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Risk Based Maintenance For Drones In Compliance With EASA Requirements: Case Study From Norway

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Abstract

The advantages of drones have led to their increased volume in the airspace. Drone systems are characterized as complex, and they are prone to failures, and require regular maintenance to ensure acceptable quality. Considering these aspects, the European Union Aviation Safety Agency (EASA) mandates that operators have a risk-based maintenance program. However, it is challenging to determine how to implement these programs in a risk-based manner. In this paper, we address the requirements set forth by EASA and discuss how to understand and adopt them. EASA has a specific definition of the concept of risk and provides guidance on risk categorization, serving as a basis for the discussion. We critically assess these requirements and consider the use of Risk-Based Maintenance (RBM) as a method to satisfy the requirements given by EASA. There is a lack of clear guidance on how to meet, especially regarding how to satisfy the requirements. A real case from a Norwegian drone operator is used to illustrate the situation, and some recommendations are provided on how to perform risk-based maintenance planning in alignment with current standards.

Keywords: maintenance, drone operations, Safety, EASA Directives, risk based inspection, regulatory requirements, uncertainty

1. Introduction

The increasing presence of Unmanned Aircraft Systems (UAS), commonly referred to as drones, in our airspace, has introduced significant challenges related to safety and efficiency. There is a need for high reliability. This highlights the need for proper maintenance.

Recent advancements in regulatory standards from the European Union Aviation Safety Agency (EASA) have progressed towards a risk-based approach for drone maintenance. However, there seems to be a lack of practical application of these regulations. Although point to risk-based maintenance, they lack explicit instructions on how to implement it.

This absence of detailed guidance presents a challenge for the UAS industry. The regulations give maintenance requirements, emphasizing planning and execution, focusing on potential risks, but fall short in describing the method. This lack leaves operators and maintenance personnel seeking the most effective methods to comply with these safety requirements.

One alternative is Risk-Based Maintenance (RBM). This method offers a possible solution to the challenges faced in the maintenance of UAS, particularly within the regulatory frameworks set by EASA. This paper explores the potential of RBM as a way to meet maintenance requirements, an area that requires further investigation and understanding. By examining various RBM strategies and assessing their alignment with EASA's standards, this study seeks to strengthen drone maintenance practices. The objective is to address the existing lack of regulations and provide practical insights, potentially developing a more structured, efficient, and safe maintenance regime in a fast-evolving industry.

The remaining paper is structured as follows. Chapter 2 introduces relevant UAS maintenance regulations. Chapter 3 gives a brief description of the RBM method. Chapter 4 then addresses UAS maintenance criteria and requirements, considering the principles of RBM. Chapter 5 presents a case study of the maintenance guide of a Norwegian drone operator in the context of RBM, offering practical insights. Chapter 6 analyzes these findings in depth and enhances understanding of how RBM can meet UAS maintenance requirements. Finally, the study concludes in Chapter 7, summarizing the key findings and proposing strategic recommendations for effectively applying RBM in drone maintenance, aiming to advance UAS maintenance practices and safety.

2. Maintenance references in drone regulation

UAS has seen rapid growth and increased complexity. Maintenance of these systems is essential to ensure safety operations. Recognizing this, EASA has moved towards a risk-based approach for drone maintenance. This approach evaluates potential hazards in drone operations and formulates maintenance strategies to mitigate these risks. This shift is reflected in four key regulatory documents (See Figure 1).

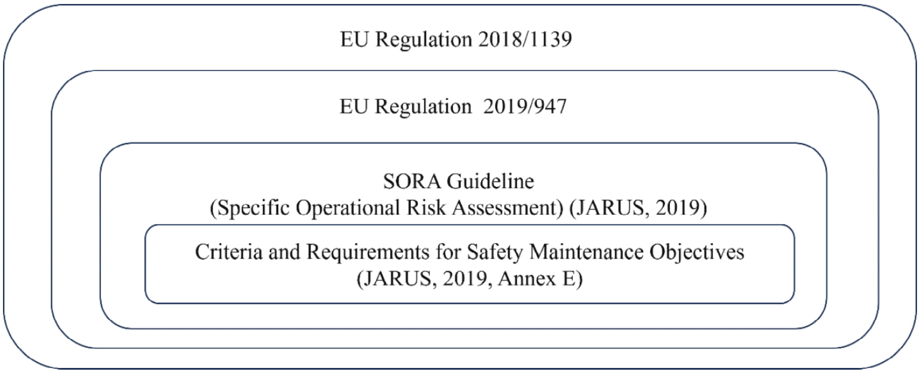

Fig. 1. Maintenance regulatory framework for drones.

EU Regulation 2018/1139 serves as the primary regulatory framework for the design, production, maintenance, and operation of UAS. This regulation details stringent design standards for UAS to reduce malfunctions and underscores the necessity of precise maintenance instructions and the proficiency of maintenance staff. These requirements adopted a risk-based approach to UAS maintenance, which is further refined in the EU Regulation 2019/947 and the Specific Operations Risk Assessment (SORA) guidelines (JARUS, 2019).

EU Regulation 2019/947 serves as a pivotal document for establishing a comprehensive risk-based maintenance management system for drones. The primary focus is on operational safety, promoting a maintenance approach based on the assessment and management of risks. This regulation highlights the operator's responsibilities in maintaining the UAS in a condition suitable for safe operation. This includes, as a minimum requirement, the development of detailed maintenance instructions and the engagement of maintenance staff who are adequately trained and qualified for the task. This regulation, along with the SORA guidelines, marked a significant step towards integrating risk assessment and management into drone maintenance practices (JARUS, 2019).

The SORA guidelines, complementing the EU Regulation 2019/947, provide detailed guidance for risk-based drone maintenance aligned with the risk levels identified in drone operations. This document is particularly crucial in complex drone operations where proactive risk management is essential for enhancing safety. In its approach, SORA specifies criteria based on the risk levels identified in the risk assessment. Additionally, it outlines the corresponding requirements necessary to mitigate potential hazards during the maintenance process.

İn Annex E of the SORA guideline, it is established criteria and requirements for maintenance and training. Subsequently, the requirements section for these criteria emphasizes the importance of maintenance instructions to ensure that maintenance processes are specific and effective for each UAS model (see Table 1). It highlights the critical role of skilled and authorized personnel in performing these tasks, which are key to minimizing maintenance-related failures and operational incident risks. This approach underscores the proactive management of potential risks in drone operations and demonstrates that safety can be ensured through careful planning and execution of maintenance activities. Furthermore, it reinforces the importance of maintaining detailed records for monitoring performance in drone maintenance.

Table 1. Requirements for maintenance (JARUS, 2019).

Criterion	Requirements based on risk level		
	Low	**Medium**	**High**
Procedure	• The UAS maintenance instructions must be defined. • Maintenance personnel are required to be competent and possess authorized certifications to conduct UAS maintenance. • Maintenance operations must be performed according to the UAS maintenance instructions.	Same as Low. In addition: • Scheduled maintenance of each UAS must be organized. • The maintenance log system must be used to record all maintenance conducted on the UAS including releases.	Same as Medium. In addition: • Procedure manual must encompass; -record-keeping; -instructions; -tool and material usage; -component handling; -managing defects.
Training	• It's required to maintain an up-to-date record documenting all maintenance staff's qualifications, experiences, and completed training.	• Initial training programs must align with the maintenance authorizations of the staff. • Staff release authorization must receive model-specific initial training. • All maintenance staff are required to complete initial training.	• Establishment of a recurrent training program for staff holding maintenance release authorizations is required; and • This training program must be validated by a competent and independent third party.

However, despite the comprehensive frameworks outlined in regulations and guidelines, there seems to be a notable lack in their applicability. Firstly, while these guidelines focus on maintenance, they fail to provide a structured inspection plan. This absence of a detailed inspection framework is a critical oversight, as such a plan is essential for devising an effective maintenance strategy. The second gap is related to the absence of a specified method for fulfilling the maintenance requirement. These documents, while outlining regulatory requirements for risk-based maintenance, do not provide explicit guidance on the practical execution of these requirements. This leaves a substantial challenge in how drone operators and maintenance personnel can adhere to these standards in their operational practices.

To remedy these deficiencies, the subsequent sections will focus on the RBM method that effectively connects the theoretical aspects of risk-based maintenance with operational execution. This will present how both maintenance and inspection plans can be developed by thinking of EASA's regulatory context. The objective is to elucidate a pathway that transforms the theoretical elements of risk-based maintenance into practical, compliant practices, thereby advancing the safety and efficiency of drone operations.

3. RBM description

RBM has evolved as a method within various industries, particularly in aviation, to minimize unexpected failures, production losses, and high costs (Krishnasamy et al., 2005). Originating in the 1970s, RBM's development was propelled by the need for efficient risk management in complex systems and was further shaped by significant industrial accidents such as Flixborough, Seveso, and Piper Alpha (Santos et al., 2023). In aviation, RBM plays a pivotal role in ensuring the structural integrity of aircraft through inspections, significantly contributing to the life extension of these structures (Lee et al., 2022).

In the subsequent section, we will address some key concepts in RBM and describe how the RBM method offers insights into how it builds up the maintenance management framework.

3.1. Key concepts

In RBM, as presented in Khan and Haddara (2003) and Santos et al. (2023), risk is defined as the combination of the probability of system failures and their consequences. This combination evaluates both the probability of a failure occurring and the potential impact it may have on operations, safety, and finances. It emphasizes a comprehensive understanding of how different factors, including the operating environment, influence the overall risk associated with organizational assets.

EASA documents do not explicitly define risk; however, their approach to risk indicates a focus on probabilities and consequences of potential hazards. For example, in the SORA Guideline document (JARUS, 2019), UAS operational risks are assessed by considering both the probabilities and consequences of hazards in the air and on the ground. The assessment of risk does not only focus on preventing immediate harmful incidents like UAS crashes but also considers the potential for serious harm to third parties.

ISO 31000 (2018) defines risk as the “effect of uncertainty on objectives”. According to this definition, uncertainty is a key concept in risk management. Unlike the way risk is expressed in traditional risk matrices, in ISO 31000 (2018) uncertainty encompasses not only the probability and consequence but also how well these probabilities and outcomes are understood. In this regard, the ISO 31000 (2018) standard states that managing uncertainty is more than just the process of identifying, analyzing, and evaluating risks. The management of uncertainty addresses understanding the strength of current knowledge, how to deal with incomplete or uncertain information, and how to enhance decision-making processes considering this knowledge. Therefore, ISO 31000 (2018) suggests considering how these processes will deal with uncertainty and adapt to continuously evolving knowledge while integrating risk management into an organization's overall management processes.

In addition to risk, there is also a focus on detectability. As defined in MIL-STD-1629A (1980), detectability involves the methods by which failures can be identified. This concept is crucial for the early detection and mitigation of potential system failures, enhancing overall safety and operational efficiency. By prioritizing detectability, RBM not only addresses the risks but also proactively identifies and manages latent risks, aligning with proactive risk management strategies.

There seems to be a gap between the traditional way suggested by EASA and the ISO 31000 (2018) standard way concerning the focus on uncertainty. This standard emphasizes the focus of uncertainty when dealing with a risk. Detectability, as a key concept in RBM, involves identifying potential failures early on, thus enhancing proactive risk management. Therefore, ISO 31000, with its wider framework focusing on uncertainty, struggles to fully align with EASA's more narrowly focused risk management framework.

3.2. RBM method description

RBM fundamentally consists of four main steps: risk assessment, maintenance assessment based on the results of assessment, implementation, and performance monitoring. The RBM framework is illustrated in Figure 2. This method aims to achieve a suitable maintenance program that effectively manages risks. Emphasized by Wang et al. (2012), RBM is an important tool for improving maintenance decisions in industrial facilities and complex machinery systems, ensuring that maintenance strategies are effectively aligned with the identified risks.

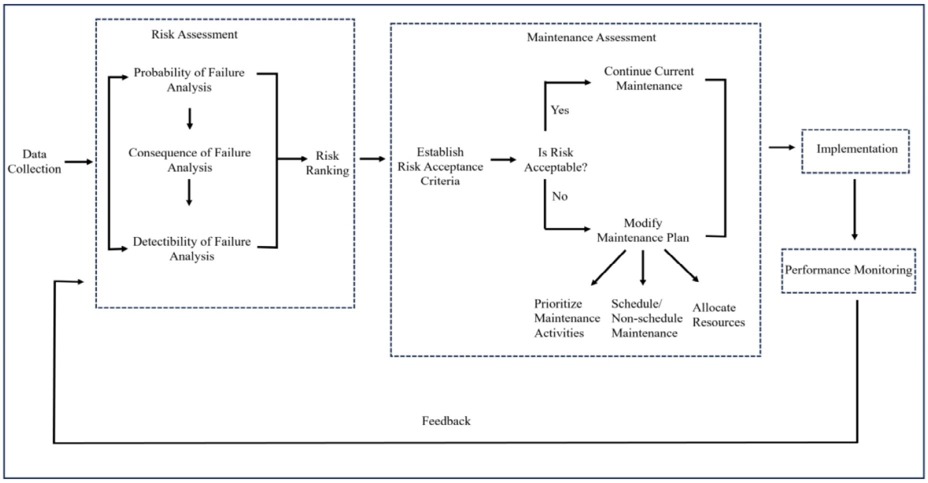

Fig. 2. Risk-based maintenance framework.

3.3. Risk assessment

The risk assessment step in RBM is organized to evaluate the risk profiles of components and systems, as input to the subsequent maintenance planning. (Santos et al., 2023; Krishnasamy et al., 2005; Arunraj and Maiti, 2007). Although the data collection process is not the initial stage of risk assessment, it provides necessary information. The data collected is essential for identifying potential failure modes associated with a component or the integration process and serves as a key input for the risk assessment.

The risk assessment step is pivotal in identifying and prioritizing potential failures. This step involves a systematic analysis of risks for each probable failure, which is assessed through numerical data or expert judgment.

Santos et al. (2023) detail this process, which includes creating a matrix to map the probability, consequence, and detectability of occurrence. The process also encompasses identifying detection methods for failures, either through data from normal operations or diagnostic analyses by maintenance personnel. Santos et al. (2023) utilize the Failure Mode Effects Analysis (FMEA) model at this stage. Additionally, a risk priority number is calculated by combining the likelihood and impact of failures, as described by Khan and Haddara (2003). This calculation is instrumental in prioritizing risk considering not only one component but also the overall performance of the system. Khan and Haddara (2003) have developed scenarios that can describe potential system failures. In the risk ranking part that follows, risks are prioritized based on the data obtained from the risk analysis. The phase is utilized to determine how risks should be addressed as a priority, ensuring that the most critical issues are focused on first for maintenance and management actions (Khan and Haddara, 2003).

3.3.1. Maintenance assessment

The primary objective of maintenance planning is to select and schedule appropriate maintenance activities based on the level of risk, with a focus on optimizing maintenance interventions for components that meet or exceed acceptable risk criteria. This process involves making strategic decisions to design a comprehensive maintenance program that effectively mitigates identified risks. These decisions are crucial for shaping a maintenance program that not only addresses immediate risk concerns but also lays the groundwork for the detailed risk assessment and maintenance plan formulation that follows.

In this regard, based on the risks identified and prioritized during the risk assessment stage, the next step involves formulating a maintenance plan for each system's components. At this step, acceptable risk criteria, based on the results from the risk analysis, are defined. This step, highlighted by Khan and Haddara (2003), is critical for identifying failure modes that exceed the established criteria, thereby prioritizing components for maintenance based on potential system impact. Santos et al. (2023) emphasize the application of the ALARP principle in this part, aiming to reduce risks to the lowest practicable level while balancing safety and cost-effectiveness. Krishnasamy et al. (2005) note that this step also entails applying these criteria to each system component, directing maintenance efforts towards units exceeding the risk threshold. This approach ensures targeted and efficient maintenance planning, focusing on components regarding their risk levels.

If the risks remain within acceptable limits, current maintenance continues. However, if the risks associated with the components exceed acceptable limits, then a maintenance plan is modified. This planning process involves prioritizing maintenance actions based on the significance of the risks, considering applicability and effectiveness, followed by scheduling maintenance and reallocating resources accordingly (Krishnasamy et al., 2005).

3.3.2. Implementation

During the implementation phase, a formulated maintenance plan is put into action. This involves executing the scheduled preventive and corrective maintenance tasks, nonscheduled maintenance, integrating redundancy systems where necessary, and deploying advanced monitoring technologies to enhance failure detectability. This step is critical as it actualizes the risk mitigation plans, aiming to enhance system reliability and ensure continuity of operations. The success of this phase is determined during implementation by achieving a maintenance program that effectively minimizes the identified risks.

3.3.3. Performance monitoring

Following the implementation of maintenance, performance monitoring is an important step in formulating responses to identified risks and focuses on effectively observing the maintenance condition. At this step, safety indicators are utilized to observe the outcomes of maintenance work to assess whether the maintenance is achieving the desired impact. These indicators provide insights not only into the effectiveness of maintenance activities but also help ensure compliance with legal standards. Thus, this step is vital not only for enhancing operational safety but also for ensuring adherence to evolving regulations and standards (Fiix Software, 2023).

During the performance monitoring phase, risks may exceed acceptable limits. In such cases, a decision to reassess risks based on data obtained after performance monitoring is another step in RBM. This involves re-examining malfunctioning components, maintenance systems, or maintenance personnel management when operational performance exceeds accepted risk criteria and risks increase. In this scenario, data obtained during the monitoring process provides feedback for a new risk assessment (Fiix Software, 2023).

4. Assessment of EASA's maintenance requirement considering RBM

In this section, we critically assess the UAS maintenance requirements as specified by EASA, focusing on aspects such as maintenance management in organizations, maintenance instructions, record-keeping systems, and the qualifications and training of maintenance personnel. Additionally, this chapter highlights the lack of instructions in EASA regulations regarding scheduled and unscheduled maintenance, particularly in the context of specific procedures, timing, and implementation methods. Through this assessment, we will evaluate how the RBM method might serve as a potential solution to satisfy these specified and unspecified requirements, effectively addressing both the explicit guidelines and the lack within EASA's framework.

4.1. Requirements given in EU Regulations 2018/1139 and 2019/947

EU Regulations 2018/1139 and 2019/947 emphasize the importance of a risk process in maintenance management but do not delineate a specific management framework or propose explicit criteria for implementing these processes. In the absence of such detailed guidance, the RBM method becomes particularly relevant. In RBM, it is addressed the necessity of a risk-based approach in maintenance management to support safe operations, emphasizing a structured approach for all maintenance processes. In the context of UAS maintenance, as highlighted by Misto (2007), the organizational structure is critical in ensuring effective maintenance and safety. This involves comprehensive guidance approved by a responsible manager, which outlines the organization's scope and maintenance standards. As Keane et al. (2017) further elaborate, this structure emphasizes the pivotal role of qualified personnel, where meticulous training, documented competencies, and essential qualifications are necessary to uphold aviation safety standards. Martinetti et al. (2017) underscore the need for management in planning, implementing, and reviewing maintenance tasks, along with maintaining a controlled inventory. Their framework advocates for the periodic updating of maintenance programs by integrating data from real field experiences to enhance performance. This managerial structure and related details ensure that the maintenance team is adequately prepared and skilled to handle the various challenges in UAS maintenance, thereby assuring the reliability and safety of UAS operations.

4.2. Requirements given in the EASA document

EASA documents, specifically in the SORA Guideline (JARUS, 2019), specify maintenance requirements for UAS related to instructions, record-keeping systems, as well as qualified maintenance personnel. The following paragraphs will assess these requirements and indicate how the RBM approach might present a suitable solution.

The SORA guideline provides criteria and requirements for instruction, considering the risk environment created by ground and air risks specific to UAS operations. SORA leaves the responsibility of meeting this requirement based on identified risks to the UAS operators without proposing a criteria table. This leads to two main challenges for drone operators: First, they frequently face a lack of detailed instructions that meet SORA's requirements. Second, it's common for UAS to be provided without detailed maintenance instructions (Karunakaran, 2022). Hobbs and Herwitz (2008) argue that RBM advocates customization of the maintenance instruction according to the type of operation. In this sense, it is emphasized that organizations might follow a way for maintenance instruction to meet maintenance requirements according to acceptable risk criteria determined during the maintenance planning phase.

Further, the planning of maintenance is based on data collection about the UAS. It is stipulated in SORA that maintenance performed on UAS must be recorded in a maintenance record system (JARUS, 2019). When looking at the means of compliance in another EASA (2022) document, the necessity of such a record system for addressing maintenance requirements is also presented. This perspective is present in the RBM method, which requires a log system applicable to all UAS operations based on appropriate risk assessments in the initial step. This record system is also used after maintenance planning to observe the suitability of the maintenance program. In this evaluation, by Khan and Haddara (2003) and Santos et al. (2023) defining the scope of recorded flight data and safety performance indicators for each part of the UAS is essential.

EASA emphasizes specific training requirements for UAS maintenance personnel, underscoring the importance of well-documented qualifications and competencies. However, EASA does not offer a detailed method for achieving these educational goals. In this context, the RBM method, also indicated by Khan and Haddara (2003) and Wang et al. (2012), guides the development of training programs that might align with EASA's requirements. Within the framework of RBM, this training program encompasses not only enhancing the quality of maintenance personnel but also developing skills in risk assessment, maintenance planning, and critical decision-making. Consequently, the implementation of the RBM method results in solutions that not only meet technical proficiency requirements but also equip personnel to handle the evolving challenges in UAS maintenance and ensure compliance with the safety standards set by EASA.

Maintenance of the UAS is essential to ensure the safety and reliability of flights. There are two main types of maintenance in aviation: scheduled and unscheduled maintenance. The main aim of scheduled maintenance is to prevent issues from arising in the first place, by identifying and addressing potential challenges before they can cause major issues. On the other hand, unscheduled maintenance known as preventive and corrective, is performed when unexpected issues arise. This type of maintenance typically occurs because of challenges that are identified during scheduled maintenance or through in-flight monitoring systems (Herwitz and Hobbs, 2006).

However, EASA does not prescribe tasks within the maintenance organization, such as scheduled and unscheduled maintenance, to ensure an acceptable level of safety. On the other hand, in RBM, a potential scheduled maintenance solution is outlined by integrating risk assessments with operational tasks, ensuring that maintenance does not compromise system safety. Additionally, unscheduled routines are established for timely intervention in critical components. Moreover, the location of maintenance activities (whether in the field, a workshop, or a manufacturer/specialist facility) is crucial. Hobbs and Herwitz (2008) demonstrate that RBM's practical application in this context adapts maintenance strategies to different operational environments and balances immediate repair needs with long-term maintenance planning.

Within the RBM framework, identifying critical components for the UAS maintenance program is an important aspect. EASA requirements do not specify any way to prioritize components in maintenance. However, the RBM method necessitates a significant focus on the primary component, varying considerably based on the systems. Guiding operators in this area, pioneering work by Nick et al. (2017), Hobbs and Herwitz (2008) and Aukland and Young (2019), and guidelines published by Japan Civil Aviation (2022), UK Ministry of Defence (2006), and Jordan Civil Aviation (Misto, 2007), emphasize the inclusion of critical components such as engines, propellers, batteries, and others in maintenance procedures.

5. Implementing RBM in a Norwegian Drone Operator's Maintenance Manual

This section discusses the integration of RBM into the maintenance manual of a Norwegian drone operator. The primary focus is to examine the company's current maintenance processes and how RBM can be applied. This will assist in understanding the practical applicability of RBM in UAS maintenance and identifying areas for potential improvement, thereby shedding light on how to meet EASA requirements. Subsequent sections will initially provide information about the Norwegian drone company and its maintenance manual. Then, using the RBM method, the company's maintenance manual will be thoroughly analyzed, and data in the manual will be presented according to each stage of RBM. Subsequently, inputs on how RBM might be utilized in the company's maintenance considering the RBM method will be made. The final section will offer a broader explanation of the mentioned inputs.

5.1. Norwegian Drone Operator's Maintenance Manual

The drone company operates in Norway, the UK, and the USA, conducting Beyond Line-of-Sight flights for line inspections. Beyond visual flight is an automatic flight performed beyond the visual contact of the pilot and requires high technology. The key element of the manual consists of a general system description, airworthiness limitation, maintenance tasks, servicing and routine maintenance, and standard practice. The examined maintenance manual includes various maintenance tasks, procedures, and checklists, along with a well-prepared data collection system. Additionally, the manual contains a training module for maintenance personnel. Detailed explanations are provided for specific maintenance activities such as engine maintenance, propeller assembly, battery control, and fuselage inspection. Each process includes defined steps and requirements, documented in an applicable and tangible manner.

5.2. Analysing and Applying RBM in Drone Maintenance

In this section, we delve into the integration of RBM within a Norwegian drone operator's maintenance manual. The focus is on assessing the company's current maintenance methods and applying RBM effectively. We will examine how RBM can be effectively integrated into drone maintenance by following the RBM steps of risk assessment, maintenance assessment, implementation, and performance monitoring.

- Risk Assessment

Currently, the company's maintenance planning does not systematically incorporate risk assessment, relying instead on varied industry experiences. This approach has led to challenges in maintaining motors and propellers, and the only risk assessment activity involves test flights for new component integration. Maintenance personnel also show a lack of expertise in risk assessment, with training primarily based on the manual but not specifically addressing front-line pilots with maintenance authority. In RBM, it is stressed that a well-defined maintenance organization with clear roles is crucial, preventing unauthorized practices and improving safety compliance for reliable operations. RBM significantly improves maintenance personnel and pilots' training, focusing on risk assessment, technical knowledge, and safety. It encourages pilots' participation in maintenance, enhancing safety and operational risk understanding. Systematic tracking and analysis of each component's performance data, focusing on operational contexts, are recommended to prioritize maintenance for critical components. This method enhances safety and reduces in-flight failures through early detection of component degradation or failure.

- Maintenance Assessment

The Uncrewed Maintenance Manual lacks structured maintenance management and responsibilities. The operator provides detailed maintenance instructions for each component but lacks clear criteria for prioritization. There is no distinct planning for maintenance responsibilities, and the company does not have clear guidelines for unscheduled maintenance or directives for drone pilots in field operations. In RBM, it can be implemented tailored risk acceptance criteria for each component, enabling maintenance scheduled and non-scheduled and efficient resource allocation. This approach would minimize time and cost losses while reducing failure risks. In RBM, it is also stressed the importance of clear organizational structures based on risk criteria, focusing maintenance on components with higher risk profiles for more efficient, targeted care.

- Implementation

The operator has a maintenance program tailored to beyond-visual-line-of-sight flight criteria, with maintenance activities implemented on-site and on time. However, maintenance is sometimes conducted in the field due to cost reasons, without existing risk assessments. In RBM, it involves setting up a detailed maintenance program for critical components, focusing on high-risk parts to enhance operational efficiency and reduce failures. It also defines field pilot responsibilities, ensuring that maintenance tasks are performed by qualified individuals, which contributes to aircraft safety and operational readiness.

- Performance Monitoring

The operator has a system for data collection, recording, and management. Based on the data obtained, acute solutions are implemented for components when they exhibit failures related to ongoing flight operations at the operational site or issues within the maintenance structure. In RBM, maintenance structure changes or operational challenges regarding components are guided by risk assessments based on risk factors. This data-driven approach necessitates a new risk assessment. This step ensures the renewal of the maintenance structure in response to evolving risks in the operational field.

5.3. Incorporating RBM into the maintenance manual of a Norwegian drone operator

Incorporating RBM into the maintenance manual of a Norwegian drone operator enhances the overall maintenance structure. The first step in this integration is risk assessment. The organization should focus on enhancing its risk assessment capabilities, incorporating systematic tracking and analysis of each component's performance data, as emphasized in section 5.2. This will improve the identification and prioritization of maintenance for high-risk components. This process involves evaluating each component's failure modes, their probability, and consequences on operations. Such an approach not only allows for a more targeted maintenance assessment but also aligns maintenance resources with the most critical areas, optimizing operational safety and efficiency.

The next phase, based on the foundation of risk assessment, involves a maintenance assessment. In this stage, as highlighted in section 5.2, the operator should refine its maintenance assessments, aligning them with the structured risk criteria developed in the risk assessment phase, to ensure clarity in maintenance prioritization and responsibilities. It requires balancing planned and unplanned maintenance activities and justifying each action based on its risk outcomes. With the implementation of RBM, the company ensures that maintenance is not only routine but also driven by a clear understanding of the risks associated with each component. In RBM, this step is used to transition from a traditional, time-based maintenance approach to a more condition-based and risk-informed maintenance approach. This phase aims to create both a proactive and adaptable maintenance program, reducing the probability of unexpected failures and optimizing the lifespan of each component, which can be easily adapted by the relevant drone company.

The implementation phase is where the planning and evaluation stages turn into actionable steps. In this stage of RBM, maintenance procedures determined through risk and maintenance assessments are put into practice.

During this phase, the Norwegian drone company can organize a detailed execution plan that specifies who will perform each task and identifies the allocated resources. This stage is significant for effectively translating the theoretical aspects of RBM into practical, on-site maintenance. It also includes training the maintenance team and flight crews on maintenance and ensuring they have the equipment to fulfill their roles within the RBM framework. This step reflects a consistent approach to drone maintenance, ensuring not only well-planned but also well-executed maintenance strategies.

Finally, performance monitoring is an integral part of RBM and provides feedback and foresight regarding the effectiveness of the applied maintenance structure. Building on the approach outlined in section 5.2, this step involves the company engaging in continuous monitoring of drone component performance, emphasizing the need for new risk assessments based on the collected data to renew the maintenance structure in response to evolving risks. By systematically monitoring performance, the organization might detect emerging components early. However, it is after this stage that corrective actions can be immediately implemented and refined over time through a risk assessment process to enhance maintenance strategies. This ongoing process also fosters a learning capability that guides the organization toward higher levels of safety and efficiency.

With this phased approach, the integration of RBM into the drone operator's maintenance manual and structure becomes consistent. It ensures that every aspect of maintenance, from risk assessment to performance monitoring, is systematically addressed, ultimately enhancing the safety, efficiency, and reliability of drone operations.

6. Discussion

EASA’s risk-based approach to UAS maintenance and the challenges faced in its practical implementation are thoroughly addressed in Chapter 4 of this study. The risk-based maintenance reflected in EASA's EU Regulation 2018/1139 and 2019/947, as well as SORA guidelines, emphasize detailed maintenance instructions, the need for adequately trained personnel, record-keeping systems, and maintenance management in organization for the safe operation of UASs. However, it has been identified that there is a significant lack in the practical applicability of these regulations and guidelines. This is primarily due to the absence of specific methods for meeting maintenance requirements. Such a condition creates challenges for drone operators and maintenance personnel in adhering to these standards. For EASA and national aviation authorities, the different maintenance practices of each operator bring challenges in terms of audibility and safety levels. Given these identified needs, some insights have been proposed that the RBM approach might offer certain solutions to address these specified requirements. For instance, within the RBM framework, the provision of customized maintenance instructions based on the nature of operations might potentially fulfill the detailed instructional requirements outlined by SORA. Additionally, integrating comprehensive training programs that include elements of risk assessment, maintenance planning, and decision-making skills might contribute to meeting EASA's qualification criteria.

The Norwegian drone operator examined in Chapter 5 implements maintenance that considers the requirements of EASA's risk-based maintenance approach. The operator's maintenance planning faces some challenges with critical components like motors and propellers due to a lack of risk assessment and reliance on various industry experiences. The absence of maintenance personnel's expertise in risk assessment and the unclear responsibilities of pilots regarding maintenance create risks in terms of operational effectiveness and safety. While the operator provides detailed maintenance instructions for each component, it lacks planning for prioritization and unscheduled maintenance. Maintenance activities are sometimes conducted in the field without risk assessment due to cost reasons. The operator has developed certain responses by implementing data-based emergency solutions for components that malfunction, affecting flight operations or the maintenance structure. However, since these responses are not subjected to risk assessment either, similar challenges arise, particularly with critical components, leading to occasional changes in scheduled maintenance.

The effectiveness of the RBM method in reducing unexpected failures, production losses, and high costs in aviation and other industries has been acknowledged since the 1970s. The findings of this study illustrate how the four main steps of RBM (risk assessment, maintenance evaluation, implementation, and performance monitoring) contribute significantly to the effective management of risks in UAS maintenance. Specifically, the application of the RBM method to the operator's maintenance manual emphasizes an organizational structure, qualified personnel, data recording, and a detailed maintenance program, which could potentially meet EASA's current requirements and thereby potentially enhance the safety and efficiency of UAS operations. Additionally, in the context of maintenance practices in the operational field, the study draws attention to the requirements for maintenance authorization of the flight crew. Lastly, the study strongly recommends implementing a risk assessment process during maintenance implementation when the performance data of components exceed acceptable risk criteria, whether it involves renewing the maintenance structure or applying new maintenance to the relevant component. Furthermore, this study draws EASA's attention by highlighting the lack of requirements for both scheduled and non-scheduled maintenance.

These findings provide valuable insights into how RBM could serve as an effective solution in UAS maintenance and address current challenges within the UAS industry.

7. Conclusions

This study examines the maintenance requirements for UAS within the framework of EASA regulations and the RBM method as a solution to meet these requirements. An in-depth evaluation of a UAS operator's maintenance practices in Norway revealed that RBM might be a viable solution for meeting EASA's requirements under real operational conditions. The findings demonstrate that RBM has a solid foundation in aspects such as data collection and customization of maintenance programs according to specific UAS types and their operational contexts. Additionally, it addresses the creation of organizational structures and the definition of responsibilities. These highlight the challenges encountered in the rapidly evolving UAS sector. Therefore, this study emphasizes the critical need to address these challenges to enhance the efficacy of UAS maintenance programs. This necessitates the adoption of the RBM method that encompasses technical, organizational, and human factors. The proposed approach herein could represent a significant advancement in the formulation and application of UAS maintenance strategies and offers a foundational basis for future research in this domain.

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