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Flying asset: framework for developing scalable maintenance program for Unmanned Aircraft Systems (UAS)

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Purpose – The paper aims to create a Framework to provide a Scalable Maintenance Program for Unmanned Aircraft Systems (UAS) in order to choose the most suitable and feasible maintenance strategy in terms of reliability.

Design/methodology/approach – The paper opted for a Reliability-Centered Maintenance (RCM)-based approach to develop the Framework using an UAS as starting point of the research. A linear and user-friendly design of the methodology based on a Boolean flow chart was chosen in order to lead the analyst through the process avoiding as much as possible subjectivity decision making issues. Finally, the Framework was component-level performed by the a UAS company gathering feedback on its applicability.

Findings – An agile and structured decision-making framework for developing scalable maintenance program of UAS is provided. The proposed solution gives the opportunity to tailor the maintenance strategy to the technical characteristics, considering not only the single component but also situations and conditions in which the machine will operate.

Research limitations/implications – Because of the chosen research approach, the Framework is potentially applicable to every UAS. A first trial of the method was run on a multirotor vehicle equipped with 8 electric brushless motors. Further studies focused on different UAS will be mandatory in order to obtain comparable and robust findings and a reliable approach.

Practical implications – This study offers a different scheme to elaborate a specific maintenance solution related to the characteristics of the system. It strives to remedy the drawbacks of the traditional approach for manned aircraft not completely suitable for systems with such different functions, features and tasks. The authors believe that the method presented in this paper will provide a new selection tool for choosing maintenance actions based on the features of the UAS.

Originality/value – This paper provides a new and usable solution to include the maintenance actions in the management of pioneering products. In spite of the maintenance program represents an essential aspect to provide reliable assets, frameworks to create programs and to help manufacturers and users are still difficult to find or to apply to different UAS. This gap enhances the misunderstanding that the maintenance is not required or essential for the unmanned aircrafts management.

Keywords: UAS, Scalable Maintenance Program, Reliability-Centered Maintenance (RCM), Maintenance Decision Making.

Definition

Remotely Piloted Aircraft (RPA), Remotely Piloted Aircraft System (RPAS), Remote Pilot Vehicle (RPV), Unmanned Aerial Vehicle (UAV), Unmanned Aircraft System (UAS) and drone are terms often used interchangeably when talking about this subject. They all describe an aircraft that requires no aircrew on board. To avoid confusion on what system a term describes, a definition of the terms is required. In this paper the term UAS will be used according to the definition of the European Aviation Safety Agency (EASA, 2009): "*an Unmanned Aircraft System (UAS) comprises individual system elements consisting of an "unmanned aircraft", the "control station" and any other system elements necessary to enable flight, i.e. "command and control link" and "launch and recovery elements". There may be multiple control stations, command & control links and launch and recovery elements within a UAS."*

1. Introduction

Fontaine *et al.*, (2016) highlight how the exceptional increase of the market for civilian purposes and for recreational activities remarks the potential of the UAS.

UAS are used extensively in the military operations for high-risk attacks as well as surveillance and for these reasons their development is currently a major research issue in the aerospace industry (Andrews *et al*., 2013). However, they are also becoming more and more common in various commercial applications; from surveying to wind turbine inspection, from agriculture to cinematographic film and television till border control, public security and for delivering packages (Reimann *et al*., 2013). There is no hard numbers available, but an approximation on the increase of the use of UAS by hobbyist pilots, based on the revenues of two popular drone manufacturers of UAS, shows that over the past few years, the amount of sold UAS tripled each years. The European Commission studies (2012) also confirm this trend.

These applications generate several technical and operational issues and great amounts of safety concerns related to the application in non-segregated airspace for civilian or recreational use. In this scenario, structured maintenance actions to keep UAS as reliable as possible become vital.

Nevertheless, despite of the growing numbers of manufactures and stakeholders in the UAS market and the need of repairing and replacing actions, the maintenance-related studies are less frequent than for the manned systems, fueling dangerous misunderstandings on the necessity of maintenance.

Studies show that deficient maintenance is recognized as one of the most common causes of system failure of an UAS (Reason and Hobbs, 2003; Manning *et al*., 2004). This is also supported by the study on UAS accidents of the US military presented by Williams (2004). Williams concluded that electrical and mechanical failures play as much, or more, of a role in accidents as human error. Furthermore, Hobbs and Herwitz (2005) addressed issues such as the lack of maintenance documentation, the poor quality of existing documents, a still incomplete formalized checklist and the absence of parts numbers, which are potential error-producing conditions. Recently, a study conducted by Wild *et al.* (2016) show that equipment problems are responsible for the 64% of all UAS accidents and incidents, underlining the need for reliable equipment and for a maintenance program.

Currently the maintenance program of several UAS companies are mainly based on knowledge gathered over time for both the planning and the required maintenance tasks. No manual on how to perform the maintenance exists, and the quality of maintenance therefore relies completely on the competence and experiences of the mechanics. In a growing market like the UAS, SMEs companies have limited resources and, due to the still unclear legislation on the development of a maintenance program, the priority for it is often disregarded.

Through an exhaustive literature study, Fraser *et al.* (2015) underline the empirical evidence of having a correct maintenance management. A negative sentiment to consider maintenance as a "dirty job" (Kobbacy and Murthy, 2008) is evolving in a recognition of a possible profit generating function (Fore and Mudavanhu, 2011).

In spite of the similarity with aircrafts and helicopters, UAS need a dedicated maintenance approach, possibly defined during the design phase. It has to able to take into account all the specific problems related to their configurations, characteristics and working conditions. This paper wants to provide a structured Framework to tailor scalable and ad hoc maintenance program based on a Reliability-Centered Maintenance (RCM) concept. It determines useful analysis tools during the development of the maintenance program and evaluates the applicability of the Framework with the obtained feedback. The Framework provides an opportunity for determining policies for maintaining the most critical components of the UAS, which can later be expanded to less critical components. This approach not only enables to quickly provide a scalable maintenance program for the most critical components but, due to its flexibility, it also enables to expand maintenance program when time and resources allow it.

The study gives a straightforward tool to primarily help the UAS manufacturers, leading them through a complete procedure to ensure reliability and maintainability and to elaborate maintenance guidelines.

The Framework is not designed for aviation authorities to assess or write regulations since it does not take directly into account other aircrafts or operators not involved to the navigation of the UAS.

Even though the application of the Framework could improve also the safety of the operations, as highlighted by Leverson (2011) there is clear distinction between the reliability and safety and their achievements: "*Safety and reliability are different properties. One does not imply nor require the other: a system can be reliable but unsafe. It can also be safe but unreliable. In some cases, these two properties even conflict, that is, making the system safer may decrease reliability and enhancing reliability may decrease safety*."

The study has been carried out with the collaboration of an UAS (multirotor) manufacturer company to validate the results through the adoption of semi-structured recurrent interviews with the R&D department and with the operational department.

2. Structure of the research

As stated in the introduction, the main aim of the paper is to create a scalable Framework for developing a maintenance program for UAS for improving reliability in every environment.

Since every research project consists of several phases that potentially can affect the output and the results, it is important to carefully structure the study in order to increase its credibility (Brink, 1989).

The research has been structured in three main steps (Fig. 1) characterised by three research goals to address:

- Step 1 - determine the most suitable maintenance concept for UAS;
- Step 2 – develop a Framework for UAS including maintenance policies;
- Step 3 – evaluate the Framework through company feedback.

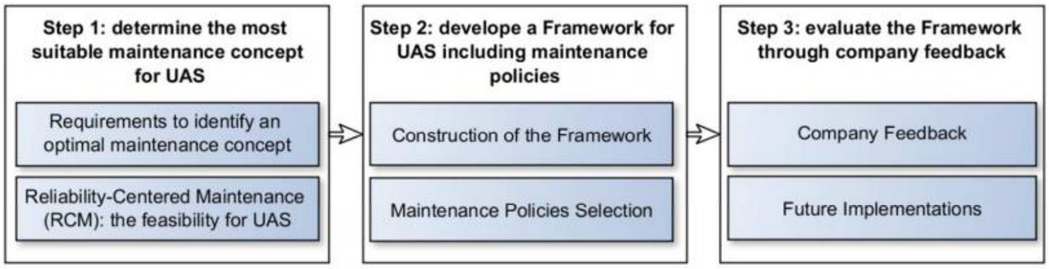


Fig 1. Structure of the research

Step 1 sets up the playground of the research, giving an overview on relevant related topics of UAS mechanical characteristics and on suitable maintenance approaches to apply. The topic of maintenance presents researches on the need for a maintenance program, the issues with current maintenance programs and requirements for the reliability of UAS based on the aviation industry experiences. Ideally, this part should also discuss existing researches on the specific aspect of maintenance approach for UAS taken into account; however, few relevant and extensive studies are available. Therefore, studies in the areas of failure analysis and prevention for UAS are discussed to provide a way of determining relevant analysis tools for building the Framework. Finally, research on failure prevention for UAS is presented.

Step 2 drives through the levels of the approach providing an insight of the Framework built up on the gathered information during the literature study. Every part of the Framework explains the proposed maintenance policies and justifies the choices made.

Finally, Step 3 shows the feedback received during the first application of the Framework by the company, explaining the encountered obstacles of the process and future implementations for possible improvements.

3. Step 1: determining the most suitable maintenance concept for an UAS

3.1 Requirements to identify an optimal maintenance concept

The creation of a maintenance plan is necessary to provide indications and suggestions in order to maintain the UAS reliable. The first reflection on the future maintenance management has to be made at a strategic level.

The maintenance concept describes the strategy of the company regarding the future maintenance. It contains a set of maintenance policies and actions at different levels and the general decision structure in which these are planned and supported (the Framework). The idea behind it is an "optimised" maintenance program that suggests an adequate combination of maintenance actions and policies which improve uptime and extend the total life cycle of the system while bearing in mind limited maintenance budgets and environmental legislation (Kobbacy and Murthy, 2008).

It becomes clear that choosing the most suitable concept represents a key moment in the research, driving the results in specific directions. Therefore, it is essential to list a pool of requirements in order to clearly identify the best solution to adopt.

The concept has to give the opportunity to include in the maintenance program both general aspects such as systems functions, operating conditions, functional failures and failure modes, and specific issues related to the peculiar technical features of the UAS. Roldan *et al.* (2013) identified that the main problem with multi-rotor flying devices is the absence of their own lift ability, "making them completely dependent from its propellers", and underlying how these fails could heavily affect human safety. In his research study Yap (2014) stated that the increased use of open source software and hardware accelerated new interesting features, generating potential complex failures and bringing the systems towards “extreme and un-desirable collateral damages”.

It becomes clear that a suitable concept will have to be (i) able to define UAS system functions, performance and operating conditions, (ii) able to determine the ways in which the system functions may fail, (iii) able to determine the significant failure modes of the UAS components, (iv) able to assess effects and consequences of the failures for a UAS, (v) able to identify maintenance actions and tasks, (vi) able to implement the maintenance plan constantly with feedback for different types of UAS and (vii) able to consider in the analysis new technologies problems and software systems.

3.2 Reliability-Centered Maintenance (RCM): the feasibility for the UAS

Fraser (2014) identified 37 maintenance management models available in the literature. However, only few of them as Total Productive Maintenance (TPM) and Reliability-Centered Maintenance (RCM) are the most discussed and tested in academic journals (Fraser *et al.*, 2011).

As also extensively described by Waeyenbergh and Pintelon (2002), RCM, Business-Centered Maintenance (BCM), TPM and Life Cycle Cost (LCC) present advantages and disadvantages not only related to the fields of application, but also related to the intrinsic characteristics of the concept itself. Complexity, cost and profits, les-structured approach and extensive need of data will always affect the performance of the chosen concept. Therefore, a good choice for a maintenance concept is mostly depending on the type of data available and available in the future, on the level of analysis required and on the importance of including cost analysis in the future maintenance Framework. As also described by Tinga (2013), the absence of data can be managed through the understanding of the physical failure mechanisms of the components creating a quantitative relation between usage of a system and its remaining life.

According to the described requirements and to the available studies, the authors decided to adopt the RCM concept as starting point for creating the Framework.

The reason to adopt the RCM for the proposed Framework lies on different aspects: (i) the accomplishment of the listed requirements in considering both performance, failures analysis, maintenance programs and future improvements, (ii) its versatility and applicability also in case of no components (or very poor) data available (Backlund, 2003) and (iii) its affinity with aviation maintenance issues and manned aircrafts systems. These factors make the RCM suitable to develop a correct Framework for developing maintenance programs for UAS.

Among RCM concepts, several versions are available in literature with different characteristics but with a recognizable basic structure and logic development (Nowlan and Heap, 1978; Moubray, 1992: Smith, 1993; IEC, 1999; NASA 2008). An always difficult characteristic of the RCM Framework to tackle is the choice for a qualitative or quantitative approach and its consequences on the process. According to observations and conclusions of a SWOT analysis on 19 RCM frameworks presented by Gupta and Mishra (2016) the major drawback of the quantitative approach is that they are often complex, time-consuming and require a lot of substantial input data. Furthermore, they observed that almost all practical applications of the RCM approach are qualitative of nature, including the original RCM approach developed by Nowlan and Heap (1978) which is still used in the aviation industry.

For the market considered in this study, the quantitative approach represents a major obstacle looking at the high rate with which components are updated or replaced in the UAS industry which quickly render obtained data useless. Moreover, the high customization of commercial UAS design makes any time consuming and complex procedure not only undesirable, but also uneasy to take in place.

Nowland and Heap (1978) also stated that RCM's primary goal is to preserve system function instead of only preserving equipment and Moubray (1992), according to this idea, underlined that RCM determines maintenance requirements of a physical asset and the actions to ensure its reliability. RCM achieves this goal by using a systematic approach analyzing maintenance problem areas (Brauer, 1987). It enables to define functions, operating context and systems boundaries, to investigate functional failures and failure modes, to create a decision diagram providing maintenance intervals and to permit audit, implementation and feedback.

Finally, the choice of the RCM concept is also supported by Juliana and Goes (2007) that presented a discussion on the use of the failure analysis methods in UAS applications. Focusing on the design review procedures with Failure Modes Effects and Criticalities Analysis (FMECA) and Fault Tree Analysis (FTA), the study shows how these tools can be implemented in the UAS industry, ranking carefully each failure mode according to its criticality and probability of occurrence. It implements these techniques during the design phase in order to optimise the results and gives to the RCM unique features for the discussed systems.

The Framework uses RCM method proposed by Moubray (1992) as starting point due to its initial development in the aviation industry, its qualitative approach and its linearity and user-friendliness, suitable for applications within the UAS market.

As stated in the introduction, the Framework will focus on improving the reliability of the UAS. The FMECA analysis, included in the RCM process, will help to investigate failure modes and related criticalities. Safety issues will have to be analyzed through different Hazard Identification Techniques and it will represent the next step of the study.

4. Step 2: building a Framework for UAS and selecting the maintenance policies to include

4.1 Characteristics of the Framework: scalable, suitable for all the technical characteristics of UAS design, easy accessible

As already briefly discussed, it is essential that the Framework has certain characteristics to ensure the feasibility within the UAS industry.

The agility of a maintenance program (called "scalability") in adapting and tailoring itself to different situations and to different detail levels is a requirement that offers the opportunity to develop protocols feasible for a wide range of working conditions. In a developing industry, such as the UAS, time to market of new applications and design specifications determine market position and are therefore essential for improving the reliability and the survival of the company. A scalable maintenance program acknowledges this problem and provides clear rules on how to develop maintenance policies for the most critical components for existing and to-design unmanned systems. Secondly, the Framework considers the technical characteristics of UAS evolution itself as the mentioned high rate with which components are updated or replaced and the high amount of customization between designs to satisfy customer demands.

Finally, the Framework provides an easy-accessible solution for the UAS manufacturer to develop a maintenance program. Most UAS companies do not have any maintenance experts as the focus still lies on R&D and marketing topics. As consequence, the required knowledge to develop a robust maintenance program is not always present or sufficient for the environments in which the UAS are deployed. The Framework should consider this aspect and provide an easy accessible solution together with all information required to develop a maintenance program supporting the analyst with an as simple and clear as possible path.

Based on the chosen approach (RCM Moubray-version 1992) and on the identified characteristics (scalable, suitable for all the technical characteristics of UAS design and easy accessible), the Framework is created to consider all relevant aspects for the development of a proper maintenance program sustainable in a company, including a feedback loop for ensuring effectiveness once deployed. A linear and user-friendly flow chart based on a binary possible choice drives the creation of the maintenance program reducing as much as possible errors or subjectivity-driven assumptions.

The Framework structure is formed by seven types of action blocks (Table 1). Each block describes an action that has to be taken before going to the next step.

Table 1. action blocks of the Framework.

Block Type	**Action**
Process block	Describes a process or action that has to be performed.
Decision block	Asks for a decision. Since the answer can only be "YES" or "NO", two separate output paths from the block are possible.
Scaling block	Requires the decision on the level of detail for scaling the maintenance program.
Start of a Loop block	Opens a loop decision moment in the Framework.
End of a Loop block	Closes a loop decision moment in the Framework.
Perform block	Bridges the flow to an extra flowchart needed to provide an output for the Framework.
Conclusion block	Describes a conclusion of an action.

The proposed Framework (Fig. 2), consists out of four main parts that divide the workflow in specific phases with different goals.

- Part 1: System Specification;
- Part 2: FMECA & Third Level of Scaling;
- Part 3: Decision Diagram / Maintenance Policies selections;
- Part 4: Living Program Phase.

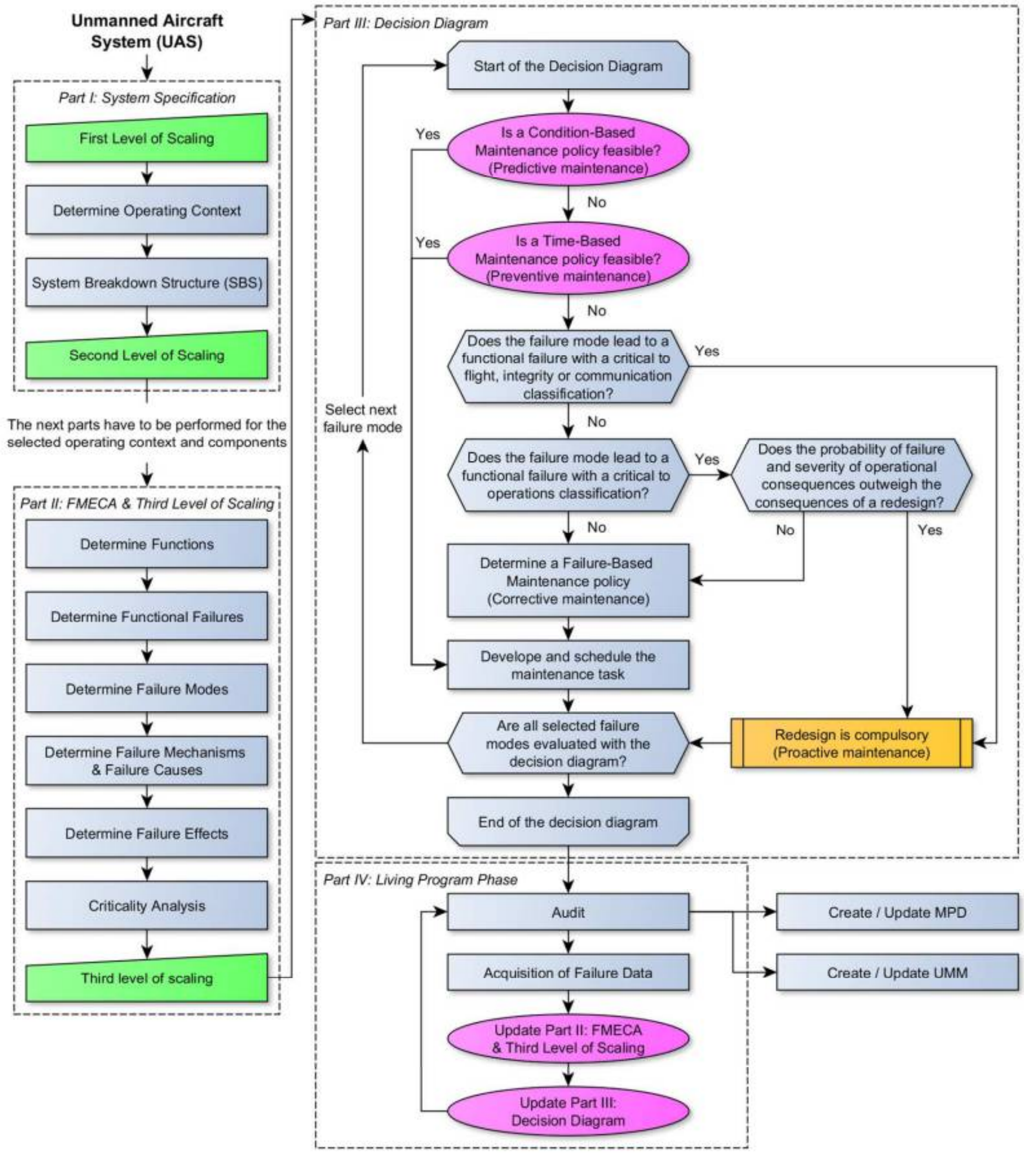


Fig 2. Scalable Maintenance Program UAS Framework

4.2 Part 1: System Specification

Part I: System Specification considers all the required aspects for performing the analyses. To make easier the process, they have been divided in (i) operating contexts and (ii) maintenance important components, both performed through two different level of scaling moments.

(i) The operating context provides an overview of the conditions in which the UAS operates, such as weather and environmental conditions and international, European and country legislations; these parameters seriously influence the occurring failures and therefore the required maintenance program. The operating context can differ per UAS and heavily depends on the location and purpose of its deployment. For example, extreme and different temperature and humidity values (cold and wet / warm and dusty) can produce different failure modes and unexpected UAS behaviors. Therefore, to consider these important aspects in the future maintenance program a first level of scaling is introduced, providing rules on how to encode operating contexts to manage these differences.

(ii) The second aspect is the selection of maintenance important components through the System Breakdown Structure (SBS) approach. It is the first step in the development of a maintenance program (Picknell, 1999).

When developing a maintenance program for an UAS, it is necessary to have a complete overview of the system with all its subsystems and components. A SBS is a hierarchical decomposition of a system into sub-systems and components and provides a clear picture of the UAS forcing the maintenance team to reflect on how the systems are built, creating a better understanding of the systems. The impact of a failure on component level on the capabilities of the UAS differs; sometimes can affect the flight capabilities while other hardly affect any capabilities at all. To focus time and resources on the most critical components, a careful selection process is required. Therefore, a second level of scaling is introduced to provide clear rules on how to prioritize components within the development of the maintenance program based on their impact on the capabilities of the UAS.

4.3 Part 2: FMECA & Third Level of Scaling

During the first part of the Framework the maintenance important components and the operating contexts are determined. The next step is to perform the analyses for the selected operating context and components. The second part (Part 2) of the Framework identifies and prioritizes failure events adopting a FMECA procedure and the third level of scaling. The FMECA procedure is always a central part of the RCM method and is intended to identify failures affecting the functioning of a system enabling priorities for actions to be set (BSI, 2009). Similar to the RCM frameworks, specialized versions have been developed for several industrial sectors. The concept and the basic procedure of these versions are undoubtedly similar, but a detailed procedure must be adapted to a specific application for each industry (Kim, 2009). In Table 2 the developed tailor made FMECA procedure for the UAS industry is shown. It is based on the technical characteristics of UAS and on an analysis of multiple FMECA forms used in the different RCM versions (Moubray, 1992; NASA, 2008), empowered with some features used in the automotive industry (SAE, 2000), in military applications (MIL, 1980) and in electronics standards (IEC, 2001).

Table 2. The FMECA procedure embedded in the Framework.

Functional Failure			Failure Mode			…
Function Description	Functional Failure	Functional Failure Classification	Failure Mode	Failure Mechanism	Failure Cause	…

…	Failure Effects	Criticality Analysis

…	Local	UAS	End	Severity	Occurrence	Detection

The analysis starts with the identification and classification of functional failures, which entails the ways in which the component under review can fail to fulfill function to the standard of performance, which is acceptable to the user (Moubray, 1992). To connect the loss of a specific function to loss of general capabilities of the UAS, a general classification model is used. The model offers the opportunity to pinpoint five different functional failures (Tab 3.) that describe the possible issues of a UAS during a mission in order to create a hierarchical approach.

Table 3. Functional Failure Classification

Rank	**Classification**	
5	Critical to Flight	The failure cause leads to critical to flight issues
4	Critical to Integrity	The failure cause leads to issues critical for integrity of the UAS
3	Critical to Communication	The failure cause leads to a functional failure critical for the communication
2	Critical to Operations	The failure cause leads to a functional failure critical for the task.
1	Non-Critical	The failure cause leads to a functional failure non-critical for the operations.

After the determination of the functional failures (and the consequent failure modes and failure causes), the effects of the functional failure are recorded on three levels: *Local, UAS* and *End* effects. Local effects describe the effect of the functional failure on the system level the analysis is performed. The UAS effects in turn describe how the UAS as a whole is affected.

After the identification, the failure causes have to be prioritized to determine the significant ones that regularly happen and affect the flight capabilities of the UAS leading to potential critical consequences. For these reasons, only failure causes that have "significant" impact on the functioning of the UAS should be considered during the maintenance program to keep it efficient and lightweight. Therefore, the failure causes are ranked according their severity (which describe its affection on the capabilities of the UAS), according their probability of occurrence and according their probability of detection (which describes the probability of detection in a stage able to avoid consequences) during the FMECA procedure. The determination of significant failure causes for which preventive measures should be taken, is determined during the Third Level of Scaling.

4.4 Part 3: Decision Diagram / Maintenance Policies Selection

The third step of the Framework (Part 3) starts with a Decision Diagram (Fig. 3) in order to select the best and feasible maintenance policies for the analysed components/subsystems. The first step will be the evaluation of the application of a Condition-Based Maintenance (CBM) policy, which recommends maintenance actions based on information collected through monitoring the condition of the system. As certain signs, conditions or indications precede 99% of all machine failures (Ellis, 2008), monitoring the status of the component enables actions to prevent these failures before they happen. According to the importance of costs and reliability Jardine *et al.* (2005) and to the opportunity to take proper actions in time (Veldman, 2011), CBM is recognized most of the times the preferable choice instead of the conventional maintenance policies such as Time-Based Maintenance (TBM) and Failure-Based Maintenance (FBM), and is therefore considered first.

4.4.1 Condition-Based Maintenance policy

As mentioned before, the evaluation of a CBM policy has been thought as an "extra" perform block to choose a feasible solution. The "extra" flowchart (Fig. 3) is based on three key steps of a CBM policy proposed by Jardine et al. (2005), on the advanced maintenance framework presented by Tiddens *et al.* (2015) and on the original requirements proposed by Moubray (1992).

The first part of the extra flowcharts is based on the identification and evaluation of potential failure (P) / functional failure (F) interval as defined by (Moubray, 1992). If a P condition is identified, the interval between its occurrence and its decay into F interval is evaluated on its consistency and length.

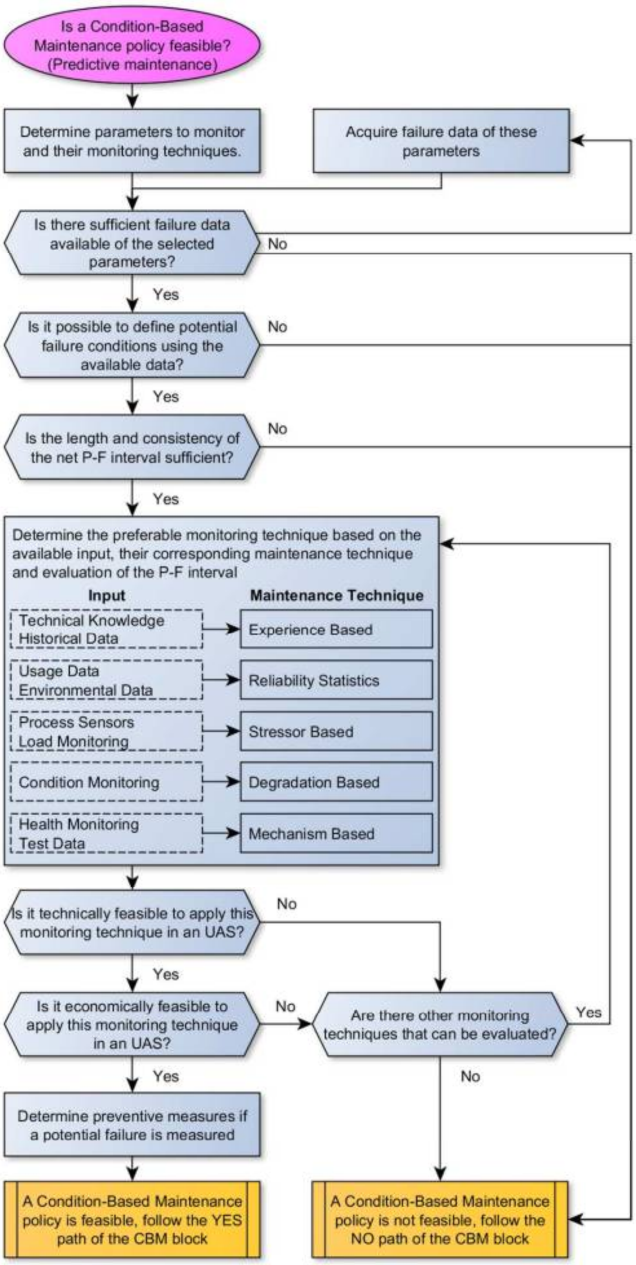


Fig 3. Evaluation feasibility of a CBM policy

As also highlighted by Tiddens *et al.,* 2016, the available data on P-F interval determines the feasible maintenance technique and the accuracy with which failures can be predicted (Table 4). In general, maintenance techniques characterised by real-time monitoring solutions offer more information and a better prediction of the occurring failure and are therefore more favourable during the selection process for further development into predictive measures of the failure mode.

After the selection of a Condition-Based maintenance technique, the "extra" flowchart considers the technical and economic feasibility and how the policies should be communicated to the pilot to achieve the desired effect.

It is important to notice how the maintenance policy has to be both technically and economically feasible, otherwise it is difficult to embed it.

Table 4: Types of data and according maintenance techniques (Tiddens *et al.,* 2015).

Input data	**Maintenance technique**	**Predictions based on**
Technical knowledge Historical data	Experience-based	Knowledge and previous experience
Usage Data Environmental data	Reliability statistics	Historical failure records of comparable equipment without considering component specific differences
Process sensors Load monitoring	Stressor-based	Historical data supplemented with stressor data
Condition monitoring	Degradation-based	Extrapolation of a general path of a prognostic parameter.
Health monitoring Test data	Mechanism-based	Direct sensing of the critical failure mechanisms and physical model.

4.4.2 Time-Based Maintenance policy

If a CBM policy is not feasible for that specific component/subsystem identified during Part 1, a TBM policy is evaluated for conserving the initial offered reliability. As for the CBM policy, a specific perform block is necessary (Fig. 4). Preconditions for this policy is that the failure probability distribution of the failure cause under similar operating conditions demonstrates a limited degree of spread and can therefore be predicted (Smit, 2014).

An important aspect is the availability of failure data and the consequences of failure. If no failure data is available, the life limit provided by the Original Equipment Manufacturer (OEM) should be evaluated taking into account how these recommendations may not be ideal due to differences in operating conditions considered by the OEM and the real operating conditions (Tam *et al.,* 2006).

If the failure is critical to flight/to integrity/to communication consequences, a safe-life limit has to be adopted to evaluate the probability of failure during the working life and whether or not this is acceptable. This topic presented by King *et al*., (2005) and discussed by Dalamagkidis *et al.* (2012) determines an Equivalent Level of Safety (ELOS) for UAS based on aviation industry experiences. If the failure has no consequences for the mentioned conditions, the life limit can be based on the minimal costs and probability of failure. According to Ahmad and Kamaruddin (2012), the most popular decision model under this policy in literature is the Age Replacement Model (ARM).

Finally, If TBM policy is not feasible, the failure consequences are evaluated to determine the right course of action. If the failure cause does not lead to potential operational consequences, a FBM policy is adopted. If the failure cause has potential safety consequences or operational consequences a redesign of the component/subsystem will be compulsory to solve the problem.

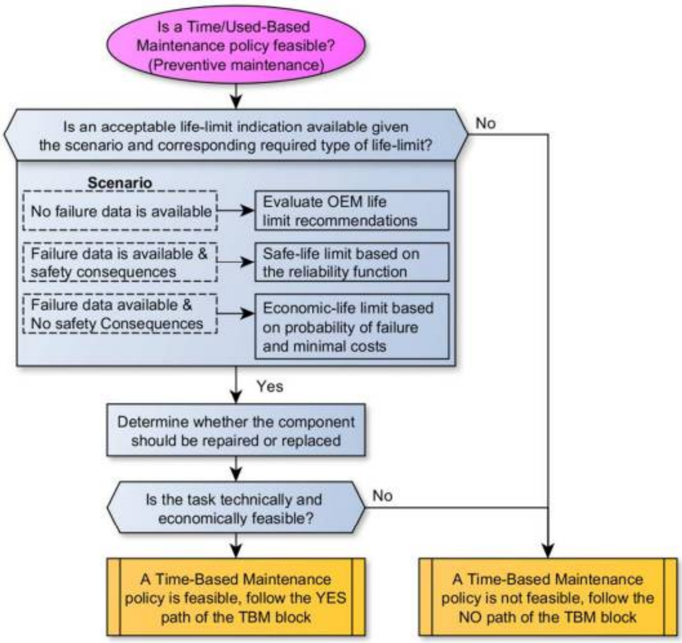


Fig 4. Evaluation feasibility TBM policy

The last step of the specific flowchart is to determine the component/subsystem reparability and replaceability, heavily depending by its intrinsic characteristics. As for the CBM flowchart, the technical and economic feasibility is evaluated.

4.5 Living Program Phase

Once maintenance policies are determined, the last part of the Framework starts: the Living Program Phase. Its aim is to perform an audit in order to formal review the previous parts, to check the obtained results within the organization and to verify the final feasibility (Moubray, 1992). After this evaluation moment, the information has to be stored in order to be easy accessible (Fig.5).

Similar to the aviation industry procedure, the planning and the manuals to put in action the maintenance policies for UAS are separated into two different documents: Maintenance Planning Document (MPD) and UAS Maintenance Manual (UMM).

The MPD contains all information on the maintenance intervals (specifications of the components, notifications that warn for possible hazardous situations etc..). It connects them to the component/subsystem and to the specific section of UMM, which consequently has all the instructions and manuals of tasks on how maintenance should be performed.

As mentioned, failure data from the field covers an important role for the reliability of the system and it has to be collected. During the evaluation of the more suitable maintenance concept in Section 3, when performing the analyses for the first time, there is (often) a lack of hard field experience and data (Brauer, 1987). Therefore, the initial maintenance program needs periodic updating to take new information into account (Smith, 1993) and to reach higher performance of the maintenance program. To achieve the full-benefit of this process, the organization must be prepared to collect and respond to real data throughout the operating life of the asset.

For facing this task, the Framework provides a feedback loop which enables Part 2 and 3 to include in the improving process available data to suggest different future choices for the development of the maintenance program.

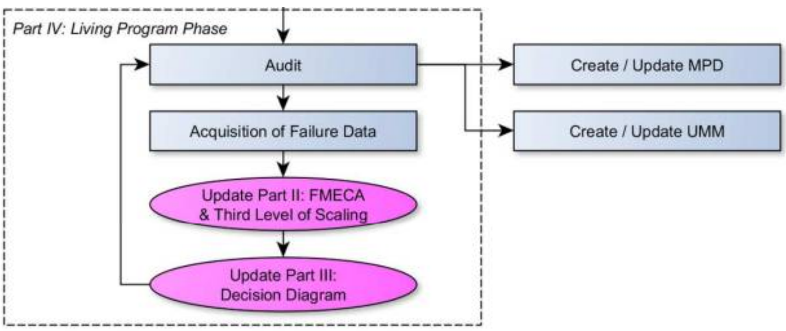


Fig 5. Living Program Phase

5. Step 3: discussion and evaluation of the Framework through company feedback

The feasibility of the Framework entails the process of developing the maintenance program and considers aspects as the accessibility, the procedure and the relevance and impact of the results.

With this aim, an UAS manufacturer company has performed the created Framework on a component level. Two specific components considered critical for the UAS by the manufacturer since heavily affected by operating conditions, were identified in the Part 1 of the Framework: the brushless electric motor and the Electronic Speed Controller (ESC). According to previous experiences of the manufacturer, these two components were responsible for the largest amount of failures in the considered multirotor UAS and they were the main cause of downtime affecting the reliability of the entire system.

However, the most attractive deliverable of the research study is not the testing of the components, but receiving feedback on the applicability of the Framework. For this reason, the paper does not discuss the performing of the Framework in detail, but it focuses on the provided feedback.

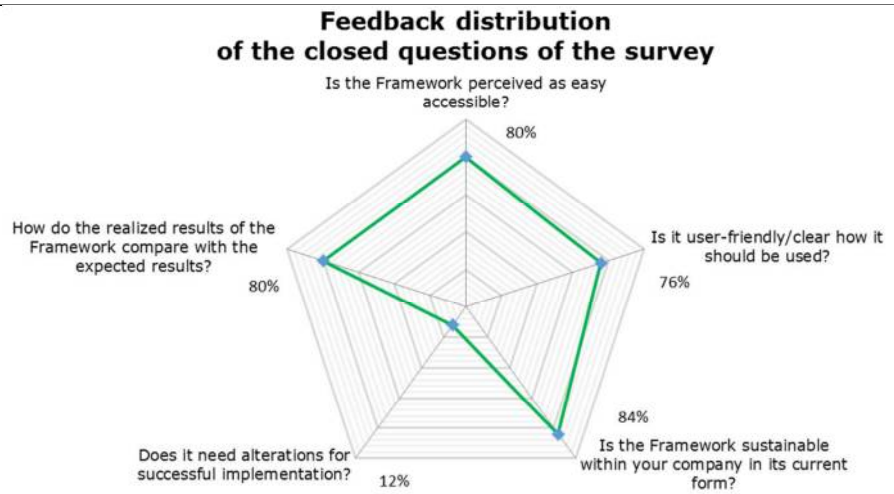
According to that, a survey among the Framework users of the R&D department and the operational department has been conducted in order to highlight possible weak points and to verify unclear steps in the process. The survey has been proposed to only five operators of the company; this small number, not statistically robust, represents the effective involvement of the company in the maintenance topic (widely common in SMEs operating in the UAS market).

As mentioned in the introduction to offer the opportunity to the interviewees to reflect and highlight the encountered problems and relevant events (Alsaawi, 2014), the survey has been created following a semi-structured approach for the interviews as proposed by Barriball and While (1994) and organised in open-ended questions (DiCiccio-Bloom and Crabtree, 2006).

The questionnaire had 5 closed questions and 1 open question to receive both direct and more elaborated suggestions (Table 5).

The Likert scale (range of value from 1-strongly disagree to 5-strongly agree) as psychometric tool to grade the responses was adopted.

Table 5: Closed and open questions used during the survey

Closed questions
1. Is the Framework perceived as easy accessible?
2. Is it user-friendly/clear how it should be used?
3. Is the Framework sustainable within your company in its current form?
4. Does it need alterations for successful implementation?
5. How do the realized results of the Framework compare with the expected results?

Open question
Which kind of modification should be made to improve the Framework towards more accessibility and flexibility within the company?

According to the results of the questionnaire and to the gathered information during the meetings carried out, two characteristics of the Framework have been observed as most relevant topics for investigating the suitability of the created approach.

The Framework is intended to be scalable, easy to apply and flexible to adapt itself to the market development in terms of technology and applications. (i) The accessibility (how accessible the Framework is, if it is user-friendly to use, if it is clear how the Framework should be used), and (ii) the sustainability of the method (if the Framework is sustainable within a UAS company in terms of time and resources) cover an essential part for evaluating its performance.

(i) The accessibility of the Framework yielded positive results. The different interviewees agreed on the easiness of use and, even if someone joined the session without consulting the corresponding chapters of the written manual, no question on the accessibility of the Framework arose. This supports the impression of a consistency of logical and coherent procedure. However, some obstacles were identified during the introduction of failure mechanisms topic due to the nature of electronic components. Even though the failure mechanism concept might provide useful information during the analyses, the main suggestion expressed by the attenders was to remove the failure mechanisms from the FMECA procedure and to adjust the detection criteria to cope with the nature of experienced failures.

(ii) According to the interviewees, the Framework obtained positive results regarding its sustainability in the current form. Nevertheless, as for the accessibility some interesting suggestions were made during the sessions. The structure of the Framework is intuitive to follow and the meetings were very effective and always focus-oriented. However, a leader should always manage the whole process to both facilitate the execution of the meeting and the interconnections between the different experts. This aspect was perceived as very relevant to increase the acceptance and the support within UAS companies that, due to the relatively new nature of the market, do not often have structured departments and resources for optimizing the process without compromising the quality of the results.

Conclusions and future research

The research study proposes and evaluates a Framework to provide a structured method of determining a Scalable Maintenance Program for UAS based on a RCM approach. The methodology of the Framework harmonizes the technical characteristics and issues of UAS, such as the high failure rate (components that constantly have to be replaced and/or updated) with the need of a clear maintenance program. With a linear and user-friendly design of the methodology based on a Boolean flow chart it leads the analyst through the process avoiding as much as possible subjective decision making issues preventing useless and incorrect maintenance actions.

The scaling approach is realised on a three levels analysis. It allows UAS manufactures to determine maintenance policies for the most critical components first, which can later be expanded to less critical components, identifying and prioritising different aspects of the maintenance program.

Based on the obtained results, it is possible to reflect on future studies to fully support the proposed method.

First, the Framework is designed to be applicable for different UAS. However, the pilot study only validated its applicability on a multirotor UAS and not on fixed wing unmanned aircrafts; more tests have to be done to provide a better conclusion on the general validity and versatility of the Framework.

Secondly, a more extensive research on the level of analysis would determine whether the chosen level is detailed enough for the maintenance actions, comparing more specifically the subsystem level with the component level. This study will also help to extend CBM policy solutions, exploring feasible data acquisition techniques and new analysis domains in the physical degradation models of the components.

The digitalization of the entire Framework with the adoption of a computer assisted-technique will help to properly manage the information, saving time during the re-application of the methodology in case of system's modifications and improving the data communication with other involved stakeholders.

Finally, this study represents a first step to acquire a maintenance program to ensure reliability for UAS. However, as multiple times stated, a reliable system is not necessarily a safe system. The next step will have to include safety as main objective to complement the presented solution with external factors such as the pilot operators.

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