Advanced Methodologies Applied in a Dynamic Maintenance Context

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ABSTRACT

Maintaining military systems in a dynamic context presents unique challenges that require advanced methodologies to ensure the operational readiness and effectiveness of the Armed Forces. This article analyses and discusses advanced methodologies applied in the maintenance of military technology, highlighting their contributions to the optimization of the maintenance process in constantly evolving operational environments. Initially, we address the importance of predictive maintenance, which uses techniques such as real-time data analysis, condition monitoring and machine learning algorithms to predict failures and proactively schedule maintenance interventions. This approach minimizes downtime, and costs associated with corrective maintenance, significantly increasing the availability of military systems. Additionally, we explore the application of emerging technologies, databases and the use of smart sensors integrated into military equipment. These technologies enable the continuous collection of performance and condition data, enabling a more comprehensive understanding of the state of each component and system. This not only facilitates early detection of anomalies, but also supports data-driven decision making, resulting in more efficient and accurate maintenance. The use of condition-based maintenance approaches is also discussed in this article. These methodologies consider not only the age or time of use of the equipment, but also its actual state of operation. By continuously monitoring operating conditions, it is possible to extend the life of systems, reduce unnecessary wear and tear, and plan maintenance interventions more effectively. Finally, we highlight the importance of integrating computer-aided maintenance management systems and decision support systems. The combination of these tools provides a comprehensive environment for planning, executing and analysing maintenance activities, enabling more efficient resource management and a more agile response to operational demands. In short, this article demonstrates how the adoption of advanced methodologies in the maintenance of military technology is fundamental to ensuring the operational readiness and effectiveness of the Armed Forces in a dynamic and constantly evolving context.

KEYWORDS

Maintenance, Advanced Methodologies, Dynamic.

1. Introduction

Implementing active and dynamic maintenance on military ship maintenance, in a challenge environment with respect to human and material resources, and regarding sustainability, may be an aim of an actual and modern Navy.

Researching about maintenance on equipment's and systems we can found a lot of scientific articles, that reveal the importance of this theme.

If we search for the keyword "Maintenance" (M) in Google Scholar, we obtain approximately 6.42 mi papers. Focusing on the theme of this paper we obtained approximately 2.78 mi papers under "Maintenance in Ships" (MS), 675 k under "Maintenance in Military Ships" (MMS), 5.47

min for Dynamic Maintenance (DM), 817 k in Dynamic Maintenance in Ships (DMS) and 267 k Dynamic Maintenance in Military Ships (DMMS), Fig. 1.

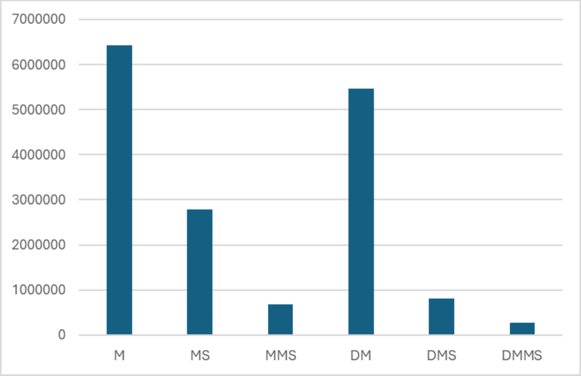

Fig. 1. - Histogram of the number of papers found in Google Scholar – 27 august 2024

By the results of the previous research, we believe that are significant work and research to do in dynamic maintenance in military ships.

2. Maintenance Management

Maintenance management is critical for asset management in various industries, aimed at optimizing the availability and performance of equipment while minimizing costs and downtime. By defining maintenance management strategies in general not only enhances the longevity and reliability of equipment but also significantly reduces operational risks and costs, ensuring safety, maintaining operational continuity (Parida and Kumar, 2006).

2.1 The Relevance of Predictive Maintenance

Predictive maintenance has gained significant importance compared to other maintenance strategies due to its ability to optimize operational efficiency, reduce costs, and prevent unexpected equipment failures. Unlike corrective maintenance, which only addresses problems after they occur, predictive maintenance utilizes advanced technologies such as real-time data analysis, condition monitoring, and machine learning algorithms to predict equipment failures before they happen. This proactive approach enables organizations to perform maintenance only, when necessary, thus minimizing downtime and reducing maintenance costs (Jardine et al., 2006).

Compared to preventive maintenance, which involves regularly scheduled maintenance tasks regardless of equipment condition, predictive maintenance is more efficient and cost-effective. Preventive maintenance can often lead to unnecessary maintenance activities that may not be needed, resulting in higher costs and wasted resources (Mobley, 2002). Predictive maintenance, on the other hand, focuses on the actual condition of the equipment, allowing for more targeted interventions and maximizing the lifespan of machinery (Lee et al., 2014).

In the context of Industry 4.0, predictive maintenance has become even more relevant. With the integration of the Internet of Things (IoT) and big data analytics, predictive maintenance systems can analyse several data from various sensors in real-time to detect anomalies and predict failures (Zhou et al., 2015). This approach not only improves the reliability and efficiency of industrial operations but also enhances safety and sustainability by reducing the likelihood of catastrophic failures (Carnero, 2006).

Overall, predictive maintenance offers significant advantages over reactive and preventive maintenance by providing a more data-driven, condition-based approach to equipment management. As industries adopt more advanced technologies, the relevance of predictive maintenance will likely increase, offering a more effective solution for optimizing maintenance processes and improving overall operational performance.

2.2 Predictive Maintenance in Ships

In the maritime context, predictive maintenance is particularly valuable due to the challenging environment in which ships operate. The use of sensors and remote monitoring technology facilitates the collection of real-time data on the performance of equipment such as engines and propulsion systems. According to Sharma and Kumar (2012), this information is analyzed to identify patterns that indicate imminent wear or failure, allowing planned rather than emergency repairs to be carried out.

This approach reduce downtime, cost savings and increased operational security. According to Jardine, Lin and Banjevic (2006), predictive maintenance can extend the useful life of equipment and prevent catastrophic failures, which are especially critical on ships, where access for repairs can be limited and expensive.

Furthermore, predictive maintenance is a sustainable practice, as it contributes to reducing resource consumption and minimizing environmental impact. As highlighted by Rastegari and Bengtsson (2015), by optimizing the use of parts and resources, ship operations become more efficient and environmentally responsible, contributing to the safe and efficient operation of ships.

3. Advanced Methodologies in Maintenance

There are many advanced technologies that can be applied in industrial, aviation, ships and military equipment and systems considering maintenance management environment.

For reason of limitation of the study we analysed 4 methodologies: Fuzzy, TRIZ, Risk Analysis and FMECA, that were superficially before and independently explored by the authors.

3.1 Fuzzy

Fuzzy logic can be applied as a tool in maintenance management, allowing to manage the uncertainty and subjectivity inherent to complex systems (Zadeh, 1965). Unlike traditional logic, which uses binary values (0 or 1), fuzzy logic works with continuous values between 0 and 1, representing degrees of truth. This is particularly useful in maintenance, where it is often necessary to make decisions based on inaccurate or incomplete information (Ross, 2010).

An important application of fuzzy logic in maintenance is failure prediction and risk analysis. By using fuzzy rules, systems can evaluate the state of equipment based on historical data and linguistic variables such as "high", "medium", or "low" probability of failure, allowing for more proactive and efficient maintenance (Jardine et al, 2006). Furthermore, fuzzy logic is used to optimize maintenance processes, helping to determine the best intervention strategies and resource allocation based on multiple criteria and uncertainties (Jardine et al, 2006).

Therefore, fuzzy logic represents an innovative and effective approach to improving the efficiency and effectiveness of maintenance operations by providing a robust tool for decision-making in uncertain environments.

The process inherent to Fuzzy Logic can be described by the following 7 stage (Jardine et al, 2006).

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

3.2 TRIZ

The Theory of Inventive Problem Solving TRIZ, is a methodology developed by Genrich Altshuller and his colleagues in the 1940s. TRIZ was designed to systematize the process of technological innovation, offering tools for solve engineering problems in an inventive way, overcoming the traditional limitations of empirical methods and brainstorming. The main premise of TRIZ is that problems and solutions are repetitive and, therefore, patterns of inventiveness can be identified and applied to new situations (Altshuller, 1996).

One of the fundamental concepts of TRIZ is the idea of contradictions. In TRIZ, a contradiction occurs when an attempt to improve one characteristic of a system results in a deterioration of another. The methodology offers tools to resolve these contradictions without compromise, promoting innovative and effective solutions. For example, rather than simply accepting a trade-off between strength and lightness in construction materials, TRIZ seeks solutions that improve both characteristics simultaneously (Savransky, 2000).

TRIZ introduces 40 inventive principles and 39 parameters to help engineers resolve technical contradictions. These principles provide guidelines for modifying systems in creative ways, such as “Segmentation” (dividing an object into independent parts) or “Dynamics” (allowing an object to change its position or shape) (Mann, 2007). Additionally, TRIZ introduces the contradiction matrix, a tool that helps identify applicable inventive principles to overcome specific contradictions.

Another important component of TRIZ is the concept of enhancement, which represents the objective of improving a system by increasing its useful functions and reducing its costs and damages. The search for enhancement leads innovators to develop solutions that minimize the use of resources and maximize benefits, aligning with the principles of sustainability and efficiency (Domb, 1998).

In recent years, TRIZ has evolved to include modern tools such as TRIZ Level 2 and TRIZ Level 3, which focus on emerging and complex technologies. This reflects the adaptability of TRIZ to face contemporary engineering challenges, such as the development of cyber-physical systems and innovation in Industry environment (Ilevbare et al., 2013). This evolution allows TRIZ to remain relevant and useful in solving complex problems across diverse industries.

Practical applications of TRIZ can be found in various industries. In the automotive industry, for example, TRIZ has been used to improve engine efficiency and reduce fuel consumption by resolving contradictions related to performance and emissions (Terninko, 1997). In the electronics industry, TRIZ was used to innovate circuit design, overcoming physical and thermal limitations to increase device performance (Litvin, 2005).

TRIZ is also valued for its ability to foster collaborative innovation. In research and development environments, teams using TRIZ are encouraged to explore multiple perspectives and approaches, facilitating collective creativity and knowledge exchange (Gadd, 2011). This is especially important in multidisciplinary projects, where the integration of different areas of expertise is crucial to success.

3.3 Risk Analysis

Risk analysis is a systematic process used to identify, evaluate and manage risks that may affect the success of projects, operations and safety in various areas, such as engineering, finance, health and environmental management. This process is fundamental to making informed decisions, allowing organizations and individuals to better understand potential threats and take proactive measures to mitigate them (Aven, 2015).

The risk analysis process is generally divided into three main steps: risk identification, risk assessment and risk management. Risk identification is the first step and involves collecting information about possible events that could result in adverse consequences. This can be done using different methods, including historical data analysis, expert interviews, brainstorming, and literature reviews. Accurate risk identification is crucial as it allows all potential threats to be considered, avoiding surprises during the execution of a project or operation (Hubbard, 2009).

The second stage, risk assessment, is the qualitative and quantitative analysis of the identified risks. Qualitative analysis involves classifying risks based on their probability and impact, using descriptive scales that allow you to prioritize the most critical risks. Quantitative analysis uses mathematical and statistical methods to estimate the probability of occurrence of each risk and the expected impact, providing a numerical basis for decision making (Aven, 2015). Combining these two approaches allows for a more complete understanding of risks and helps to allocate resources for mitigation more efficiently (Aven, 2015).

The last step in the risk analysis process is risk management, which involves developing and implementing strategies to reduce the likelihood of occurrence or impact of identified risks. Risk management strategies can include preventative measures, such as implementing security controls, and corrective measures, such as creating contingency plans to respond to adverse events. According to Haimes (2009), effective risk management requires a balanced approach, where the costs of mitigation measures are compared with the potential benefits of risk reduction, ensuring that resources are used efficiently.

In conclusion, risk analysis is an essential practice for any organization seeking to minimize uncertainty and maximize safety and efficiency. With the appropriate use of risk identification, assessment and management methods, it is possible to significantly improve resilience and responsiveness to unexpected events.

3.4 FMECA

Failure Modes, Effects, and Criticality Analysis (FMECA) is a systematic methodology for identifying, analysing and classifying potential failures in systems, products or processes. The main objective of FMECA is to prevent failures, improve reliability and increase the safety of systems, especially in critical sectors such as aerospace, automotive and manufacturing (Stamatis, 2003).

The FMECA process begins with identifying potential failure modes, which are the ways in which a component, subsystem, or system can fail. Then, the effects of each failure are analysed to understand the impact on the overall system and product operation (Dhillon, 2008). This analysis helps identify failures that could have serious consequences and therefore need special attention during design or operation. For each failure mode identified, FMECA also considers criticality, which evaluates the severity of the failure effect, the probability of occurrence, and the ability to detect it before the negative effect occurs (Rausand and Hoyland, 2004).

Criticality is an important part of FMECA as it provides a metric for prioritizing corrective actions. According to Pulkkinen and Reunanen (2007), failures that have high severity and high probability of occurrence are considered critical and, therefore, must be addressed immediately to reduce the associated risk. The prioritization process allows engineers focus issues resolution that have the potential to negatively impact system performance or security.

The application of FMECA has been fundamental in projects where reliability is essential. For example, in the aerospace industry, failure mode analysis is used to ensure that critical systems such as avionics and engines operate safely and efficiently throughout the life of the aircraft (Sankar and Prabhu, 2001). In the automotive industry, FMECA is applied to improve component durability and ensure that safety systems function correctly under all operating conditions (Bowles and Peláez, 1995).

Recently, the integration of FMECA with new technologies, such as data analysis and artificial intelligence, has expanded its applications. According to Li et al. (2019), these advanced tools allow for faster and more accurate analysis, facilitating the identification of failure patterns and the implementation of preventive actions. Furthermore, automation of the FMECA process through specialized software improves the efficiency and accuracy of the analysis, reducing the possibility of human error.

However, the successful application of FMECA depends on an understanding of the system being analysed and the availability of accurate data. As highlighted by Rausand and Hoyland (2004), one of the challenges of FMECA is to ensure that all possible failures are identified, and that the analysis is detailed enough to cover all eventualities. Lack of data or inadequate analysis can result in undetected failures, which can compromise system reliability. FMECA may be modified and integrate condition control data of the monitored equipment´s.

4. Analysis of Advanced Methodologies in Maintenance

For better understanding of the four present methodologies, it was built Table nr 1. The table integrate the methodology advantages and disadvantages.

Table nr 1- Advantages and disadvantages of Fuzzy, Triz, Risk Analysis and FMECA

Method	Advantages	Disadvantages
Fuzzy	• Improves handling of untreated data; • Easier process of specifying the rules of a system; • Responses Intuitive using words instead of numbers; • Easier the resolution of complex problems; (Zanette, 2006)	• Difficult to analyse aspects (ex.: optimization); • Precision of the fuzzy system is limited by the data managers experience and knowledge; • System is influenced by all its variables (ex.: chosen method for fuzzification, number of rules, etc.). (Sousa, 2014)
Triz	• Ability to provide innovative and systematic solutions to complex problems (Mann & Domb, 1999). • The application of TRIZ can lead to improved reliability and efficiency of equipment, resulting in reduced costs and increased operating time (Salamatov, 1999). • The methodology encourages creative thinking, helping maintenance managers to develop solutions that go beyond conventional practices (Altshuller, 1984)	• The methodology can be complex and require in-depth knowledge of its principles and tools to be applied correctly (Mann & Domb, 1999). This requires a considerable investment in training and time, which can be an obstacle for some organizations (Salamatov, 1999). • TRIZ's structured approach can be perceived as rigid, limiting flexibility and speed in responding to emergency situations (Altshuller, 1984).
Risk Analysis	• Allows you to identify, evaluate and mitigate potential risks before they become real problems. • Ability to anticipate adverse events and develop response strategies, improving decision-making and resource allocation (Aven, 2015). Risk analysis promotes a culture of safety and prevention, encouraging proactive practices and reducing the likelihood of critical failures (Haimes, 2009).	• The process can be complex and time-consuming, especially in highly uncertain environments or with a lot of data to consider (Hubbard, 2009). • Possibility of inaccuracies in probability and impact estimates, which can lead to inappropriate decisions if risks are not assessed correctly (Aven, 2015). Risk analysis can create a false sense of security, leading to risks being underestimated or misinterpreted (Haimes, 2009).
FMECA	• Ability to prioritize failures based on criticality, allowing resources to be allocated effectively to mitigate the most significant risks (Stamatis, 2003). • Provides a systematic approach to identifying potential failures, improving system reliability and safety throughout the product life cycle (Dhillon, 2008).	• Applying the methodology can be time-consuming and require a certain quantity of data and specialized knowledge, which can be a barrier for some organizations (Stamatis, 2003). • FMECA tends to focus mainly on individual component failures, possibly neglecting systemic failures or complex interactions between different parts of the system (Dhillon, 2008).

The fourth methodologies have their advantages and disadvantages, it is believed that the Triz may be used for optimizing the already implemented maintenance systems. And between Fuzzy, Risk Analysis and FMECA, because in some way it supports the decision making in maintenance, we choose FMECA, that with some modification and using not only the equipment state but the already maintenance management implemented system on an organization but also integrating condition control practice may lead to an accurate knowledge of the system.

6. Conclusions

The Fuzzy, Triz Risk Analysis and FMECA have been explored in various industrial areas, but it may also be used in maintenance management as a support for decision or to optimize de systems implemented.

Triz may be applied for optimize the implemented maintenance system, Fuzzy can be a support for prioritizing maintenance and risk analysis, and Risk Analysis and FMECA may support the analysis of risk of damage in the systems.

It is believed that the four methodologies may be applied in a decision support system, although the author believed that Triz as an enhancement system and a FMECA with integrated data from equipment´s condition control will be a good choice for continuous monitoring of equipment's and system from military ships.

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