement of the fast link seals every seven years (it can be done every eight years if the inspection at the end of the seven years does not coincide with an inspection involving the withdrawal of the Powerpack) or in an equivalent manner 1750 Engine Hours. This decision was made, since for failure modes related to seal degradation was made.an MTBF estimate of 1827 Engine Hours and because it is the most recurrent type of failure in the cooling system.

This is an intervention with an acceptable cost (the replacement of the seals of the entire fleet will cost 1782

euros, which represents per vehicle and per year a cost of about 1.41 euros) and it is considered that it can reduce considerably the occurrence of failures of this type.

Another proposed task was to clean the radiator every 10 years, since it is a very important component for the operation of the cooling system and with an estimated MTBF of about 2500 Engine Hours, which is equivalent to about ten years. This cleaning is considered necessary because it is a military equipment, which is used in off-road conditions which is a propitious terrain to the accumulation of dirt in this type of components (that is why it has been chosen to maintain the suction of the radiator annually as well). The calculation of the Weibull distribution for this mode of failure, allowed to obtain a value of $\beta \approx 1$, which reveals the random character of the occurrence of these failures, and allows to conclude that the accumulation of dirt in this component is caused and is due to the operational context in which the Pandur II are used. For the other two components where MTBF (level sensor and decompression valve) calculation was also performed, no scheduled maintenance actions were proposed, corrective maintenance having been defined as the risk management strategy to be adopted, since those are components with high MTBF values (much higher than the number of engine hours that any vehicle currently has), with random failure character and where there is no information on indicators that can be used to perform condition based maintenance.

Resorting to existing life component databases, its possible to check for several of the components that form the cooling system, that these are items with typically large MTBF values. This combined with existence of very few information related with automobiles cooling system maintenance in the literature, corroborates the decision of apply corrective maintenance to most of this system components, and not condition based maintenance, for instance.

5. Conclusions

By taking stock of the work carried out, it is possible to draw a series of lessons regarding the maintenance of the

Pandur II cooling system, both in terms of the procedure related to the recording and processing of information related to failures, and in terms of the maintenance tasks carried out, which have resulted in a set of proposals that are believed to bring improvements to the Portuguese Army in terms of the execution and management of the maintenance of the Pandur II weapon's system and which can be extended to all Army equipment. Taking this in consideration, besides the proposed maintenance plan, this paper has identified the need to improve the recording of failures in the Portuguese Army:

- Obligation to include information about the failure mode in the failure records. Can be used, for instance, the failure modes identified in this dissertation;
- Obligation to include Engine Hours, Kilometers and Power Train Hours information in the failure records;
- Definition of a generalized procedure to be used when opening and closing work orders, so that the time they are open effectively corresponds to the time since the fault was detected until it was repaired.

After the analysis made during this dissertation, it is possible to conclude that this is a robust system, with several components with few or no failures, and in the case of the components with more recurrent failure modes, they present high MTBF values. In the case of the latter failure modes, the determination of the Weibull distribution associated with them revealed values of the parameter β close to 1, confirming that the failure rates reveal that the components are in the life stage, presenting random failures and difficult to predict.

The manufacturer's maintenance plan also proved to be adequate, requiring only a few adjustments in order to mitigate the risks associated with the most recurrent failure modes, however the impossibility of obtaining failure rate values (or MTBF) that forced the use of databases, becomes a limitation, as it prevents maintenance actions from being defined for these components, with greater accuracy and more appropriate to the reality of the life of this specific system. Another added value of this dissertation lies in the fact that it has shown that it is possible to perform an analysis of this kind, without the need for major investment and with resources to tools available in the Portuguese Army.

Regarding the application of the RCM3 methodology, it brought some differences from the RCM2 methodology, namely:

- The operational context of the equipment under analysis was taken into account, which allowed operational requirements associated with the use of Pandur II to be taken into account;
- The failure modes were divided into cause and mechanism, identifying the concrete failure, and the potential cause that will be at its origin;
- The risk analysis and the decision diagram took into consideration the consequences and environmental sustainability;
- The description of the failure effects is made in a more detailed way and providing more information to support the decision;
- The RCM3 decision diagram itself presents some differences from the RCM2 decision diagram in the way it proposes to handle and treat risk.

Limitations

During the execution of this work, some limitations have arisen that have been assumed and often forced to adopt simplifications, which have an influence on the development of the work and the application of the methodology, and consequently influenced the obtained results. Another limitation with great importance for the work and the results is related to the work orders (documents where the maintenance actions are registered) and the information recorded in them. Many of the work orders analyzed did not present a description of the type of failure (referring only, as an example: inoperative level sensor), which difficult the identification of the failure mode in question and led to the assumption in this dissertation that the probability of occurrence was the same for all failure modes related to the same component (as was the case with the level sensor, for example), which is not true. Besides the lack of detail in the description of the failures, it was also found that several work orders did not contain the information relative to the number of engine hours, or mileage of the vehicle on the date the failure occurred, which makes it impossible to determine the associated failure time. These gaps led to several work orders regarding the cooling system not being used in this dissertation (specifically in the MTBF determination part). Another inaccuracy identified in the work orders is related to the time between opening and closing the order, there being cases with duration of 0 hours and others with duration of 78000 hours, which revealed to be unreliable information that was disregarded.

Future Works Proposals

Finally, following the work done in this dissertation, the following future works are proposed:

- Extend the RCM3 analysis to the whole Pandur II weapons system, treating it as a single system;
- Adopt this methodology for another Portuguese Army weapon's systems;
- Use models with Petri Nets, as a representation of the real dynamics of the process including failure conditions;
- Analyze the feasibility of applying predictive maintenance strategies related to the application of mathematical and computational models, involving artificial intelligence models, to the cooling system;
- Awareness raising of all actors involved in the management and execution of weapons systems maintenance for the more accurate and objective recording of work orders regarding system failures in order to facilitate the collection and processing of reliability data, namely regarding failure rates.

References

[1] BSI, *BS EN 13306:2017 - Maintenance Terminology*. United Kingdom, 2017.

[2] John Moubray, *RCM II - Reliability Centered Maintenance*, 2nd Editio. Oxford, 1997.

[3] Marius Basson, *RCM 3: Risk-Based Reliability Centered Maintenance*. South Norwalk: Industrial Press, INC., 2018.

[4] F.S.Nowlan and Howard Heap, "Reliability centred maintenance," 1978.

[5] Maintenance Steering Group - 3 Task Force, "Maintenance Program Development Document MSG-3," Washington DC, 1983.

[6] SAE, *SAE JA1011 - Evaluation Criteria for Reliability-Centered Maintenance (RCM) Process*, vol. 4970. United States of America, 2009.

[7] SAE International, *SAE JA1012- A Guide to the Reliability-Centered Maintenance (RCM) Standard*. Warrendale, Pensylvania, United States of America, 2002.

[8] The Aladon Network, "Aladon - Reliability Centered Maintenance (RCM)," 2020. [Online]. Available: https://www.thealadonnetwork.com/about-aladon/methodologies/reliability-centered-maintenance-rcm/. [Accessed: 19-Mar-2020].

[9] "BS EN 60300-3-11 : 2009 BSI Standards Publication Dependability management — maintenance," 2009.

[10] M. Rausand and A. Hoyland, *System reliability theory*, 2nd Editio. New Jersey: John Wiley and Sons, Inc., 2004.

[11] ReliaWiki, "Life data classification," 2015. [Online]. Available: http://reliawiki.org/index.php/Life_Data_Classification. [Accessed: 18-Sep-2020].

[12] D. N. Murthy, M. Xie, and R. Jiang, *Weibull Models*, vol. 100, no. 471. New Jersey: John Wiley and Sons, Inc., 2004.

[13] R. M. Gondim and M. A. V. Duarte, "Aplicação da estatística na manutenção preditiva," *FAMAT em Rev.*, vol. 05, pp. 211–223, 2005.

[14] ReliaWiki, "The Weibull Distribution," 2018. [Online]. Available: http://reliawiki.org/index.php/The_Weibull_Distribution. [Accessed: 15-Sep-2020].

[15] R. B. Abernethy, *The new Weibull handbook*, 5th ed. Florida: Robert B. Abernethy, 2006.

[16] L. A. Ferreira and J. L. Silva, "Parameter estimation for Weibull distribution with right censored data using EM algorithm," *Eksploat. i Niezawodn. - Maint. Reliab.*, vol. 19, no. 2, pp. 310–315, 2017, doi: 10.17531/ein.2017.2.20.

[17] L. Held and D. Sabanés Bové, *Applied statistical inference: Likelihood and bayes*, vol. 9783642378. 2014.

[18] WordPress, "Real Statistics using Excell - Fitting Weibull parameters via MLE." [Online]. Available: https://www.real-statistics.com/distribution-fitting/distribution-fitting-via-maximum-likelihood/fitting-weibull-parameters-mle/. [Accessed: 20-Jul-2020].

[19] Steyr Daimler Puch Spezialfahrzeug GmbH, *Ministério da Defesa Nacional - Manual do Operador VBR Pandur 8x8 12,7 mm*, vol. 1. Viena: Ministério da Defesa nacional - Portugal, 2011.

[20] Fundação Francisco Manuel dos Santos, "PORDATA - Base de Dados Portugal Contemporâneo." [Online]. Available: https://www.pordata.pt/DB/Portugal/Ambiente+de+Consulta/Tabela. [Accessed: 17-Aug-2020].