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RELIABILITY-BASED MAINTENANCE STRATEGY FOR A MILITARY WEAPON SYSTEM – A CASE STUDY

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Military Weapons Systems are currently facing increasing use in a worldwide intensification of military conflicts, leading to various changes to improve and solve problems in logistics operations. The main objective of this paper is to use RCM (Reliability Centered Maintenance) and FMECA (Failure Modes, Effects, and Criticality Analysis) methodology applied to this High-Tech Weapon System to identify the need for spare parts by improving the current maintenance plan. A functional analysis was performed. Then, functional failures, failure modes, and effects are defined. This methodology manages the identified risks, knowing which components have a high failure rate, improving maintenance plans, and identifying the need for spare parts at the earliest possible stage. Thus, the study was supported by "ReliaSoft RCM++" software that facilitates the RCM analysis approach. This software supports all major RCM industry standards such as ATA, MSG-3, MIL-STD-1629A, SAE JA1011, and SAE JA1012 and provides complete capabilities for FMECA. This study aims to identify the systems, subsystems, and components that frequently fail, ensuring operational capability and corrective actions to improve the weapon system's plans, maintenance schedules, and availability. This technique is powerful as decision support to the Military Logistics Command because it identifies the need for spare parts as early as possible.

Keywords: Maintenance; Weibull distribution; Reliability; RCM3; Weapon System; FMECA.

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1. INTRODUCTION

The technological advantage is a factor that is one of the most decisive in modern warfare operations, providing its user with a competitive advantage. Therefore, many countries have always considered the procurement of modern and highly technological weapons systems a primordial issue in military strategic planning by many countries, Rostamkhani (2021). With today's technological advancements, the trade-off between a determined level of reliability and its underlying costs of maintenance strategies is one of the most critical challenges with which complex systems senior managers deal (Ashrafi *et al.*, 2019). Society has grown to depend increasingly on mechanical and automated means of production. It is essential to control its failure rates to maintain equipment availability to reduce negative impacts on productivity. Attempting to avoid negative consequences of failures, both from a security and production point of view, is the main aim of various maintenance methodologies and processes. One of the most used is RCM – Reliability Centered Maintenance.

This work aims to study a highly technological Weapon System to propose a maintenance framework based on RCM. In this Weapon System, the need for reliability is exceptionally high since an unexpected failure can result in the loss of human lives. This motivated a previous study about implementing the RCM3 methodology in the cooling system of this same Weapon System (Silva *et al.*, 2021). Thus, this study aims to continue that work by addressing the remaining systems and subsystems of the weapon system. It is still maintained using the maintenance program suggested by its manufacturer. Since this is a combat vehicle of significant importance and is highly technological, the necessity for reliability increases radically.

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This unique situation motivated the application of the RCM3 methodology to this vehicle with the ambition to produce an improved maintenance plan that will be specifically suited to these vehicles operating in specific conditions.

This paper proposes a framework that allows for better operationalization and availability of high-tech military vehicles in an operational environment. This paper starts with studying the critical failure modes in these operational situations. Based on these approaches, choosing the most appropriate and customized maintenance strategy for all industrial equipment is possible based on its criticality score and reliability parameters (Vishnu *et al*., 2016). Risk assessment plays a critical role in supporting decision-making in maintenance management by assisting maintenance specialists in identifying, analyzing, evaluating, and systematizing equipment failures. Such failures are often mitigated by defining effective maintenance strategies (Vera-García *et al*., 2019). In asset maintenance, well-known risk assessment techniques include FMECA (Chemweno *et al.*, 2015). Also, in utilizing the UAV Safety Assessment, FMECA is a method for demonstrating proof of safety and reliability. (Gonçalves *et al.,* 2017). Risk assessment is also used in preventive analysis tasks in product design and production planning processes, Chang (2009). Using FMECA methodology can make maintenance work more efficient, target the most critical components, and reduce administrative costs for enterprises by establishing, for example, a framework that uses FMECA to address the problem of spare part classification and management (Jianqiang *et al.*, 2022). However, there is a gap regarding highly technological armored weapon systems where practically no information is available, and this gap is the main novelty brought by this study. Therefore, this study's primary goal applied RCM and FMECA methodology to comprehensively highlight the importance of critical components to identify needed spares as early as possible and identify the most critical systems and subsystems to ensure operational capability and corrective actions to improve maintenance plans and schedules. It is required to achieve this goal by performing incremental work following the characteristic steps of the methodology (Silva *et al.,* 2021). Thus, the proposed framework is parameterized and supported by the software "ReliaSoft RCM++" (Hottinger *et al*., 2021) to fulfill the described structure:

- Define the operational context of the vehicle under study;
- Define the vehicle systems to be analyzed;
- Perform a functional analysis of the systems under analysis;
- Identify the potential failures that may occur in each system;
- Define a standard that distinguishes tolerable risks and intolerable risks;
- Quantify the Risk associated with each failure previously defined;
- Define maintenance tasks to reduce intolerable risks to tolerable risk levels;

This framework makes it possible to identify the critical systems and components required to ensure operational capability and corrective actions to improve maintenance plans and schedules and support the Military Logistics Command's decisions regarding the need for spare parts.

2. METHODOLOGY

2.1. RCM – Reliability-Centered Maintenance

The methodology was developed by reliability-focused maintenance because several industries increased safety and productivity requirements. By the late 1950s, there was already a wide variety of data on equipment maintenance and reliability in the aviation industry. The cost associated with maintenance was already high enough to justify rethinking how maintenance was done. Maintenance until then was based on the premise that a component of an asset has an "ideal" overhaul period that would ensure the safety and reliability of the asset. However, studies conducted in the early 1960s revealed that the control of the overhaul times of a component is not directly related to the asset reliability, contrary to what was assumed until then. With this new knowledge, several attempts were made to reorganize maintenance to guarantee the availability of the equipment when needed, describing the development and application of the RCM methodology. It represented the first iteration of the RCM methodology (Nowlan *et al*., 1978).

Later, in 1991, John Moubray authored the book Reliability Centered Maintenance II, which presented an improved RCM implementation process compared to Nowlan and Heap's work, which became RCM2. Moubray's book brought several minor improvements to Nowlan and Heap's work. Still, the main change that justified the RCM2 nomenclature was the distinction between environmental and safety risks that had not been considered until then. Safety and environmental risks were placed in the same category, which meant that ecological risks were often undervalued before (Nowlan *et al*., 1978)

More recently, in 2018, the book RCM3: Risk-Based Reliability Centered Maintenance was published by Marius Basson. This book continues Moubray's work. RCM3 adds a concern for the operational context of equipment, making the first step in applying the RCM3 methodology the definition of the operational context of the equipment. This change helps understand the operation of the equipment and create its risk management plan. In addition, the RCM3 methodology distinguishes between causes and mechanisms of failure modes. Also, it asks for recording the event that causes a functional failure (cause). This distinction allows recording the mechanisms that cause degradation of the equipment and lead to the occurrence of the failure mode. A separation of the effects of the failure is also made that did not exist in RCM2. Thus, the effects are separated: local effect, top-level effect, final effect, and worst-case scenario effect (Basson *et al.*, 2019).

Regardless of the RCM methodology applied in various industrial fields, the framework selected for this paper was the RCM, which has been used for different applications, as seen in this paragraph. However, there is a gap about military vehicles where there is practically no information available.

2.2. RCM3 – Reliability-Centered Maintenance 3

The RCM3 methodology consists of (Silva *et al.*, 2021) creating asset maintenance strategies and plans by identifying risks arising from the failures of that asset and its components. The qualification of those failures according to the risk level, and finally, the determination and construction of the best modality to prevent and correct them (Basson *et al.*, 2019). This methodology arises from the need to mitigate an organization's physical, safety, environmental or economic risks, thus promoting the efficiency and effectiveness of maintaining those assets.

The RCM3 methodology promotes a new "dimension" in the strategy, maximizing the risk management efficiency and the maintenance of the adequate reliability level of the assets, which is based on SAE standards (SAE JA 1011 and SAE JA 1012) and ISO standards (ISO 31000 and ISO 55000).

This methodology, once in place, should deliver these six primary outcomes:

1. Define an operational context;
2. Define and quantify inherent risks (operational and asset maintenance);
3. Structured maintenance calendar to be implemented by the organization;
4. Operational and maintenance procedures reviewed;
5. Revised risks after new risk management strategies are in place;
6. One-time changes (related to the project or operational changes).

Figure 1 shows what the process of the RCM application looks like

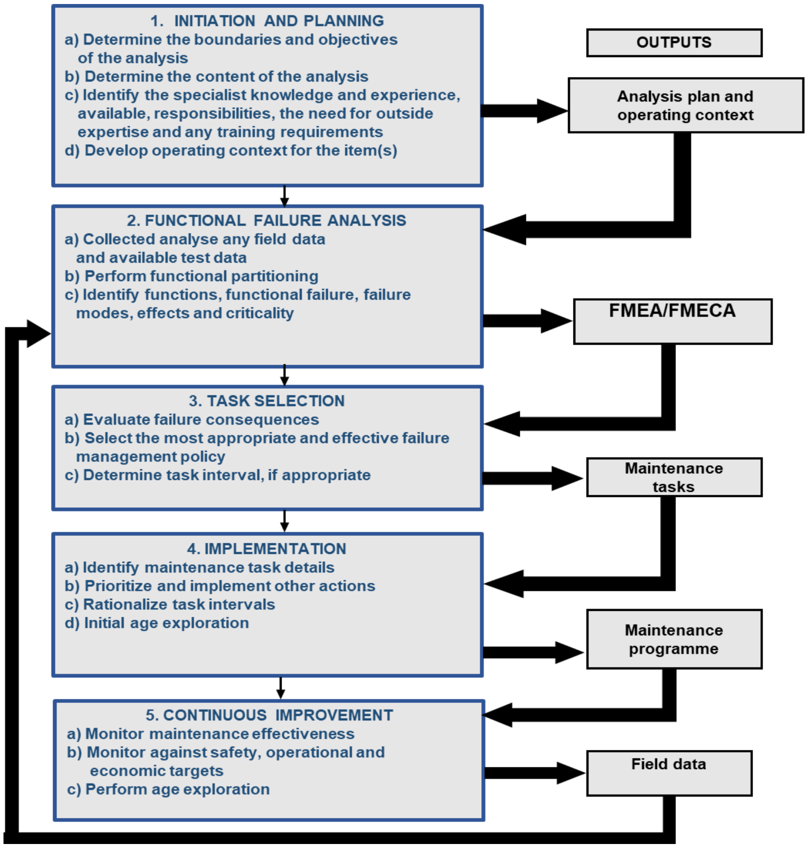


Figure 1. RCM Overview (BSI, 2009)

To achieve this standard, the RCM3 book Basson & Aladon (2019) defined the eight questions of RCM3, which, once answered, should provide the main objectives of this analysis:

a) What are the operational conditions?
b) What functions and performance standards are related to the system's current operational context?
c) How does the system fail to accomplish its functions?
d) What causes each failure state (failure modes)?
e) What happens when each failure occurs?
f) What is each failure-associated risk (quantification of Inherent Risk)?
g) What should be done to decrease intolerable risks to a tolerable level (using proactive risk management strategies)?
h) What can be done to manage or reduce the tolerable risks economically viable way?

These questions can and should guide the implementation of an RCM3 analysis (Basson *et al.*, 2019).

2.3. Comparison between RCM2 and RCM3 Methodologies

The most recent iteration of the RCM methodology is the RCM3. This methodology was created by improving the previous version of RCM, the RCM2, Moubray (2001). The RCM3 (Basson *et al.*, 2019) was the method that added awareness to the asset's operational context in the study, becoming the working context definition of the first step in applying the RCM3 methodology. Furthermore, this novel approach distinguishes between causes and mechanisms in failure mode. This distinction allows a deeper understanding of events that lead to failed states. Also, it has created a new separation between several types of failure effects, creating four categories: local products, next-higher-level development; end effect; potential worst-case scenarios.

The essential upgrade from RCM2 to RCM3 is how Risk is considered. The RCM2, Moubray (2001) approach avoided the Risk at all costs, but the RCM3 process made more efficient risk management. In an RCM3 analysis, the Risk is quantified and, using a predefined standard, distinguished between tolerable and intolerable Risk. With this approach, sending resources to unacceptable risks is only necessary.

2.4. Risk Assessment

The risk analysis (Nahavandi *et al.*, 2022) used in this paper is based on the FMECA methodology. FMECA is a method used to analyze each system in sequence to classify each potential failure mode according to its severity and identify its effects on the system MIL-STD-1629A (1980). It was initially developed in the 1940s by the US military in MIL-P-1629. It is widely used in the military and space nowadays (Ranasinghe *et al.*, 2022). FMECA includes a Failure Mode and Effect Analysis (FMEA) and Criticality Analysis (CA). FMEA is used to identify failure modes, potential causes, and effects. CA is a method for calculating the probability of failure modes against the severity of their consequences, MIL-STD-1629A (1980). The Risk Priority Number (RPN) demonstrates the Risk of failure mode. It is a function of occurrence probability, the potential final effect (severity), and the likelihood of detection. By multiplying the amounts for severity (S), occurrence (O), and detectability (D), the team obtains a risk priority number (RPN = O x S x D) (Y. Li *et al.*, 2011).

RPN is an important technique used to identify and eliminate known or potential failures to improve the safety and reliability of complex systems and is intended to provide information for making risk management decisions. The maintenance process will better reflect the potential risks. Each failure mode is assessed in three parameters: severity, the likelihood of occurrence, and difficulty detecting the failure mode. To propose a decision-making framework, the failure mode effect and criticality analysis (FMECA) is used in such critical situations to improve emergency management in case of an oil spill (Wang *et al.*, 2014).

FMECA remains an extremely modern methodology, and, as we have seen in the literature review, it continues to cover several gaps. This article also addresses the lack of knowledge in this typology of complex systems. The framework presented in this article on a highly technological weapon system used to perform complex operational missions is a very actual and realistic new development.

2.5. Statistical Life Distributions of Reliability Models

Several probability distributions in the literature can be used to model equipment lifetimes (Bousquet *et al.*, 2006), such as the exponential distribution, the Gamma distribution, the normal distribution, and the Weibull distribution, Zaiontz (2020). Despite the wide variety of applicable mathematical models, the Weibull distribution will be the most discussed in this study; it has become very versatile, being considered one of the most used models to represent equipment life in reliability analyses (Hoyland *et al.*, 2009). In addition to the Weibull distribution, it is essential to mention the exponential distribution (for being the one that best describes the life phase, which due to previous experience with the equipment under analysis, is assumed to be the most likely life phase for the components under investigation) and the normal distribution (which allows adequate coverage of the wear-out period).

2.5.1.Censored Data

To perform any statistical analysis, such as reliability analysis, obtaining data about the object under study is necessary. In the case of the work of this study, it will be required to use data about the lifetime of specific equipment until a failure occurs. However, it is possible that during the time interval of the observation of the equipment, a loss does not happen, and in this case, it will not be possible to obtain a value about the failure time of that equipment. In this case, we are facing an example of right-censored data. In Right Censored Data, a data set is censored when there is no complete information about its behavior. As mentioned earlier, the most common example of censored data occurs in the scope of this study because it is impossible to determine the failure time of a particular piece of equipment. This is because the analysis time was not long enough for failures to occur before a preventive maintenance intervention, Nachlas (2017).

Therefore, it is essential for data censoring to estimate the correct distribution parameters. In cases like this, where there is no complete information about the end of life of a piece of equipment, the data is said to be directly censored. In these cases, the exact failure time is unknown, so that time is known to be longer than a known time (the end of information logging time). Figure 4 shows an example of 5 assets where 2 of them do not fail during the observation time, and therefore this is a case of right-censored data (Ferreira *et al*., 2017):

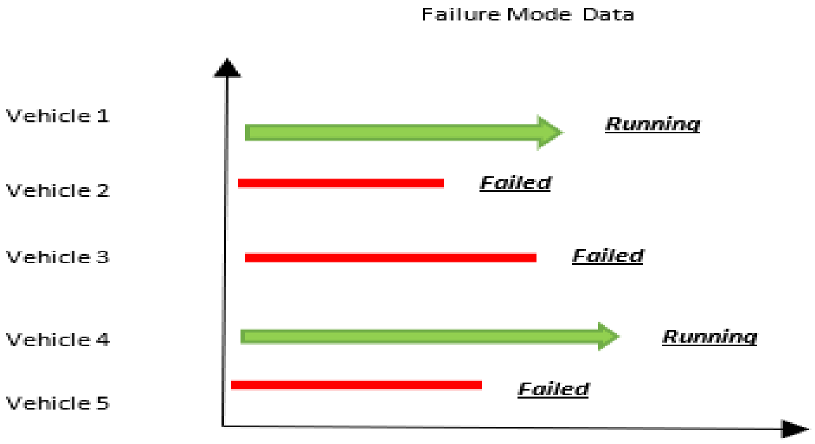


Figure 2. Censored Data to the Right (Chambel *et al*., 2021)

Within the category of right-censored data, it is further possible to divide the data into Type 1 censorship and Type 2 censorship:

- Type 1: Information recording ends after a predetermined time (for economic reasons, time available, and others). Observation time, in this case, is fixed; at the end of the record, as already mentioned, only the lifetime of the assets that failed before the observation end time will be known.
- Type 2: Information recording ends after a predetermined number of failures (defined at the beginning of the analysis). All assets are understudied until the desired number of failures are observed, and the observation time, in this case, is variable.

2.5.2.Software Used

Implementing the RCM methodology to these Military *Weapon systems*, a machine with a high degree of complexity, was a complex and laborious task. So, the study was supported by *ReliaSoft Software* (Bruel & Kjaer *et al.*, 2021) to make this process faster and more efficient.

A Weibull distribution was applied to the existing data. In this case, the Weibull distribution was the most appropriate one. The software supports all types of life data analysis, including Complete (failure time), Right censored (suspension time), Left censored, Interval censored, and Freeform. Regarding the Parameter estimation, options for standard life data analysis include Rank Regression on X (RRX), Rank Regression on Y (RRY), Maximum Likelihood Estimation (MLE), Non-Linear

Rank Regression, Fractional Failure Analysis, and Image. All major lifetime distributions (including all forms of the Weibull distribution) are also supported: Weibull, Normal and Log-normal, Exponential, Gamma, and Generalized Gamma, Logistic and Loglogistic, Gumbel, Bayesian-Weibull, Mixed Weibull, Competing Failure Modes (CFM), (HOTTINGER BRUEL *et al.*, 2021). This information makes it possible to choose the most appropriate distribution (following the software's suggestion) and calculate the distribution parameters. After the parameters are calculated, it is then possible to calculate the MTBF of the equipment under analysis.

3. CASE STUDY

The *Weapon System* under study is an Armored Wheeled Vehicle that aims to ensure tactical mobility on the ground, give medium-sized forces flexibility, and provide them with armored protection. This *Weapon System* has accomplished missions worldwide.

The available failure data was a limitation because it is a new military high-performance vehicle that has been in service for a very brief time and whose faults for this system are few. The data was compiled from a Computerized Maintenance Management System (CMMS) from the beginning of 2013 to the end of 2021. The failure rate for the component failure modes for which no data existed was estimated from literature (Vera-García *et al.*, 2019) and databases (Denson *et al.*, 1994). Implementing the proposed methodology was a great experiment since data is confidential. Despite several difficulties in their processing, these data have excellent statistical significance. Throughout this paper, it might be possible to find scenarios in which the statements and conclusions presented might need confidential information for more clarity which was a limitation of the proposed paper.

The weapon system was divided into its systems and subsystems to implement the proposed framework and then applied to the RCM methodology. The vehicle's division is based on the technical manuals produced by the manufacturer. However, this division was adjusted to group the vehicle's various components according to their function. Additionally, a sorting was made to avoid a too high level of detail, which would be counterproductive for the global analysis of the *Weapon System*, which is the objective of this study.

The work required for this case study following the steps defined by the RCM3 methodology was achieved (Chambel *et al.*, 2021) for the Weapon System. For this reason, eight systems were considered: Power system, Power transfer system, Security system, Hydraulic System, Pneumatic system, Heat, and cooling system, Electric System, and Hull (Armored shell). The land vehicle (*Weapon System*) was divided into systems and subsystems, as shown in Figures 5, 6, 7, 8, and 9.

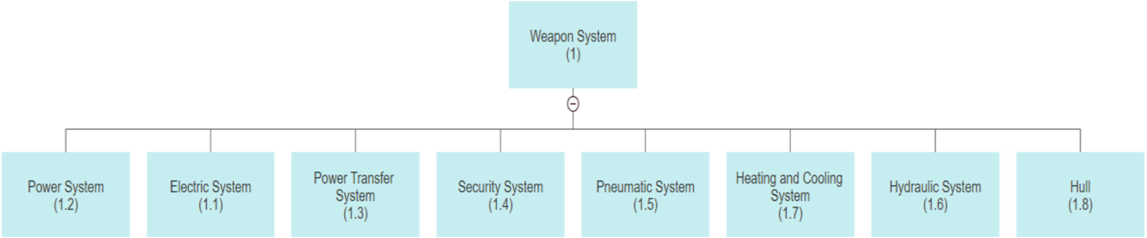


Figure 3. Top-level functional decomposition of the Weapon System in the Study

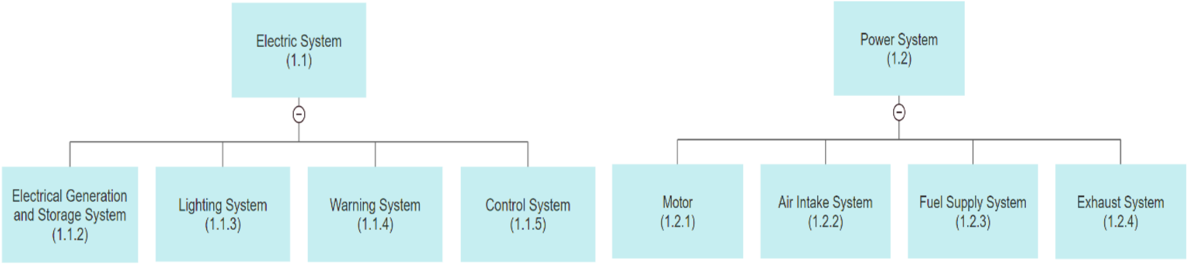


Figure 4. Second-level functional decomposition for Electrical and Power Subsystems.

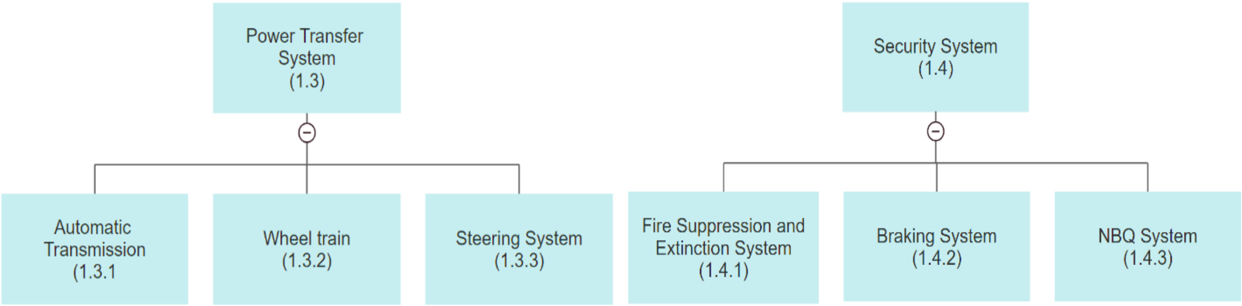


Figure 5. Second-level functional decomposition for Power transfer and security subsystems.

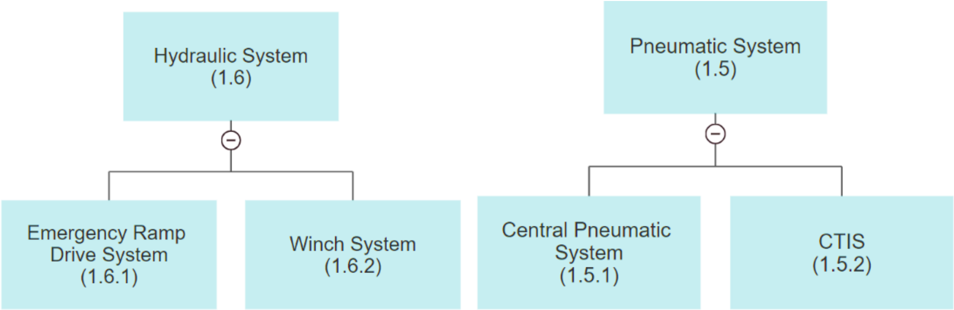


Figure 6. Second-level functional decomposition for Hydraulic and Pneumatic Subsystems.

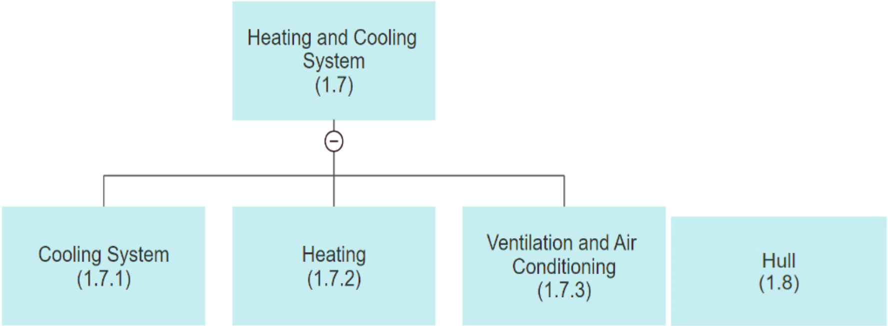


Figure 7. Second-level functional decomposition for Heating /Cooling and Hull Subsystems.

3.1. Current Maintenance Plan of the Military *Weapon System* under Study

The Military Weapon System manufacturer produces the current maintenance plan. This plan consists of preventive measures with specific periodicities for various vehicle systems.

Maintenance tasks with annual periodicity must be performed annually, every 250 engine hours, or every 5000 km, depending on which occurs first. Likewise, bi-annual tasks should be performed every two years, every 500 engine hours, or every 10,000 km, depending on which occurs first. Maintenance tasks with a 6-year frequency should be performed every six years or 1500 engine hours, depending on which occurs first.

3.2. Operational Context

As previously explained, defining the operational context is the first step in applying the RCM (Basson *et al*., 2019). The mainland is divided into two regions: one with a temperate climate with dry and hot summer and another with a temperate climate with rainy winter and dry and not very hot summer. This information shows that the vehicles are used in mild climate conditions and not exposed to too high or low temperatures. This Weapon System is engaged in missions abroad.

3.3. RCM3 Information Sheet

An information sheet model was developed to implement the RCM3 methodology (with the help of *ReliaSoft Software*). These sheets contain tables that record the necessary information about each system for implementing the RCM3 method. An example is shown in Table1:

Table 1. RCM3 Datasheet Header

Hydraulic System										
Function	Functional Failure	Failure Mode (cause)	Description of the effect on the local level	Description of the effect on the subsequent level	Description of the final effect	worst-case scenario effect	Si	Oi	Di	RPNi

These sheets are divided by the various systems being studied on the vehicle (the example above shows the hydraulic system highlighted in green. The set of his functions will be described, such as the functional failures that can occur and the various failure modes associated with them. The effects associated with each failure mode are also described. Local-level, top-level, final, and worst-case scenario effects are considered. Finally, the last four columns represent the values needed to calculate the initial Risk Priority Number (RPNi) associated with each failure mode. They are "Si", the initial severity, "Oi" the initial occurrence level; and "Di" the initial detectability.

3.4. Functional Analysis

To perform the functional analysis of each of the systems under study, it was necessary to understand what inherent functions of the system, thus defining the main functions. In addition, the subsystems/components of that system were analyzed. If they perform functions vital to the system's proper functioning, they are also defined as a system's function. In addition to defining the system's functions, the functional failures associated with the various functions were also defined. Table 2 shows an example of the registration of a function and its respective functional failure of the hydraulic system.

Table 2. Example of recording functions on the information sheet.

Function	Functional Failure
Hydraulic System	
Opening and closing the rear ramp	Do not open or close the rear ramp.

3.5. Failure Modes Analysis

After performing a functional analysis of the various vehicle systems, it was necessary to identify the failure modes (causes) associated with each functional failure. To this end, the records of all failures that occurred between 2014 and 2020 were consulted, and criticality analysis of the various systems was performed to find out if there were any possible failures not yet detected due to the short life span of the vehicles (the vehicles under study have been in operation since 2010. Table 3 shows an example of the records of the failure modes for the hydraulic system.

Table 3. Example of records of failure modes on the information sheet

Function	Functional Failure	Failure Mode (cause)
Hydraulic System		
Opening and closing the rear ramp	Do not open or close the rear ramp.	Oil leakage in the hydraulic cylinder of the ramp
		The ramp electric control valve is inoperative

Description of the effects of the failure

A description of the effects of the failure was made for each failure mode recorded. This description will be essential in the next phase of risk analysis as it describes the consequences of the failure modes. Table 4 shows an example of records describing the effects of two failure modes of the hydraulic system.

Table 4. Example of recording the effects of the failure on the information sheet

Function	Functional Failure	Failure Mode (cause)	Description of the effect at the local level	Description of the effect on the subsequent level	Description of the end effect	Worst-case effect
Hydraulic System						
Opening and closing the rear ramp	Do not open or close the rear ramp.	Oil leakage in the hydraulic cylinder of the ramp	Lack of pressure in the ramp cylinders	Due to the lack of pressure, the cylinders cannot move the ramp to open or close it, and it stays still.	Replacement of the damaged cylinder	The ramp unable to stay fixed, causing an accident
		The ramp electric control valve is inoperative.	Inoperative valves do not direct the hydraulic oil to move the cylinders	It is not possible to control the opening and closing of the rear ramp	Replacing non-operational valves	The ramp unable to stay fixed, causing an accident

In accordance with HOTTINGER BRUEL & KJAER INC. (2021):

- *The local failure effect* describes the consequence of the occurrence of the failure mode on the system itself.
- *Next, the higher-level effect describes the impact of the failure mode on the higher system in which the failure mode occurs* and the sequence of events caused by the failure mode.
- *End effect*: describes the consequences of the failure mode on safety, environment, and operational capability and what must be done to repair the failed equipment.
- *The potential worst-case effect* describes the consequences of the occurrence of the failure mode if no action is taken to detect, prevent or repair the failure.

The consequences of the failure modes have been defined as the operational impacts and the warning signs of the occurrences, and their estimated frequency. The frequency of occurrence of the failure modes has been evaluated by determining their MTBF. For the failure modes with a lack of failure information, it was considered that its probability of occurrence was low. The *Weapon System* had never been analyzed before, and there was no knowledge about its behavior or components because the available failure information was limited. After all, it is a new military high-performance vehicle that has been in service for a brief time. Nevertheless, it was possible to estimate the MTBF for specific failure modes. The MTBF for the component failure modes for which no data existed were estimated from literature and databases.

3.6. Risk Priority Number – RPN

Risk priority numbers help the team identify the components with higher risk and systems used to measure the three factors. Thus, the proposed framework is supported by the software “ReliaSoft RCM++” (HOTTINGER BRUEL & KJAER INC, 2021), which is parameterized with MIL-STD1629A (1980) to fulfill the proposed framework. Failure modes with high RPN values are assumed to be a more critical and higher priority than those with lower RPN values. Tables 5, 6, and 7 are Maintenance fault modes of the *Severe* level S (severity), *Occurrence* probability 0 (occurrence), and the degree of fault mode *Detection* D (detection). The integral equation for RPN can be defined as follows:

$$RPN = O \times S \times D \qquad (1$$

Table 5. The criteria for evaluating maintenance failure mode Severity (S), MIL-STD1629A (1980).

Value	*Influence of maintenance failure modes*	*Criteria*
1	IV - Minor	A failure is not severe enough to cause injury, property damage, or system damage but which will result in unscheduled maintenance or repair.
2	III - Marginal	A failure that may cause minor injury, minor property damage, or minor system damage will cause a delay or decrease in availability or mission loss.
3	II - Critical	A failure that may cause severe injury, significant property damage, or significant system damage will result in mission loss.
4	I - Catastrophic	A failure that may cause death or weapon system loss (i.e., aircraft, tank, missile, ship)

Table 6. The criteria for evaluating maintenance failure mode probability of Occurrence (O), MIL-STD1629A (1980).

Value	*The probability of the associated failure modes occurring*	*Criteria*
1	Level E – Extremely Unlikely	The probability of occurrence is essentially zero during item operation time intervals. A one-time failure mode probability of occurrence is less than 0.001 of the overall probability of failure during the item operation time.
2	Level D – Remote	Unlikely probability of occurrence during item operation time interval. A one-time failure mode probability of occurrence is higher than 0.001 but lower than 0.01 of the total probability of failure during the system operation time.
3	Level C – Occasional	Occasional probability of occurrence during item operation time interval. A one-time failure mode probability of occurrence is more than 0.01 but less than 0.1 of the overall probability of failure during the item operation time.
4	Level B – Reasonable Probable	A moderate probability of occurrence during item operation time interval. A one-time failure mode probability of occurrence is more than 0.1 but less than 0.2 of the overall probability of failure during the item operation time.
5	Level A – Frequent	A high probability of occurrence during item operation time interval. A one-time failure mode probability of occurrence is more significant than 0.2 of the overall probability of failure during the item operation time.

Table 7. The criteria for evaluating maintenance failure mode degree of *Detection* D, MIL-STD1629A (1980).

Value	*Detection Description*	*Criteria 1*	*Criteria 2*
1	Almost Certain	Error (Cause) prevention results from fixture design, machine design, or part design. Discrepant parts cannot be made because the process/product design has error-proofed the item.	Detection is not applicable; error prevention.
2	Very High	Error (Cause) detection in-station by automated controls will detect errors and prevent discrepancies from being made.	Error detection or problem prevention
3	High	Failure Mode detection in-station by automated controls detects discrepant parts and automatically locks parts in a station to prevent further processing.	Problem detection at the source
4	Moderately High	Failure Mode detection post-processing by automated controls detects discrepant parts and locks parts to prevent further processing.	Problem detection post-processing
5	Moderate	Failure Mode or Error (cause) detection in-station by the operator through variable gauging or by automated controls in-station that will detect discrepant parts and notify the operator. It was gauging performed on setup and first-piece check (setup-causes only).	Problem detection at the source
6	Low	Failure Mode detection post-processing by the operator through the use of variable gauging or in the station by the operator through the use of attribute gauging (go/no-go, manual torque check, clicker wrench)	Problem detection post-processing

7	Very Low	Failure Mode detection in the station by the operator through the use of visual/tactile/audible means or the use of attribute gauging (go/no-go, manual torque check, clicker wrench)	Problem detection at the source
8	Remote	Failure Mode detection post-processing by the operator through visual/tactile/audible means.	Problem detection post-processing
9	Very Remote	Failure Mode and/or Error (cause) is not easily detected (e.g., random audits)	Not likely to detect at any stage
10	Almost Impossible	No current process control: it Cannot detect or is not analyzed	No detection opportunity

The last step in filling out the information sheets is determining the RPNi based on the following Tables 5, 6, and 7 (HOTTINGER BRUEL & KJAER INC, 2021).

$$RPNi = Si \times Oi \times Di \tag{2}$$

With "Si" being the initial severity before any maintenance activity is implemented, "Oi" is the probability of occurrence before any maintenance activity is implemented; and "Di" is the detectability of the failure implemented before any maintenance activity.

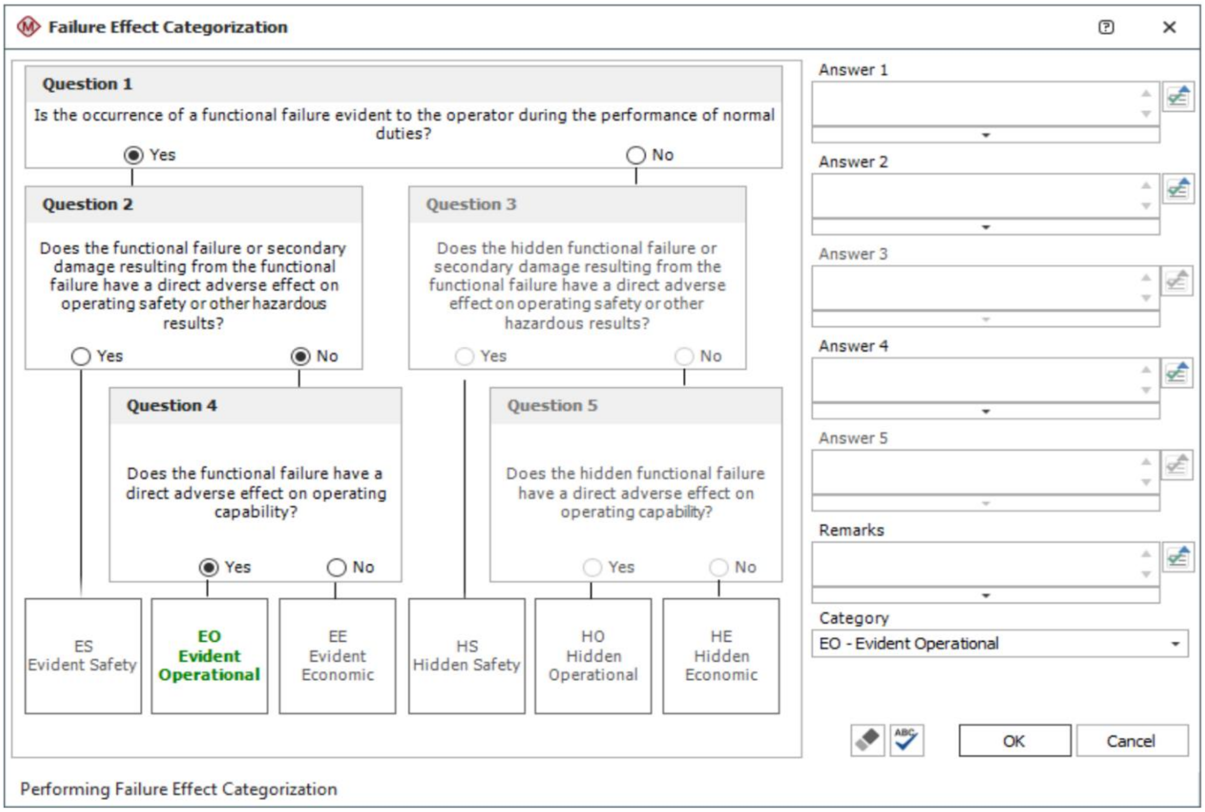
Thus, a Risk Priority Number value can be calculated before any maintenance activity is implemented. The first step is to use the software that analyzes the equipment life data and the most appropriate distribution to represent the data under analysis. The research determines the Weibull distribution parameters assigning to each fault record a failure mode. With the information in the records about the engine hours of each car at the time of the failure, it was possible to determine the MTBFs. Based on the MTBFs obtained, it was possible to determine a value of the probability of the initial occurrence of the failure modes to which these MTBFs correspond. However, assigning the initial probability of occurrence values for the remaining failure modes was necessary. Databases were consulted about the MTBF of similar equipment and a similar application to those studied. Failure modes were also analyzed in conjunction with technical experts in this area, using their experience in the field so that appropriate values for each failure mode could be found. Finally, it is possible to determine the RPNi values of all the failure modes. Table 5 can be seen as an example of all the information sheets filled in. The same methodology used for the hydraulic system presented in Tables 1, 2, 3, and 4 was performed for all systems and subsystems of the high technological Weapon System under study.

Table 8. Example of recording the RPNi values on the information sheet.

Function	Functional Failure	Failure Mode (cause)	Description of the effect at the local level	Description of the effect on the subsequent level	Description of the end effect	Worst-case effect	SI	OI	DI	RPNI
Hydraulic System										
Opening and closing the rear ramp	Do not open or close the rear ramp.	Oil leakage in the hydraulic cylinder of the ramp	Lack of pressure in the ramp cylinders	Due to the lack of pressure, the cylinders are not able to move the ramp to open or close it, and it stays still	Replacement of the damaged cylinder	The ramp unable to remain fixed, causing an accident	4	5	6	**120**
		The ramp electric control valve is inoperative	Inoperative valves do not direct the hydraulic oil to move the cylinders	It is not possible to control the opening and closing of the rear ramp	Replacing non-operational valves	The ramp unable to stay fixed, causing an accident	4	3	9	**108**

A risk matrix was proposed in the literature on RCM by (Denson *et al*., 1994) to do a quantitative risk analysis. According to the standard RCM of the Reliasoft software, a risk matrix, MIL-STD1629A (1980), combines the severity of the consequence with the probability of failure mode occurrence, thus obtaining a risk rating value.

The decision-making process of defining risk mitigation tasks (for example, in Figure. 11) using the RCM3 methodology is done using the RCM3 decision diagram (Basson *et al.*, 2019). The *ReliaSoft Software* decision diagram was used to categorize faults, as shown in Figure 10, categorizing a failure as security evident.



Failure Effect Categorization

Question 1
Is the occurrence of a functional failure evident to the operator during the performance of normal duties?
● Yes ○ No

Question 2
Does the functional failure or secondary damage resulting from the functional failure have a direct adverse effect on operating safety or other hazardous results?
○ Yes ● No

Question 3
Does the hidden functional failure or secondary damage resulting from the functional failure have a direct adverse effect on operating safety or other hazardous results?
○ Yes ○ No

Question 4
Does the functional failure have a direct adverse effect on operating capability?
● Yes ○ No

Question 5
Does the hidden functional failure have a direct adverse effect on operating capability?
○ Yes ○ No

Category: EO - Evident Operational

Performing Failure Effect Categorization

Figure 10. ReliaSoft Software Decision Diagram. (ReliaSoft Software)

4. RESULTS

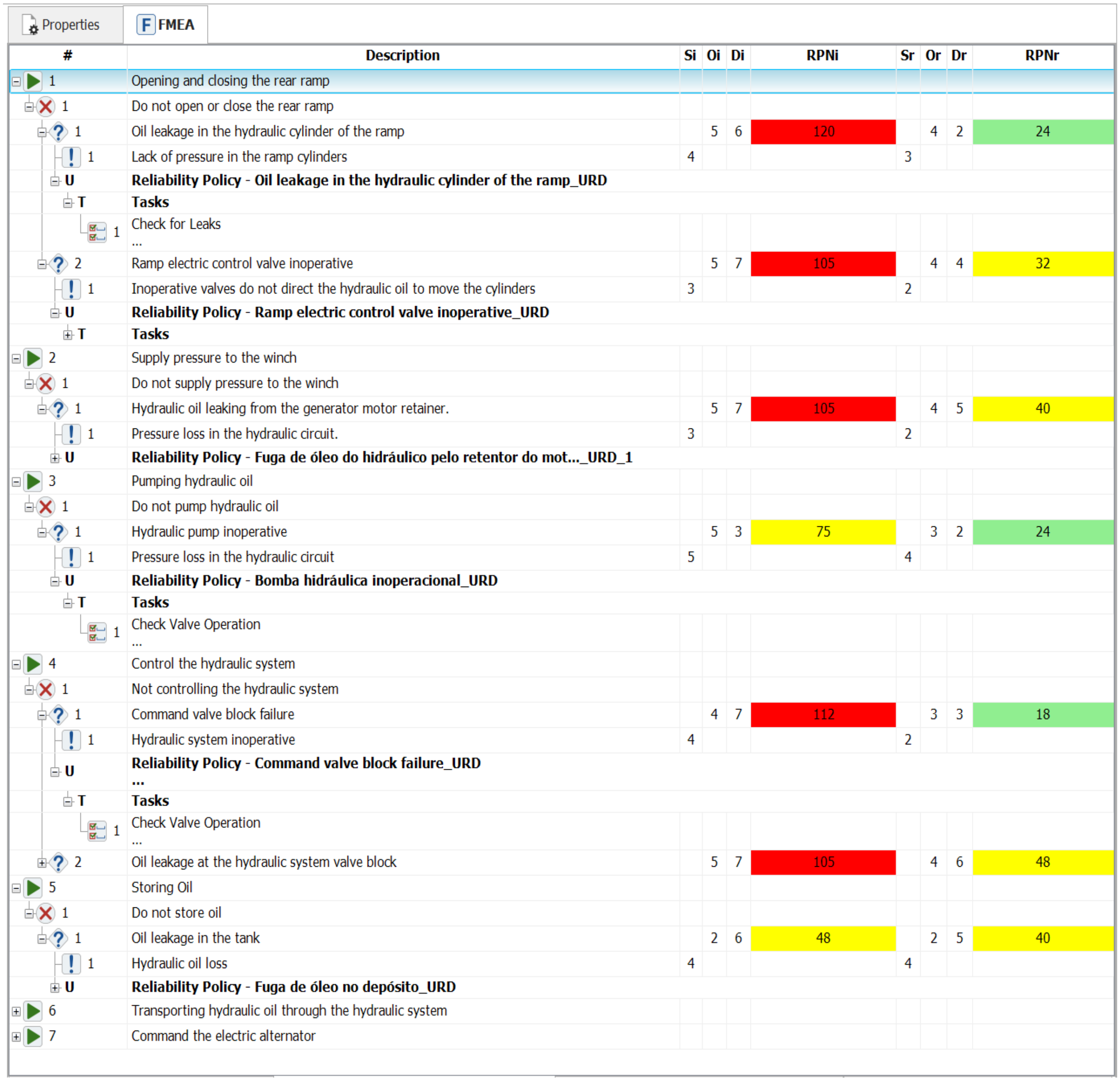
To avoid introducing a higher degree of complexity to the vehicle maintenance process, the proposed changes to the maintenance plan only include tasks to be performed with a periodicity already contemplated in the original maintenance plan. According to the initial maintenance plan, vehicles are submitted to various maintenance tasks conducted every six months, annually, every two years, every four years, every six years, or every ten years. Therefore, new tasks were planned to be performed within these intervals. The Risk associated with a failure is evaluated by combining the probability of occurrence and severity. Thus, with the information about the risk levels associated with each failure, the systems or subsystems whose maintenance plan needs to be changed are defined. FMECA analysis was carried out and implemented new maintenance tasks (in cases where the Risk was intolerable) were to reduce the probability of the fault occurring or reducing its severity, or both, thus reducing the risk to tolerable levels. Figure 11 shows the Failure Mode, Effects & Criticality Analysis held.

The hydraulic system consists of the winch and the emergency ramp drive subsystem, as shown in figure 8. FMECA analysis for the hydraulic system through ReliaSoft Software is shown in Figure 11 and Table 9, where it can be seen in addition to the main subsystems and their main components. The hydraulic system was chosen as an example in this article because it is the one that presents failure modes with higher RPN. This information is essential to ensure operational capability and corrective actions to improve maintenance plans and schedules. However, observing table 9, which is representative of the hydraulic system, it is possible to see that several components present failures, such as:

- The water pump;
- The electric alternator;
- The hydraulic pump;

- The valve block control;
- The winch cable;
- The emergency pump control solenoid valve;
- The hydraulic cylinder of the ramp;
- The hydraulic oil tank;
- Specific retainers for each location of the hydraulic circuit pipes.

These components can be used to create a spare parts list that will support the logistics of this highly technological weapon system. Identifying these components will result in efficient and effective maintenance that will guarantee the availability of this weapon system, which is crucial for its commitment to be prepared for the worst scenario of combat missions around the world.



#	Description	Si	Oi	Di	RPNi	Sr	Or	Dr	RPNr
1	Opening and closing the rear ramp								
1	Do not open or close the rear ramp								
1	Oil leakage in the hydraulic cylinder of the ramp		5	6	120		4	2	24
1	Lack of pressure in the ramp cylinders	4				3			
U	**Reliability Policy - Oil leakage in the hydraulic cylinder of the ramp_URD**								
T	**Tasks**								
1	Check for Leaks ...								
2	Ramp electric control valve inoperative		5	7	105		4	4	32
1	Inoperative valves do not direct the hydraulic oil to move the cylinders	3				2			
U	**Reliability Policy - Ramp electric control valve inoperative_URD**								
T	**Tasks**								
2	Supply pressure to the winch								
1	Do not supply pressure to the winch								
1	Hydraulic oil leaking from the generator motor retainer.		5	7	105		4	5	40
1	Pressure loss in the hydraulic circuit.	3				2			
U	**Reliability Policy - Fuga de óleo do hidráulico pelo retentor do mot..._URD_1**								
3	Pumping hydraulic oil								
1	Do not pump hydraulic oil								
1	Hydraulic pump inoperative		5	3	75		3	2	24
1	Pressure loss in the hydraulic circuit	5				4			
U	**Reliability Policy - Bomba hidráulica inoperacional_URD**								
T	**Tasks**								
1	Check Valve Operation ...								
4	Control the hydraulic system								
1	Not controlling the hydraulic system								
1	Command valve block failure		4	7	112		3	3	18
1	Hydraulic system inoperative	4				2			
U	**Reliability Policy - Command valve block failure_URD** **...**								
T	**Tasks**								
1	Check Valve Operation ...								
2	Oil leakage at the hydraulic system valve block		5	7	105		4	6	48
5	Storing Oil								
1	Do not store oil								
1	Oil leakage in the tank		2	6	48		2	5	40
1	Hydraulic oil loss	4				4			
U	**Reliability Policy - Fuga de óleo no depósito_URD**								
6	Transporting hydraulic oil through the hydraulic system								
7	Command the electric alternator								

Figure 11. FMECA for the Hydraulic System. (ReliaSoft Software).

Table 9. Revised RPN for some functional failures of the hydraulic system

Function	Failure Modes	Si	Causes	Oi	Di	RPNi	Sr	Or	Dr	RPNr
1.6 - Hydraulic System										
Opening and closing the rear ramp	Do not open or close the rear ramp	4	Oil leakage in the hydraulic cylinder of the ramp	5	6	120	3	4	2	24
		3	The ramp electric control valve is inoperative	5	7	105	2	4	4	32
Supply pressure to the winch	Do not supply pressure to the winch	3	Hydraulic oil is leaking from the generator motor retainer.	5	7	105	2	4	5	40
Pumping hydraulic oil	Do not pump hydraulic oil	5	Hydraulic pump inoperative	5	3	75	4	3	2	24
Control the hydraulic system	Not controlling the hydraulic system	4	Command valve block failure	4	7	112	2	3	3	18
		3	Oil leakage at the hydraulic system valve block	5	7	105	2	4	6	48
Storing Oil	Do not store oil	4	Oil leakage in the tank	2	6	48	4	2	5	40
Transporting hydraulic oil through the hydraulic system	Do not carry hydraulic oil through the hydraulic system	2	Hydraulic oil leakage in an unidentified location	4	2	16	2	3	2	12
Command the electric alternator	Do not run the electric alternator	4	Hydraulic oil leakage in the generator comnad	5	4	80	3	4	3	36
1.6.1 - Winch System										
Inform the cable length unrolled	Do not inform the cable length per unrolling	3	Cable without red marks	6	8	144	2	4	5	40
Tracionar the system	Not able to pull the car	4	Hydraulic motor inoperative	3	3	36	3	2	2	12
		5	Winch cable damaged	6	8	240	3	5	4	60
		4	Leaky winch hydraulic circuit	8	4	128	2	7	3	42
1.6.2 - Emergency Ramp Drive System										
Operate the tail lift in case of hydraulic system failure	Do not operate the tail boom if the hydraulic system fails	5	Defective emergency pump	3	9	135	2	2	4	16
		4	Emergency pump control solenoid valve inoperative	4	9	144	2	2	4	16

Table 10 shows the revised RPN for the Weapon System. It is important to highlight in table 10 the risk improvement obtained with the new maintenance methodology compared to the old one. As shown in table 10, the reduction in total RPN was 64.4%. The hull system has the best RPN reduction due to the easiness of access to perform the corrective tasks, with a decrease of 77.9%. The reductions obtained in the heating and cooling system and the hydraulic system of 59.4% and 71.1% are significant because they have the highest associated Risk and the highest number of failures. Therefore, the hydraulic system shown in table 9 has the highest associated risk and has been chosen as an example in this article.

Table 10. Revised RPN for the Weapon System

System	Si	Oi	Di	RPNi	Sr	Or	Dr	RPNr	RPN Reduction Ratio (%)
Power System	63	75	77	1014	42	54	49	288	71,6%
Power Transfer System	59	65	76	973	43	50	65	419	56,9%
Security System	34	37	58	701	23	28	47	290	58,6%
Hydraulic System	57	70	90	1593	38	53	54	460	71,1%
Pneumatic System	30	43	55	768	21	32	36	252	67,2%
Heating/cooling system	101	150	193	2124	70	120	149	862	59,4%
Electrical System	38	54	33	424	28	40	24	157	63,0%
Hull System	13	16	17	181	8	13	11	40	77,9%
	TOTAL			7778				2768	64,4%

5. CONCLUSIONS

Improved maintenance strategies are essential to increase system reliability and reduce costs. This paper proposes a reliability-focused maintenance strategy selection framework that allows for better operationalization and availability of the highly technological weapon systems present on the battlefield today. Thus, the initial RPN was reviewed, considering the experience of highly specialized military technicians and engineers responsible for this weapon system maintenance management.

Through the initial review of the RPN process, severity, probability of occurrence, and detectability values were defined, which allowed the RPN values to be revised. Furthermore, with an overview, all RPNs were reduced by an average of 64,4%, with most faults showing reductions of 56,9% to 77,9%, and the most negligible reduction was 56.9%. The reductions achieved in the heating and cooling system and the hydraulics system of 59.4% and 71.1% are significant because they have the highest associated risk and the highest number of failures. The methodology identified optimal maintenance strategies by identifying critical components related to their systems and subsystems. This study aimed to improve a high-performance military ground vehicle maintenance program using RCM through FMECA methodologies. Improved maintenance plans and schedules were achieved. After implementing this maintenance plan, most of the failure modes considered have a fair associated risk value, revealing that the contributions to the improvement of the maintenance program are acceptable.

This technique is powerful as decision support to the Military Logistics Command because it identifies the need for spare parts as early as possible. It also allows excellent help in planning spares lists needed when preparing a military force to accomplish a specific mission.

The limitations of this work can be identified by the amount of data from the CMMS (Computerized Management System) that manages this Weapon System, which was not much because this Weapon System is recent. This data was not ideal because the data used was not as much as desired. The more data used, the better the quality of the results. In the literature, it wasn't found any study related to this weapon system.

The state's future work will use simulation tools based on Reliability and Maintenance Assessment Models currently under development. These tools will be Generalized Stochastic and Colored Petri Nets. These models will allow the analysis of failure conditions leading to the identification of critical events that will enable simulations to be performed for future operational situations and improve maintenance logistics, operability, and availability of the equipment under study.

Highlights:

- **The methodology identified optimal maintenance strategies by identifying critical components related to their systems and subsystems.**
- **The results will serve to improve technical knowledge of the Weapon System and anticipate maintenance actions.**

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