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A Review Of Advanced Risk Management Techniques And Strategic Approaches For Enhancing Efficiency In Maintenance, Repair, And Overhaul (MRO) Practices

Yousef Saleh Alzammam

Department of Engineering Management
Prince Sultan University Email: 222120353@psu.edu.sa

Abstract

Maintenance, Repair, and Overhaul (MRO) is a critical industry sector that ensures the optimal performance and safety of aircraft and marine systems through comprehensive servicing, inspection, and repair. This literature review explores the complexities and challenges of MRO management, emphasizing its significance in maintaining airworthiness, operational safety, and compliance with regulations. It examines various risk management techniques, including Failure Mode and Effect Analysis (FMEA) and its extensions, to address equipment failures and enhance maintenance strategies. The review highlights how proactive and systematic approaches, such as risk analysis and Pareto analysis, are used to identify key issues impacting production efficiency and safety. Additionally, it discusses the growing role of advanced organizational practices and interdisciplinary considerations in optimizing maintenance outcomes. The review concludes by introducing the concept of modeling and simulation as valuable tools for improving MRO processes. By leveraging these techniques, organizations can better predict and manage maintenance needs, optimize resource allocation, and enhance overall operational performance.

Introduction

Maintenance, repair, and overhaul (MRO) is a highly specialized industry that plays a critical role in the lifecycle management of various systems and equipment. This sector is devoted to a comprehensive range of activities, including the servicing, inspection, testing, repair, and overhaul of machinery and components. In the aviation industry, MRO is particularly crucial due to its direct impact on the safety and performance of aircraft. Ensuring that aircraft remain fully operational and meet the stringent standards required for safe flight is of paramount importance. The MRO process is not only vital for maintaining optimal performance and safety but also for complying with the rigorous aviation regulations that govern airworthiness and operational safety [1].

Maintenance, broadly defined, refers to the process of ensuring that a system operates consistently at its intended level of reliability and safety throughout its entire lifecycle [2]. This involves a systematic approach to managing and performing maintenance tasks to prevent failures and extend the longevity of the equipment. According to Yoon [3], maintenance activities can be categorized into two main types: on-aircraft and off-aircraft maintenance. On-aircraft maintenance involves performing repairs and inspections directly on the aircraft while it is in service. In contrast, off-aircraft maintenance entails removing equipment and components from the aircraft, replacing them with serviceable units, and sending the removed units to a specialized repair facility. Although off-aircraft maintenance may be slower compared to on-aircraft maintenance, the thorough refurbishment and testing of components during this process are often essential for ensuring long-term reliability and performance. The quick turnaround time of off-aircraft maintenance is crucial and sometimes necessary to meet operational demands.

Miroux [4] highlights that the field of MRO management has grown increasingly complex due to factors such as business expansion, specialization, and the diversity of operational requirements. This complexity arises from various considerations, including cost factors (e.g., cheap versus expensive components), movement rates (e.g., none or slow movers versus high movers), item types (e.g., repairable versus consumable), criticality (e.g., critical versus non-critical components), standardization (e.g., standard versus specific requirements), and supplier lead times. Each of these factors introduces unique challenges that require sophisticated expertise and strategic management. Managing inventory, forecasting demand, overseeing supply chain operations, and handling return and repair flows all contribute to the intricate nature of MRO management. As a result, organizations within the MRO sector are increasingly compelled to reevaluate and adapt their strategies to effectively address these challenges and maintain operational efficiency.

MRO providers are increasingly expanding their geographical reach and upgrading their capabilities to evolve into comprehensive regional and global service providers [5]. This trend reflects a broader shift within the industry, where MRO companies are seeking to capture new markets and enhance their service offerings to meet the growing demands of a globalized aviation sector. Emerging countries, in particular, are witnessing a rise in the number of MRO companies due to several factors, including lower labor costs and strategic partnerships between system suppliers and aircraft manufacturers. These partnerships often involve collaborations that leverage the expertise and resources of established aerospace companies with local knowledge and operational advantages. Notable examples of such collaborations include strategic alliances between Pratt & Whitney and China Eastern, General Electric and Singapore Technologies Aerospace, Boeing and Shanghai Aviation Services Co., and Bombardier and Tianjin Airport. These partnerships not only facilitate the expansion of MRO services into new regions but also contribute to the development of a more interconnected and efficient global MRO network.

In the realm of aircraft MRO, companies face a variety of challenges, with one of the most pressing issues being the delay in completing maintenance and repair tasks. Such delays can have significant consequences for MRO providers, leading to increased operational work time and associated costs. Additionally, delays can result in penalty fees imposed by lessors for late handovers, as well as disruptions to subsequent maintenance activities scheduled for the aircraft. These issues underscore the critical nature of timely and efficient MRO operations [6]. The impact of delays extends beyond immediate financial implications and can affect the overall operational efficiency and customer satisfaction of MRO providers.

Organizations, regardless of their size or type, are influenced by a range of internal and external factors that can impact their ability to achieve their objectives. The concept of "risk" encompasses the uncertainty surrounding these factors and their potential effects on an organization's goals and operations

[7]. Risk can be quantified by evaluating its likelihood of occurrence and the potential impact it may have on the organization. To address and mitigate these uncertainties, organizations engage in risk management practices. Risk management involves a systematic approach to identifying, assessing, and addressing risks to minimize their adverse effects. This approach is integral to various management practices and is widely utilized across multiple fields, including manufacturing, insurance, services, and economics [8]. By effectively managing risks, organizations can enhance their resilience, optimize their operations, and achieve their strategic objectives more effectively.

Mandes, Vieira, and Mano [9] have significantly contributed to the field of risk management in aviation maintenance through their comprehensive systematic literature review. Historically, research in aviation safety has predominantly adopted a reactive approach. This traditional method involves analyzing past accidents, investigating their root causes, and recommending corrective actions to prevent similar incidents in the future [10]. However, this reactive paradigm has become increasingly inadequate for the complex and evolving field of aviation maintenance. The dynamic nature of modern aviation demands a shift towards more proactive methodologies. Proactive risk management not only involves identifying potential issues before they escalate into major problems but also requires the integration of various approaches to be truly effective. Performance indicators play a crucial role in this proactive framework by measuring and identifying organizational risks. Despite this, many latent conditions—those underlying issues that may not be immediately apparent—often go undetected or unreported. This necessitates a vigilant approach to risk management, where organizations must strive to identify latent risks at the earliest stage and implement timely and targeted countermeasures. By adopting a proactive stance, organizations can enhance their ability to preemptively address risks and improve overall safety and operational efficiency in aviation maintenance.

According to Drożyner [11], maintenance tasks are inherently interdisciplinary and encompass a wide array of challenges beyond just technical issues. These challenges include not only the technical aspects of degradation, wear, diagnostics, and technological advancements but also a spectrum of legal, regulatory, and managerial considerations. Addressing these multifaceted issues is essential for achieving goals related to production efficiency, quality assurance, environmental sustainability, and workplace safety. The scope of modern maintenance extends far beyond the traditional focus on efficient tool use and quick damage detection. Contemporary maintenance practices involve predicting and understanding the origins of technical conditions, ensuring high product quality, and safeguarding both people and the environment. Additionally, maintenance processes must be adaptable to ongoing technical and technological developments. This comprehensive approach requires the development or adoption of sophisticated tools and methodologies to make informed and effective decisions regarding the prioritization and scope of maintenance, repair, or investment activities. Enterprises that embrace advanced organizational cultures and technologies recognize that maintenance processes can have profound effects on production output, costs, and the overall quality of the final product, as well as on the safety of personnel and the environment. Maintenance services are tasked with making critical decisions, whether these are right or wrong, related to essential activities such as machine inspection, alignment, and balancing. The choice of operational strategies and purchasing policies can significantly influence technical and technological development, thereby affecting the overall efficiency and effectiveness of the enterprise. The article underscores the importance of using various tools—such as Pareto analysis, two-criteria Pareto analysis, and risk analysis using reliability indicators—to identify critical equipment failures that impact production processes. It highlights that risk analysis, which leverages available operational data such as failure rates and response times, is a pivotal tool for guiding maintenance services. Furthermore, the article emphasizes the critical role of data collection and classification methods in supporting effective maintenance decision-making.

Delays in the redelivery of aircraft from Maintenance, Repair, and Overhaul (MRO) companies to their respective owners have been a significant concern and have been extensively examined in research conducted by Pratiwi, Wessiani, Dzakiyah, and Nurhalizah [6]. Their study utilizes a comprehensive and systematic approach to risk management, leveraging the ISO

31000:2018 framework [12], which is renowned for its robust methodology in risk assessment. This framework is applied in conjunction with root-cause analysis and Pareto analysis to fortify and enrich the analytical structure of their investigation. During the risk analysis process, the researchers employed detailed scales to assess both the likelihood and potential impact of risks. These scales were integral to developing a nuanced understanding of risk profiles and tailoring appropriate risk treatment strategies. To thoroughly identify the root causes of risks, the study involved conducting focus group discussions and interviews with key stakeholders. These discussions were crucial for uncovering the underlying issues contributing to delays. The use of Pareto analysis facilitated the classification of risks by highlighting the most significant factors causing delays. Through root-cause analysis, the researchers discovered that a critical factor in these delays was the lateness in decision-making concerning newly identified findings or issues. This insight underscores the importance of timely decision-making in mitigating delays. To achieve more comprehensive and actionable results, the study advocates for the full implementation of the risk management framework outlined in ISO 31000:2018 [12]. This includes enhancing risk treatment activities to address identified risks more effectively. The ISO risk management process, as depicted in Figure 1, provides a structured approach for managing risks by integrating risk identification, assessment, and treatment into a cohesive strategy, ultimately aiming to reduce the incidence of delays and improve overall efficiency in the MRO industry.

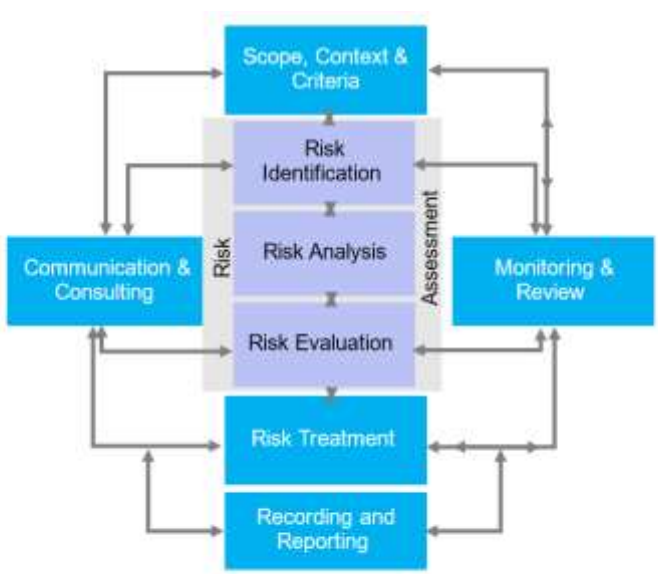

Figure 1: Risk Management Process as Per ISO 31000:2018.

Risk management has become increasingly integral to the internal supply chain within the agricultural industry, as illustrated by the work of Said and Wessiani [13]. They employed a combination of Failure Mode and Effect Analysis (FMEA) and Value at Risk (VaR) techniques to address the complex and variable nature of risks present in this sector. The agricultural industry is characterized by high variability in risk factors, including but not limited to, fluctuations in weather conditions, pest infestations, and supply chain disruptions, which can lead to significant issues such as harvest failures, productivity problems, and quality concerns. To navigate these challenges effectively, companies must rigorously map and assess these risks. The FMEA technique, which has its origins in the 1920s, gained prominence and detailed documentation in the early 1960s. It was initially developed by NASA during the 1960s as a method to enhance the reliability and safety of military equipment [14]. FMEA has since become a cornerstone of risk management strategies, encompassing various techniques designed to identify, assess, and control risks. These techniques are generally categorized into two main types: qualitative and quantitative. Qualitative methods are often utilized by smaller companies with fewer operational activities, focusing on descriptive assessments and expert judgments. In contrast, quantitative methods are more frequently employed by larger organizations with extensive operations, relying on numerical data and statistical analysis to evaluate risk levels. Among these methods, FMEA stands out as a particularly effective tool for identifying, assessing, and managing risks across different sectors [15].

The FMEA method, established in 1950, was originally created to assess reliability and safety within military systems. Its utility and effectiveness quickly led to its adoption in various high-stakes industries, including aerospace and nuclear safety. The method was notably applied to evaluate the safety of iconic aircraft such as the Concorde and Airbus, showcasing its relevance in ensuring aviation safety. Additionally, FMEA was adapted for use in nuclear safety assessments following the Maryland disaster [16]. As a comprehensive engineering technique, FMEA is designed to enhance the quality, reliability, and safety of products, systems, and services by proactively identifying, defining, and addressing potential failures before they reach the customer [17]. FMEA utilizes the Risk Priority Number (RPN) to evaluate and prioritize risks across three critical categories: Occurrence (O), which assesses the likelihood of a specific failure occurring; Severity (S), which evaluates the seriousness of the potential failure's impact on the process, system, or its surroundings; and Detection (D), which measures the probability that the monitoring system will identify a failure cause before the component or system is compromised [18]. The RPN is derived by multiplying these three indexes, providing a quantitative measure of the severity of potential risks affecting the reliability, safety, or productivity of systems or processes. This approach allows organizations to focus their resources and efforts on mitigating the most critical risks, thereby enhancing overall operational effectiveness and safety [19].

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D} \tag{1}$$

In their comprehensive study, Cicek and Celik utilized FMEA to thoroughly analyze the risk of engine crankcase explosions aboard ships [20]. This in-depth investigation highlighted the severe implications such failures could have, including extensive damage to the ship’s structural integrity and potential harm to the crew members onboard. To improve the reliability of the machinery system and ensure a higher level of safety, the researchers meticulously identified and evaluated various components, including system parts, potential failure modes, the potential effects of these failures, the severity of their impacts, the underlying causes, occurrences, and the detectability of these issues. By calculating the RPN for each identified failure mode, the study was able to quantify and prioritize risks. One significant finding was that excessive wear on the piston flame was identified as the most critical failure mode within the engine system. Crankcase explosions, as a result, emerged as a critical risk that necessitates stringent precautionary measures and preventive strategies to safeguard both the vessel and its crew. The study underscores the importance of detailed risk assessments in preventing catastrophic failures and ensuring maritime safety.

Li, Díaz, and Soares [21] conducted an extensive failure analysis of floating offshore wind turbines employing an advanced risk assessment technique known as AHP-FMEA, which integrates the Analytic Hierarchy Process (AHP) with FMEA through sophisticated numerical algorithms. The primary objective of their research was to identify and address deficiencies during the design phase of wind turbines, analyzing the potential failures of each component and their broader impact on the entire system [22]. Their analysis identified a total of fifteen different failure scenarios and proposed both preventive and corrective measures to mitigate these identified risks. The study involved assigning weights to each factor to facilitate the effective implementation of the AHP-FMEA technique. The results revealed that the wind turbine was the most critical component in terms of risk. The study also highlighted a notable aspect of FMEA, namely its inherent subjectivity, as the outcomes of the risk assessments can vary based on the personal judgments of different specialists, leading to differing RPNs. This variability in results emphasizes the need for a more standardized approach to ensure consistency and reliability in risk assessments.

Kahrobaee and Asgarpoor [23] proposed a novel extension to the traditional FMEA method, known as Risk-Based FMEA (RB-FMEA), which incorporates the cost associated with each failure mode. This innovative concept, which has been only marginally explored in existing literature [24, 25], offers a practical approach by introducing cost as a common metric that spans various aspects of turbine design, operation, and maintenance. RB-FMEA presents a quantitative approach that aligns well with the performance metrics of wind turbines, facilitating a straightforward comparison of costs associated with different maintenance strategies or design improvements to make more informed and optimal decisions. One notable advantage of this method is its simplicity; it is implemented using Microsoft Excel worksheets, which are easily modifiable and adaptable by manufacturers of various types of wind turbines. The practical application of RB-FMEA to a 3MW direct drive wind turbine demonstrated that it can yield more realistic, credible, and actionable results. This approach not only enhances the decision-making process but also provides a clear framework for evaluating and managing risks in wind turbine operations.

In a study conducted by Hieminga and Turkoglu [26] concerning the risks associated with aircraft maintenance within the European commercial air transport sector, it was concluded that the aviation MRO industry could substantially enhance safety by placing greater emphasis on the proper application of procedures during installation and removal tasks within maintenance programs. The study also noted the importance of reviewing and clarifying procedures for deferring acceptable defects, as this aspect also ranks highly in terms of importance. By examining the narratives of related incidents, the researchers aimed to identify common factors that could provide insights for further investigation. The study suggested that additional research into the distribution of incidents over time or the correlation between the number of incidents and specific aircraft types could refine and improve recommendations for the MRO industry. However, the analysis was limited by the constraints of the available data set, which restricted the examination of variations between different countries or regions, highlighting a need for more comprehensive and varied data to better inform safety recommendations.

In the context of preventive maintenance for marine engine systems, Cicek, Kadir, et al. [27] highlighted that while there is a substantial body of literature on risk-based preventive maintenance planning and FMEA analysis, there is a notable gap in studies focusing specifically on the application of these tools to marine engine systems, particularly within fuel oil systems. Their study is distinguished by its unique application, addressing an area that had not been extensively investigated before. The general structure of the FMEA procedure was found to be effective and suitable for developing a risk-based preventive maintenance plan for marine systems. The study utilized FMEA to evaluate significant failures in the fuel oil system, incorporating feedback, brainstorming, and expert judgments into the analysis process. The preventive maintenance plan derived from this analysis aimed to enhance the reliability of the system by prioritizing corrective actions for issues such as fuel valve dripping and premature opening, abnormal sounds in transfer/supply/booster pumps, low supply pressure in the high-pressure fuel pump, and clogged strainers. By addressing these issues, the study demonstrated that the frequency of failures in the fuel oil system could be significantly reduced, thereby improving overall system reliability and operational efficiency.

Results

The literature provides a comprehensive overview of the critical findings and developments in the field of MRO, with particular focus on aviation and marine systems. The review underscores the essential role that MRO plays in maintaining aircraft safety and ensuring compliance with stringent regulatory requirements. It highlights how various factors—such as costs associated with maintenance, the rates at which items move through the supply chain, the types of items handled, and the lead times of suppliers—introduce significant complexity into the MRO process. This complexity necessitates a high level of expertise in several areas, including inventory management, forecasting, and supply chain management. The intricacies of these factors mean that effective MRO management requires advanced skills and strategies to navigate the challenges and ensure that all aspects of the maintenance process are addressed efficiently and effectively.

The evolution of MRO management has been driven by increased business growth and specialization within the industry. Companies are not only expanding their geographical reach to become regional and global service providers but are also forming strategic partnerships to enhance their capabilities. Noteworthy examples of such collaborations include the partnerships between major industry players like Pratt & Whitney and China Eastern, General Electric and Singapore Technologies Aerospace, Boeing and Shanghai Aviation Services Co., and Bombardier and Tianjin Airport. These alliances highlight the trend towards globalization in MRO services and reflect the industry's response to the growing demand for comprehensive and integrated maintenance solutions.

Delays in aircraft maintenance and repair, as emphasized by the study conducted by Pratiwi et al., present significant operational challenges for MRO companies. These delays can lead to increased operational costs, penalty fees for late handover from lessors, and disruptions to subsequent maintenance schedules, all of which can impact the overall efficiency and safety of aircraft operations. To address these challenges, the study advocates for the use of ISO 31000:2018 as a framework for risk assessment, combined with root-cause analysis and Pareto analysis.

Implementing these methodologies can enhance the risk management framework by identifying the underlying causes of delays and developing effective strategies to mitigate them.

Maintenance tasks are increasingly recognized as inherently interdisciplinary, involving not just technical aspects but also legal, regulatory, and managerial considerations. Modern maintenance practices now extend beyond the traditional focus on tool use and damage detection to include forecasting technical conditions, ensuring product quality, and safeguarding environmental impacts. Effective decision-making in this context requires the application of advanced tools and methods to prioritize maintenance, repair, and investment activities. This approach ensures that resources are allocated efficiently and that maintenance strategies are aligned with broader organizational goals.

The utilization of various analytical tools, including Pareto analysis, two-criteria Pareto analysis, and risk analysis with reliability indicators, has proven to be effective in identifying critical equipment failures that can significantly impact production efficiency. Risk analysis, in particular, leverages operational data such as the frequency of failures and the time required for repairs to guide maintenance decisions. The literature review emphasizes the critical role of accurate data collection and classification in this process, underscoring the need for reliable information to support effective risk management and decision-making.

Risk management techniques such as FMEA and its extensions have been applied across a range of industries to address various risk factors. For example, FMEA has been used to analyze risks in marine engine systems, with a focus on critical failures like fuel valve issues and pump malfunctions. The study by Cicek et al. demonstrates the effectiveness of FMEA in enhancing preventive maintenance plans for marine systems. By prioritizing corrective actions based on FMEA analysis, the study has shown a reduction in failure frequencies and improved system reliability. Additionally, innovations such as Risk-Based FMEA (RB-FMEA) that incorporate cost considerations provide a practical approach for evaluating maintenance strategies. RB-FMEA offers a quantitative method that aligns with performance metrics, allowing for better decision-making regarding maintenance and design improvements. This approach, particularly when applied to wind turbine maintenance, highlights the benefits of integrating cost considerations into risk management practices.

Overall, the literature illustrates the evolving nature of MRO practices and the growing importance of integrating diverse analytical methods to optimize maintenance strategies. This evolution reflects an ongoing effort to enhance system reliability, safety, and overall operational efficiency. The integration of advanced analytical techniques and comprehensive risk management frameworks underscores the industry's commitment to addressing the complex challenges associated with MRO and achieving higher standards of performance and safety.

Conclusion

Research highlights the importance of delving deeper into the distribution of maintenance incidents over time and examining their correlation with specific aircraft types. This area of study is crucial for understanding patterns and trends in maintenance issues, which can help in predicting and preventing future problems. Additionally, there is a need for more targeted research focusing on the application of maintenance tools to specific systems, such as marine fuel oil systems. Such investigations can provide valuable insights into enhancing the reliability and operational efficiency of these critical systems. Further research should also explore the implementation of additional techniques designed to mitigate risks associated with delays in MRO processes. Delays can be exacerbated by a lack of effective tools, but techniques such as process modeling and simulation could be employed to address and alleviate these issues. By simulating various scenarios and processes, organizations can better anticipate potential delays and develop strategies to minimize their impact.

The literature review emphasizes the intricate and multifaceted nature of MRO practices, particularly within the realms of aviation and marine systems. It underscores the critical role that MRO plays in ensuring operational safety and compliance with regulatory standards. The complexity of MRO management is influenced by numerous factors, including cost considerations, the rates at which items move through the supply chain, and the lead times of suppliers. This complexity necessitates the development and implementation of advanced strategies and tools to enhance both efficiency and effectiveness in MRO operations. Delays in maintenance and repair activities present significant challenges, leading to increased operational costs and disruptions. In this context, the integration of sophisticated risk management techniques, such as FMEA and its extensions, has proven to be effective in identifying and addressing critical equipment failures. These techniques help optimize maintenance strategies and improve overall operational performance.

To effectively address the growing complexity and dynamic nature of MRO processes, modeling and simulation techniques have emerged as valuable tools. These methods offer substantial benefits by providing a structured approach to analyzing and predicting the impacts of various maintenance strategies and operational conditions. Through the use of modeling and simulation, organizations can create virtual representations of MRO processes, which allows for the exploration of different scenarios, the evaluation of potential risks, and the assessment of the effectiveness of various maintenance strategies before they are implemented. This approach enables a more thorough understanding of the potential outcomes and impacts of different maintenance actions.

By incorporating modeling and simulation into their MRO practices, organizations can significantly enhance their ability to make informed, data-driven decisions. This integration supports the anticipation and mitigation of potential issues, optimizes maintenance schedules, and improves resource allocation. The use of these techniques not only enhances the accuracy of risk assessments but also contributes to the development of more effective and efficient maintenance plans. Ultimately, the adoption of modeling and simulation in MRO practices leads to more robust and adaptive strategies, fostering improved operational performance, reduced costs, and enhanced safety across both aviation and marine systems. This forward-looking approach underscores the importance of leveraging advanced analytical tools to navigate the complexities of modern MRO challenges.

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