Maintenance optimization of an aircraft fleet considering IVHM based on cost and availability considering the use of additive manufacturing

Adrian Cubillo[1], Suresh Perinpanayagam[2], and Manuel Esperon-Miguez[3]

[1, 2, 3] Cranfield University- IVHM Centre, Cranfield, Bedfordshire, MK43 0AL, United Kingdom

a.cubillo@cranfield.ac.uk
suresh.nayagam@cranfield.ac.uk
m.esperonmiguez@cranfield.ac.uk

Abstract

PHM and Integrated Vehicle Health Management (IVHM) are extensive areas of research. Whereas a lot of work has been done in diagnostics and prognostics, the economic viability is also an important aspect. The availability of aircraft in the aerospace sector is a critical factor; thus, cost and downtime are the main parameters to assess the impact of IVHM. Additionally, new technologies such as additive manufacturing have the potential to become standard repair procedures and its viability also has to be assessed. However, to accurately study the impact of these factors the particularities of the aerospace sector have to be taken into account. Several systems of the aircraft are considered as part of a single Line Replaceable Unit (LRU) that is replaced, and later repaired in the workshop without affecting the availability of the aircraft when a subcomponent fails; whereas other parts can be repaired while the aircraft is on the ground and assembled again in the same aircraft. This aspect affects the cost and downtime, and also has to be taken into account to assess the viability of any new technology or IVHM system.

This paper describes an extensive cost and downtime model to take into account all these scenarios including the impact of using different types of IVHM systems. The impact of IVHM and new repair technologies are discussed comparing maintenance cost and downtime of parts of LRUs and parts repaired on the ground.

1. INTRODUCTION

Integrated Vehicle Health Management (IVHM) includes all the sensors, data analysis, algorithms, and further actions to enhance the use of prognostics and diagnostics and improve reliability, safety and availability of a single vehicle or in a fleet. It also covers the consideration of the available resources and operational demand of the whole fleet (Jennions, 2011). The concept of IVHM can be divided in several subareas the architecture is normally divided based on the Open System Architecture for Condition Based Maintenance (OSA CBM) (Dunson & Harrington, 2008; Xia et al., 2010). Following this classification the approach presented in this paper lies under the level called “Advisory generation”.

The potential benefit of IVHM for the maintainer is shown in the reduction of maintenance cost and increased availability of the fleet. This is due to a reduced maintenance time thanks to diagnostics capabilities that allow fault localization and fault isolation, the reduced cost and time of planned maintenance operations when long term prognostics is implemented and the avoided cost of secondary damage in short-term prognostics systems (Esperon-Miguez 2013).

However, these benefits should be assessed against the potential drawbacks of having an IVHM system, e.g. extra costs include the remaining life of the component when it is replaced before it fails and the cost of implementing the IVHM system. Additionally, false alarms can lead to unnecessary inspections with the subsequent extra cost and downtime. Undetected failures would also lead to additional costs and downtimes. The effect of these factors in the availability of the fleet was analysed by Datta and Squires (2004).

The maintenance of aircraft can be divided between the entity that decides the maintenance actions and the entity that executes these actions. The former, commonly called Continuing Airworthiness Management Organization (CAMO) can be the airline or the Maintenance Repair and Overhaul (MRO) provider; while the latter is commonly the MRO provider. Therefore, the approach presented in this paper falls over the scope of the CAMO (EASA, 2003).

A maintenance operation is triggered by the CAMO when a fault is detected during routine inspection or thanks to the IVHM system.

In terms of maintenance there is an important difference between the Line Replaceable Units (LRUs), which are not repaired on the ground and single components: damaged LRUs are replaced as a whole to minimize the downtime and inspected and repaired without affecting the availability of the aircraft in the workshop and installed in another aircraft (Kumar & Varkey, 2012). However, for simpler faulty systems the inspection and repair process can be done on the ground.

This paper presents an approach to estimate the cost and downtime of an aircraft fleet based on the initial methodology of Esperon-Miguez (2013) with additional functionalities to consider not only the effect of IVHM, but also the consideration of using Additive Manufacturing (AM) for metals as a repair procedure instead of traditional methods.

The metrics that define the performance of an IVHM system (in terms of cost and availability) should be known to account for the effect of IVHM. This is effectively done by knowing the probability of correctly predicting a failure (long-term prognostics), detecting a failure prior failure (short-term prognostics), detecting a failure after it has occurred (diagnostics) and knowing the rate of false alarms (Esperon-Miguez, 2013).

These metrics are available in already installed IVHM systems though historic data. However, if a new IVHM system is under development the estimation of these metrics is challenging. If no historic data is available, the metrics used by the model can be considered as requirements for the IVHM system.

AM for metals, also called 3D printing, consists in the building a component by adding material instead of the well-established subtractive processes.. The most relevant AM processes are powder-based processes, in which the part is formed by melting the powder-bed layer by layer, and direct metal deposition, where the powder is deposited only where needed. The melting pool is normally heated with a laser, but electron beam melting can also be used.

There is a great interesting in the use of AM for metals in the aerospace industry (Uriondo et al., 2014). These alternatives will have a different impact in terms of cost and downtime depending on the type of maintenance, i.e. whether the damaged component is part of a LRU or not.

Section 2 describes the model that estimates the cost and downtime and all the parameters that are considered. The case studies analysed are described in section 3. Section 4 presents the results and section 5 discusses the results and summarizes the conclusions.

2. COST AND DOWNTIME MODEL

2.1. Model overview

This model focuses on a specific component/failure mode and calculates the cost of its maintenance based on: probability of failure, whether there is a health condition monitoring tool or not, and the repair procedure and its associated costs and times, which can be the traditional repair method or a novel procedure, e.g. AM. The algorithm does not aim to evaluate the maintenance cost of the whole aircraft or LRU

First the scenarios are defined (subsection 2.2). Then the probabilities are described (subsection 2.3), followed by the maintenance costs (subsection 2.4) and times (subsection 2.5). Finally, the computation of the total cost and downtime is described in subsection 2.6.

2.2. Scenarios.

This section introduces the different scenarios that will be later compared and discussed. Regarding IVHM, 3 possible scenarios are considered:

- **Scenario IVHM-1**: No health condition monitoring tool is installed in the component
- **Scenario IVHM-2**: A health condition monitoring tool capable of detecting failures prior to total failure (short term prognosis) but not preventing failure during operation.
- **Scenario IVHM-3**: A health monitoring tool capable of long term prognosis; thus, allowing for scheduled maintenance.

Regarding the repair procedure of the damaged component, 4 scenarios are considered:

- **Scenario Repair-1**: The whole LRU is replaced by a new one and the faulty LRU is repaired and ready to be re-installed in a new aircraft in less than 30 days. The repair procedure consists of traditional methods (no AM). Therefore, the repair and inspection of the LRU does not affect the downtime of the aircraft.
- **Scenario Repair-2**: Identical to Scenario Repair-1 but the part is repaired using AM.
- **Scenario Repair-3**: The part is repaired and re-installed on the ground. Traditional repair procedures are considered and the part is replaced in the same aircraft. Mean Time To Repair (MTTR) is a critical factor as the availability of the aircraft is compromised.
- **Scenario Repair-4**: The part is repaired and re-installed on the ground as in Repair-3 by using AM. MTTR is a critical factor because it affects the availability of the aircraft.

All the possible combination of IVHM and Repair scenarios, making a total of 12 scenarios, are analysed and discussed in the following sections.

2.3. Probabilities

This section defines all the probabilities that have to be defined for the model regarding the failure (Input probabilities) and the probabilities that define the characteristics of the IVHM system (IVHM probabilities).

2.3.1. Input probabilities

The model is based on a set of probabilities. In this section all the probabilities considered by the model are presented. It should be noted that the case studies will be based on commercial aircraft and some of these probabilities are only relevant for military vehicles. The input probabilities, summarized in Table 1, are as follows:

Table 1. Input probabilities

Abbreviation	Description
P_S	Probability of component failure per flying hour
P_VL	Probability of catastrophic failure
P_MF	Probability of being unable to complete the mission (Mission failure)
P_MA	Probability of aborting the mission due to a failure alarm (Mission failure)
P_RC	Probability of the failure causing reduced capability for future missions
P_RA	Probability of the failure causing reduction of availability
P_RDA	Probability of the diagnosis/repair/replacement resulting in a loss of availability
P_CA	Probability of loss of availability due to the check of the system due to an alarm
P_no_stock	Probability of not having stock of the faulty component on the ground

- **Probability of failure (P_S):** defines the chances of having a component failure. Because it is defined as probability per flying hour all the total costs and downtimes generated by the algorithm will also be obtained per flying hour. It is considered, to be 8.10^{-6}.
- **Probability of losing the vehicle due to the failure (P_VL):** this probability is only taken into account if a failure occurs and it is not predicted by the IVHM system. The case is considered catastrophic and values in terms of cost and downtime are irrelevant. It is considered 0 for the case studies because the component examined is not safety critical.
- **Probability of not completing the mission due to the failure (P_MF):** the probability of not completing the mission due to the failure is considered if the failure occurs, is undetected by the prognostics IVHM system and no catastrophic failure occurs but the mission cannot be completed. The case studies assume that the plane is capable of finishing the mission; thus, the probability P_MF is set to 0.
- **Probability of aborting the mission due to a failure alarm (P_MA):** consists in the probability of not completing a mission due to a failure alarm, even if it is a false alarm. This probability is computed only if there is no failure and a false alarm occurs. For the same reason as P_MF this value is set to 0.
- **Probability of reduced capability for future missions (P_RC)** consists in the probability of the failure affecting the future missions, e.g. if the failure has to be repaired or the component replaced in order to complete the next mission. It is assumed to occur always on the presented case studies. It is set to 1.
- **Probability of the repair/replacement resulting in a loss of availability (P_RA):** defines the probability of having the plane on the ground (loss of availability), e.g. a cancelled flight because the component is being replaced or repaired. This value is set to 0.35 for all scenarios.
- **Probability of the diagnosis/repair/replacement resulting in a loss of availability (P_RDA)**: This probability is identical to the previous P_RA, but due to an undiagnosed failure. It is also set to 0.35.
- **Probability of the check of the component resulting in a reduction of availability (P_CA)**: This probability considers the chances of a check of the system resulting in a loss of availability. It applies when no failure occurs but a false alarm by the IVHM system leads to the inspection of the component. For the current case study the P_CA has been set to 0.05 for all the scenarios. It should be kept in mind that this reduced of availability primary depends on the ratio of false alarms of the IVHM system.
- **Probability of not having stock (P_no_stock)**: This new probability has been incorporated to take into account additional costs if no stock is available on the ground when a part has failed and needs to be replaced on the ground. This applies to replacements of the faulty component (RepAIR-3, 4) and replacement of the whole LRU (RepAIR-1, 2).

  For the current case study it has been considered that the probability of having stock of a LRU is higher than for a spare subcomponent. Therefore, the probability for Scenarios RepAIR-1, 2 (LRU) is 0.05 and 0.1 for RepAIR-3, 4 (component replaced on the ground).

2.3.2. IVHM Probabilities

An IVHM system can be assessed from a cost analysis perspective by defining the following parameters (Esperon-Miguez, 2013):

- **Probability of failure occurring and being undetected by long term prognostics (P_LP)** defines the chances of not predicting a failure early enough to plan the maintenance in advance.

  This parameter is set to 1 for IVHM-1, 2; scenarios in which no long-term prognostics capability is installed, For IVHM-3, which refers to the system with prognostics capabilities this value is set to 0.01.

- **Probability of failure occurring and being undetected by short term prognostics (P_SP)** defines the chances of not detecting the failure by the short term prognostics.

  It should be noted that detecting a failure just before it occurs is expected to be more probable than long in advance (P_LP). Therefore this value is 1 for IVHM-1 and 10^{-4} for IVHM-2, 3.

- **Probability of false negative (P_FN)** defines the rate of failures that are undetected by the IVHM system (diagnostics).

  The detection of a failure after it has occurred is also expected to be more probable than its detection in advance. Thus, it is set to 10^{-5} for IVHM-2, 3 and at 1 for IVHM-1.

- **Probability of false alarm (P_FA)** defines the probability of an alarm by the IVHM system that will trigger the maintenance actions when there is not an actual fault in the system.

  This probability is particularly critical and should be kept to a minimum. It should be noted that it is computed against *(1- P_S)*, not against *P_S* as the previous ones; thus, it is much lower: 10^{-15} for IVHM-2, 3 and 0 for IVHM-1 because no IVHM system is installed.

2.3.3. Cases probability

This subsection describes the probabilities of each possible "case", which are function of the "input probabilities" defined in the previous subsection 2.3.1. The cases are defined sequentially depending on:

- Whether there is a failure or not.
- The reaction by the IVHM system: long term prognosis, short term prognosis, diagnosis, undetected, false negative, false alarm.
- The effect of the failure: vehicle loss, mission loss, future missions affected, availability affected, stock.

All the possible outcomes are shown in Figure 1, where the combination of probabilities for each case is shown. The probability of each case is obtained using Eq. [1].

$$P_i = \prod P_j \quad being \begin{cases} j = Prob. of\ step\ in\ the\ path \\ i = \{1 - 28\ cases\} \end{cases} \qquad [1]$$

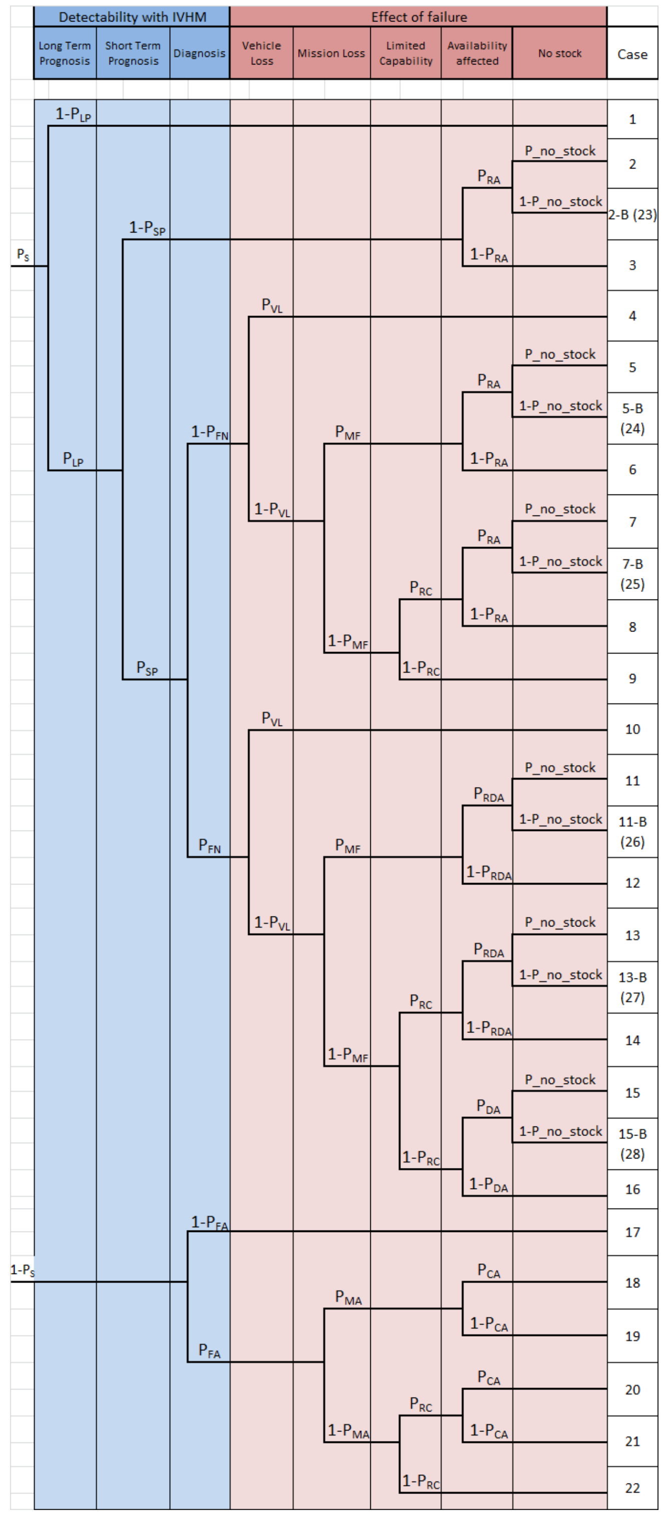

Figure 1. Case probabilities as a function of input probabilities following Eq. [1]

2.4. Input costs

This section describes the costs associated with the maintenance, the use of AM, loss of availability, compensations, etc. The different types of costs that the user can modify for each specific failure mode/component are described as follows (see Table 2):

Table 2. Input costs

Abbreviation	Description
C_SC	Scheduled maintenance component cost
C_UC	Unscheduled maintenance component cost
C_SCL	Scheduled labour cost per hour
C_UCL	Unscheduled labour cost per hour
C_RULL	Cost of prognostics remaining life lost (long term prognostics)
C_RULS	Cost of prognostics remaining life lost (short term prognostics)
C_FA	Extra cost due to false alarms
C_C	Compensation costs
C_SD	Secondary damage cost
C_FT	Replaced part flight test cost
C_LI	Loss of income
C_LO_LRU	Cost of logistics to send LRU from aircraft to workshop (LRU only)
C_R_LRU	Cost of repairing damaged part in the workshop (LRU only)
C_LA_LRU	Cost of labour in workshop (LRU only)

- **Scheduled Maintenance Component cost (C_SC):** represents the cost of the new spare/repaired part when the replacement has been planned (scheduled). If the part is a subcomponent of a LRU this cost is not associated with the whole LRU and has to be set to 0. The cost of the repairing it in the workshop will be described later (see C_R_LRU).

  This assumption implies that the value of the new LRU will be identical to the value of the faulty LRU once the damaged component is repaired or replaced at the workshop. The costs for the case studies are set to 20 MUs (Monetary Units) for RepAIR-3, 4 and 0 for RepAIR-1, 2.

- **Unscheduled Maintenance Component cost (C_UC):** is identical to the previous one, in the sense that it refers to the cost associated with the replacement of the component. But it refers to the cost of the part when it is an unscheduled replacement. The reason is that the cost could be higher if the replacement is not expected; e.g. tight delivery times lead to higher costs.

  As with the previous parameter, for LRU units C_UC is set to 0 because the cost of repairing the component in the workshop is defined by C_R_LRU (RepAIR-1, 2). For RepAIR-3, 4 C_SC is set to 30 MUs.

- **Scheduled labour cost (C_SCL):** The replacement of a part or LRU on the ground will lead to labour costs that are affected by this parameter along with the averaged repair time. This cost can vary between RepAIR3, 4 and RepAIR1, 2 because the LRU may require more resources, e.g. 3 technicians instead of 2, additionally, if AM is used the labour cost may change as well.

  For the case studies the replacement of the LRU unit is not affected by the fact of using AM so C_SLC for RepAIR-1, 2 are identical and set to 3 MU per hour. While for RepAIR-3, 4 it is considered that less labour is needed if AM is used, 2 MU per hour (RepAIR-3), and 3 MUs per hour for RepAIR-4.

- **Unscheduled labour cost (C_UCL):** is identical to the previous parameter C_SLC, but with a higher cost due to the fact that it is unplanned maintenance. Being 5 MUs per hour for RepAIR-1, 2, 3 and 4 MUs per hour for RepAIR-4.

- **Cost of prognostics remaining life lost due to long term prognostics (C_RULL):** it is necessary to take into account the value of the part that is lost due to replacing it before it actually fails, this means that there is a percentage of healthy life that is not used when long term prognostics is used.

  This cost is identical for all the scenarios and set to 5 MUs (even when no IVHM system is installed). It should be noted that the difference between different IVHM systems will not be reflected on this cost, but on the probability of detecting the failure in advance (P_LP).

- **Part false alarm cost (C_FA):** represents the cost of the part when a false alarm occurs and it is required to take into account the costs caused by an ineffective IVHM system, e.g. an IVHM system that triggers alarms when no failure has occurred. This cost takes into account the cost of replacing the part when a false alarm has occurred.

  This cost implies the assumption of no second inspection on the ground, meaning that the technicians will replace the component without further inspection. For a LRU the part is repaired in the workshop and the inexistent fault will be detected and no additional repair operations will be done, therefore C_FA should be 0 for RepAIR 1, 2 and 20 MU for RepAIR 3, 4.

- **Compensation cost (C_C):** only applies from an MRO perspective, and takes into account the compensation cost in terms of penalty that the MRO has to pay if availability expectations are not met in an availability-based contract. For the case study this value is set to 6 MU for all the scenarios.

- **Secondary damage cost (C_SD):** it is necessary to consider additional damage to adjacent components due to the initial failure. This damage is assumed to occur if the failure occurs (if the failure is undetected or diagnosed). However, if long/short prognostics detect the failure in advance this cost can be avoided.

It is important to mention that one of the main advantages of short-term prognostics compared to diagnostics is that, even if maintenance cannot be planned, a significant cost reduction due to avoiding this "secondary damage cost" can be obtained. For our case study this value is set to 30 MU.

- **Flight test cost (C_FT):** takes into account the cost associated with flight tests when the new part is installed in the aircraft. Based on previous work this value has been set to 2 MU for all the possible scenarios.
- **Loss income (C_LI):** represents compensations to the passengers due to excessive delays (downtimes). This cost can be significant; however, the cost analysis of this paper is done from the MRO's perspective and C_LI is set to 0 because it does not affect the costs of the MRO unless it is stated in the MRO-airline contract.

All the previous costs are associated with actions on the ground while the aircraft is on the ground. But there are additional costs that only apply to LRUs (RepAIR-1, 2):

- **Logistics cost for LRU only (C_LO_LRU):** considers the cost of shipping the faulty LRU to the MRO workshop specialized in that LRU and ship it back to another aircraft. C_LO_LRU is set to 2 MU (RepAIR-1, 2 only).
- **Repair cost for LRU only (C_R_LRU):** takes into account the repair of the damaged part inside the LRU once it has been shipped to the workshop. For RepAIR-1 C_R_LRU is set to 20 MU and for RepAIR-2, when AM is used, C_R_LRU is set to 15; thus, assuming that less material is required and therefore the repair cost is lower if AM is used. It should be noted that the assumption of lower cost of the repair process when AM is used is a hypothesis that has not been proved.
- **Labour cost for LRU only (C_L_LRU):** takes into account the labour cost of the repair and inspection in the workshop (not on the ground). It includes all the labour costs since the LRU arrives at the workshop until it is shipped to a new aircraft.

  For the case study it is considered identical to the cost of repairing the component on the ground, being lower if AM is used (2 MU instead of 3 MU) for RepAIR-2 because it is assumed that an AM repair procedure is highly automated and does not require highly skilled technicians.

2.5. Input times

The input times include all the necessary parameters that define the time of each task that may affect the maintenance cost and downtime of the aircraft.

Whether or not these times affect the downtime of the aircraft will depend of the "case" that is considered, e.g. MTTD is considered as downtime if there is an undetected failure but it does not affect the downtime if the maintenance task is scheduled. The input times are described as follows (see Table 3):

Table 3. Input times

Abbreviation	Description
MTTR	Mean Time To Repair (the failure)
Check-out time (T_Check)	Mean time to conduct the necessary checks
MTTD	Mean Time to detect the failure mode
Localization time (T_L)	Mean time to localize the failure
Technical delay time	Mean time delay due to technical issues
Administrative delay time (T_Adm)	Mean time delay due to administrative issues
Logistics delay time (T_LO)	Mean time delay due to logistics on the ground (assuming stock)
MTTR_LRU	Mean Time To Repair (the failure) in the workshop (LRU only)
Localization_LRU (T_L_LRU)	Mean Time to localize the failure in the workshop (LRU only)
MTTD_LRU	Mean Time To Detect (the failure) in the workshop (LRU only)
No_stock_delay (T_no_stock)	Mean time to obtain the part/LRU if there is no stock on the ground

- **Mean Time To Repair (MTTR):** accounts for the averaged time required to repair the given failure mode. It only includes the actual time required to repair it and not the time to detect it, localize it or check it.

  The scenarios differ between MTTR in RepAIR-1, 2 and MTTR in RepAIR-3, 4. The former is set to 2 Time Units (TUs) because the task simply consists in replacing the whole LRU; while the latter is set to 10 MU because the damaged component has to be replaced or repaired.
- **Check-out time (T_check):** considers the time required to check that the maintenance actions have successfully been solved the problem and the aircraft is airworthy. This value has been considered constant and set to 3 TU for all the scenarios
- **Mean Time To Detect (MTTD):** refers to the time required to identify the failure mode. It should be noted that for some systems MTTD and localization time are equivalent and only one of them should be defined.

  MTTD is set to 5 TUs for scenarios RepAIR-3, 4. For RepAIR-1, 2 the LRU is not inspected, it is simply replaced; thus, MTTD is 0.
- **Localization time (T_L):** refers to the time required to localize a failure on the ground, i.e. to find which specific component is affected.

  The case study considers that the localization of the failure is relatively simpler compared to the detection of the failure mode. Therefore, the localization time is set to 1 TU for RepAIR-3, 4. For RepAIR-1, 2 it is set to 0 because the localization time does not apply to the LRU on the ground.

- **Technical, administrative and logistic delay times:** These three times all refer to delays in the maintenance operation on the ground due to: technical, administrative and logistic delays but they are all treated by the model in the same way.

  It is considered that the technical delay is more critical for parts replaced on the ground than if the LRU is replaced because replacing a LRU is a more standard procedure. Additionally, repairing the component on the ground using AM will lead to additional certification procedures and because the process would not be standard more administrative delays are expected. The logistic delay time is considered relatively low because only refers to logistic delays on the ground and not waiting times for parts that are not in stock (see Table 4 for specific parameter values).

Table 4. Technical, administrative and logistic delays for all the scenarios

	RepAIR-1	RepAIR-2	RepAIR-3	RepAIR-4
	Technical_delay_time (TUs)			
IVHM-1	1	1	3	3
IVHM-2	1	1	3	3
IVHM-3	1	1	3	3
	RepAIR-1	RepAIR-2	RepAIR-3	RepAIR-4
	Administrative_delay_time (TUs)			
IVHM-1	1	1	1	1.5
IVHM-2	1	1	1	1.5
IVHM-3	1	1	1	1.5
	RepAIR-1	RepAIR-2	RepAIR-3	RepAIR-4
	logistic_delay_time (TUs)			
IVHM-1	1	1	1	1
IVHM-2	1	1	1	1
IVHM-3	1	1	1	1

- **Delay time caused by no stock available (no_stock_delay):** accounts for the scenarios in which no stock is available on the ground. This condition is not required in the workshop.

  This parameter defines the standard delivery time when there is no stock and its value is set to 24 TUs for all the scenarios.

The following times only apply to actions in the workshop, not on the ground. Therefore they are only applied to RepAIR-1, 2. The times are shorter than equivalent operations on the ground because an optimized process is expected in an specialized workshop.

- **Mean Time To Repair in the workshop (LRU only):** accounts for the repair time in the workshop. Therefore it only applies to RepAIR-1, 2 and it is set to 7TUs.
- **Localization time in the workshop (LRU only):** accounts for the localization time in the workshop and only applies again to RepAIR-1, 2 and it is set to 0.5 TUs.
- **Mean Time to Detect (MTTD) in the workshop (LRU only):** considers the averaged time to detect the failure mode when the LRU has been dispatched to the workshop. The parameter is set to 3 TUs for RepAIR-1, 2.

2.6. Cases cost and downtime

The previous sections described all the parameters that have to be taken into account (Input probabilities, Input costs and Input times), and Subsection *2.3.3* defined the probability of each possible case as shown in Figure 1.

In order to calculate the total cost and downtime for all the scenarios the cost and downtime of each possible case has to be calculated. There are a total of 28 cases; thus, to avoid excessively large tables in the paper please refer to appendix A to check the associated cost C_i and downtime D_i of each case.

The averaged cost and downtime of each case is computed by multiplying each cost C_i and downtime D_i for each specific probability P_i (see Eq. [2]). Additionally, the total cost C_T and downtime D_T are computed by summing all the weighted cases costs C_i^w and downtimes D_i^w.

$$\begin{cases} C_i^w = C_i \cdot P_i \\ D_i^w = D_i \cdot P_i \end{cases} \forall i \in (1-28) \qquad [2]$$

3. CASE STUDIES DEFINITION

The 4 scenarios defined in subsection 2.2 are modelled to discuss the qualitative differences between them in terms of cost and downtime.

The results are based on the parameters described in section 2. These parameters consist of synthetic data based on assumptions and similar studies (Esperon-Miguez, 2013). Therefore, the aim of the paper is to propose the approach and discuss the qualitative differences between components that are part of a LRU and how this affects the impact of an IVHM system. Additionally, the use of new technologies like AM that can potentially reduce costs and repair times can be analysed for single parts and LRUs.

The values of all the parameters for the case studies have been defined along with their description in section 2.

4. RESULTS

A variety of results can be obtained from the model. The most relevant ones are the total cost per flying hour of each maintenance scenario and the total downtime per flying hour as well (see Figure 2 and Figure 3).

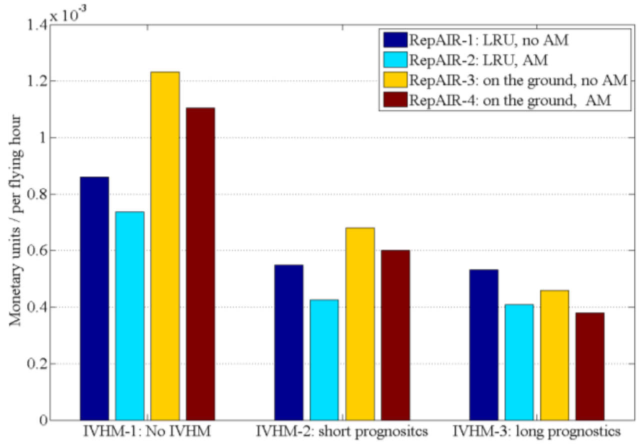

Figure 2. Total cost per flying hour of each scenario

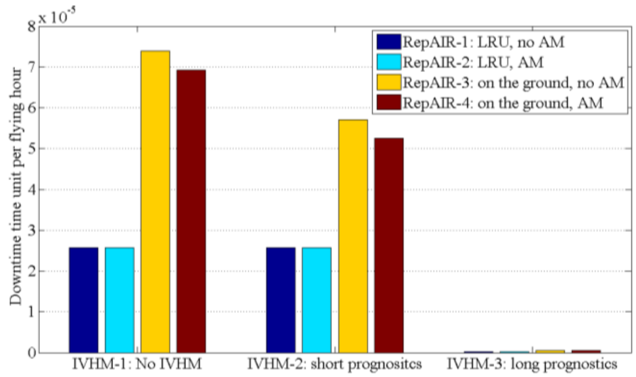

Figure 3. Total downtime per flying hour of each scenario

The cost and repair times for AM parts were assumed lower than traditional procedures. The impact in the total cost is shown in Figure 2, where repairing the part by AM is cheaper than by traditional methods regardless of doing it on the ground or in the workshop for LRUs. The reduction in time is not only reflected in the cost, but also in the downtime when the repair tasks are done on the ground (see Figure 3). However, downtime is identical for both repair procedures in LRU units because only assembly and disassembly of the LRU is done on the ground.

For the case studies presented in this paper repairing the component as part of a LRU is more convenient than repairing the component on the ground (see Figure 2) and the downtime is significantly reduced (see Figure 3) because no repair procedure is done on the ground. However, to decide whether having a LRU is more profitable than repair each single subcomponent on the ground the same study should be done over all the components and failure modes of the LRU and cannot be assessed by this single part example.

Regarding the short term IVHM system, it can be shown that having a short term prognostics IVHM system would lead to a significant reduction of the total cost (see Figure 2) due to the avoidance of secondary damage, plus the diagnostics advantages of reduced MTTD.

Additionally, the downtime is also reduced if the component is repaired on the ground (RepAIR-3, 4) as shown in Figure 3 because in that case the downtime is directly affected by the reduced MTTR. However, downtime remains unaffected for LRUs because the repair procedure does affect the availability of the aircraft.

Finally, the advantages of using a long-term prognostic IVHM system are both cost and downtime reduction. A reliable IVHM system would minimize the undetected failures early in advance to plan the maintenance and therefore the availability of the aircraft would not be compromised as shown in Figure 3. The costs are also reduced when using a long-term IVHM system because planned maintenance is not as expensive but the cost reduction is not as significant as the downtime reduction when compared to a short term prognostics IVHM system (see Figure 2).

5. DISCUSSION AND CONCLUSIONS

The results show that IVHM systems with low false alarm rates can significantly reduce the cost of the maintenance. However, the extra effort required to have reliable long-term prognostics is reflected in a great downtime reduction but not as great in terms of cost. Therefore, the benefits of developing IVHM capabilities are not identical for all the stakeholders, e.g. the airline would consider downtime reduction a priority and would be interested in long term prognostics capabilities whereas an MRO, without an availability–based contract, would not get any benefit of the downtime reduction apart from the satisfaction of its client.

In this example there is not a great influence of the type of maintenance (on the ground or as part of a LRU) in the cost and downtime of different IVHM systems. Nevertheless, for short-term prognostics (IVHM-2) and no IVHM capabilities (IVHM-1) repairing the component as part of a LRU is more efficient than as a single unit on the ground. But the cost of the LRU option is higher for the long-term prognostics (IVHM-3) than repairing it on the ground. The reasons are the reduced costs and MTTR for planned maintenance compared to unplanned on the ground when a failure is detected early in advance.

The improvement of the technology, for instance by using AM, would help to reduce the cost and time of the repair procedure. Also delivery times and probability of not having stock can be reduced because, at least in the case of AM, the powder is the only resource that has to be in stock. This is reflected in the reduced total costs for all the scenarios. However, downtime is only reduced if the component is repaired on the ground; thus, affecting the availability of the aircraft. This aspect should be taken into account when considering investing in new technologies.

From the previous discussion the following conclusions can be extracted:

- Robust IVHM systems can significantly reduce maintenance cost (even short term prognostic).
- Robust long term prognostics IVHM systems significantly reduce the downtime but that is not directly beneficial for all the stakeholders.
- The use of IVHM affects the maintenance costs and can have an influence in the optimal repair procedure.
- New technologies that reduce repair costs and the MTTR lead to lower total costs but will not reduce downtime unless the part is repaired on the ground.

The model has been devised for a specific component and failure mode, that is, costs and availability are associated with the given failure mode only. In large-scale systems the same approach can be extrapolated to different components with their associated repair alternatives. Moreover, if all the subcomponents of a LRU are analysed, the total cost and downtime associated to the whole LRU can be estimated. However, the benefits of the model apply to failure modes with more than one repair procedure.

The findings presented above are relevant, but it should be noted that the main contribution of this paper is the comprehensive description of the model. This model takes into consideration the use of new technologies and capabilities, e.g. it considers the probability of having stock and average delivery times. And most important, it accounts for the unique differences between repairing a component as part of a LRU in the workshop and repairing it on the ground. Moreover, the model allows for the consideration of using an IVHM system.

ACKNOWLEDGEMENT

Jeroen Vermeulen and Professor Ian Jennions for proof of reading.

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under Grant Agreement n°605779 (project RepAIR). The text reflects the authors' views. The European Commission is not liable for any use that may be made of the information contained therein. For further information see http://www.rep-air.eu/.

REFERENCES

Datta, K.. & Squires, D. (2004). A methodology to quantify some IVHM requirements during RLV conceptual design. *Reliability and Maintainability, 2004 Symposium-RAMS*, January 2004, pp. 485-491.

Dunsdon, J. & Harrington, M. (2008). The application of Open system architecture for condition based maintenance to complete IVHM. *IEEE Aerospace Conference*. March 2008, Big Sky, MT., pp. 1-9.

EASA (2003), *Commission Regulation (EC) No 2042/2003 of 20 November 2003 on continuing airworthiness of aircraft and aeronautical products, parts and appliances, and on the approval of organisations and personnel involved in these tasks*. Official Journal of the European Union, November 2003, pp. L 315/1 to L315/165.

Esperon-Miguez, M. (2013). *Financial and risk assessment and selection of health monitoring system design options for legacy aircraft*. Doctoral Dissertation. Cranfield University. United Kingdom.

Jennions, I. K. (2011). *Integrated vehicle health management perspectives on an emerging filed*. SAE International, Warrendale, Pa, ISBN: 0768064325.

Kumar, P. & Varkey, C. C. (2012). *Designing line replaceable units from the maintainability perspective*. White paper of Guest-global. url: https://www.quest-global.com/wp-content/uploads/2015/07/Designing-Line-Replaceable-Units-from-the-Maintainability-Perspective.pdf

Uriondo, A., Esperon-Miguez, M. & Perinpanayagam, S. (2014), The present and future of additive Manufacturing in the aerospace sector: A review of important aspects. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, vol. 229, pp. 2132-2147.

Xia, L., Rong, L., Zhao, M., Wang, L. & Man, Q. (2010). Research on Open System Architecture for equipment health management based on OSA-CBM. *IEEE International Conference on Intelligent Computing and Intelligent Systems, ICIS*, October 2010, Xiamen, Vol. 2, pp.246-250.

APPENIX A

Table 5. Costs of each case

Case	Equation
1	$C_1 = C_{SC} + C_{SCL} \cdot MTTR + C_{RULL} + C_{FT} + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
2	$C_2 = C_{UC} + C_{UCL} \cdot MTTR + C_{RULS} + C_{FT} + C_{LI} + C_C + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
2-B (23)	$C_{23} = C_{UC} + C_{UCL} \cdot MTTR + C_{RULS} + C_{FT} + C_{LI} + C_C + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
3	$C_3 = C_{UC} + C_{UCL} \cdot MTTR + C_{RULS} + C_{FT} + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
4	$C_4 = (undefined)$
5	$C_5 = C_{UC} + C_{UCL} \cdot MTTR + C_{SD} + C_{LI} + C_C + C_{FT} + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
5-B (24)	$C_{24} = C_{UC} + C_{UCL} \cdot MTTR + C_{SD} + C_{LI} + C_C + C_{FT} + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
6	$C_6 = C_{UC} + C_{UCL} \cdot MTTR + C_{SD} + C_{FT} + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
7	$C_7 = C_{UC} + C_{UCL} \cdot MTTR + C_{SD} + C_{LI} + C_C + C_{FT} + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
7-B (25)	$C_{25} = C_{UC} + C_{UCL} \cdot MTTR + C_{SD} + C_{LI} + C_C + C_{FT} + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
8	$C_8 = C_{UC} + C_{UCL} \cdot MTTR + C_{SD} + C_{FT} + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
9	$C_9 = C_{UC} + C_{UCL} \cdot MTTR + C_{SD} + C_{FT} + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
10	$C_{10} = NA\ (undefined)$
11	$C_{11} = C_{UC} + C_{UCL} \cdot (MTTR + MTTD + T_L) + C_{SD} + C_{LI} + C_C + C_{FT} + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
11-B (26)	$C_{26} = C_{UC} + C_{UCL} \cdot (MTTR + MTTD + T_L) + C_{SD} + C_{LI} + C_C + C_{FT} + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
12	$C_{12} = C_{UC} + C_{UCL} \cdot (MTTR + MTTD + T_L) + C_{RULS} + C_{SD} + C_{FT} + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
13	$C_{13} = C_{UC} + C_{UCL} \cdot (MTTR + MTTD + T_L) + C_{SD} + C_{LI} + C_C + C_{FT} + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
13-B (27)	$C_{27} = C_{UC} + C_{UCL} \cdot (MTTR + MTTD + T_L) + C_{SD} + C_{LI} + C_C + C_{FT} + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
14	$C_{14} = C_{UC} + C_{UCL} \cdot (MTTR + MTTD + T_L) + C_{SD} - + C_{FT} + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTR_{LRU} + MTTD_{LRU} + T_{L-LRU})$
15	$C_{15} = C_{UCL} \cdot (MTTD + T_L)$
15-B (28)	$C_{28} = C_{UCL} \cdot (MTTD + T_L)$
16	$C_{16} = C_{UCL} \cdot (MTTD + T_L)$
17	$C_{17} = 0$
18	$C_{18} = C_{SC} + C_{SCL} \cdot MTTD + C_{LI} + C_C + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTD_{LRU} + T_{L-LRU})$
19	$C_{19} = C_{SC} + C_{SCL} \cdot MTTD + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTD_{LRU} + T_{L-LRU})$
20	$C_{20} = C_{SC} + C_{SCL} \cdot MTTD + C_{LI} + C_C + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTD_{LRU} + T_{L-LRU})$
21	$C_{21} = C_{SC} + C_{SCL} \cdot MTTD + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTD_{LRU} + T_{L-LRU})$
22	$C_{22} = C_{SC} + C_{SCL} \cdot MTTD + C_{LO-LRU} + C_{R-LRU} + C_{LA-LRU} \cdot (MTTD_{LRU} + T_{L-LRU})$

Table 6. Downtimes of each case

Case	Equation
1	$D_1 = 0$
2	$D_2 = MTTR + T_{Check} + T_{technical-delay} + T_{admin-delay} + T_{logistic-delay}$
2-B (23)	$D_{23} = MTTR + T_{Check} + T_{technical-delay} + T_{admin-delay} + T_{logistic-delay} + T_{no-stock}$
3	$D_3 = 0$
4	$D_4 = NA\ (undefined)$
5	$D_5 = MTTR + T_{Check} + T_{technical-delay} + T_{admin-delay} + T_{logistic-delay}$
5-B (24)	$D_{24} = MTTR + T_{Check} + T_{technical-delay} + T_{admin-delay} + T_{logistic-delay} + T_{no-stock}$
6	$D_6 = 0$
7	$D_7 = MTTR + T_{Check} + T_{technical-delay} + T_{admin-delay} + T_{logistic-delay}$
7-B (25)	$D_{25} = MTTR + T_{Check} + T_{technical-delay} + T_{admin-delay} + T_{logistic-delay} + T_{no-stock}$
8	$D_8 = 0$
9	$D_9 = 0$
10	$D_{10} = 0$
11	$D_{11} = MTTR + MTTD + T_L + T_{Check} + T_{technical-delay} + T_{admin-delay} + T_{logistic-delay}$
11-B (26)	$D_{26} = MTTR + MTTD + T_L + T_{Check} + T_{technical-delay} + T_{admin-delay} + T_{logistic-delay} + T_{no-stock}$
12	$D_{12} = 0$
13	$D_{13} = MTTR + MTTD + T_L + T_{Check} + T_{technical-delay} + T_{admin-delay} + T_{logistic-delay}$
13-B (27)	$D_{27} = MTTR + MTTD + T_L + T_{Check} + T_{technical-delay} + T_{admin-delay} + T_{logistic-delay} + T_{no-stock}$
14	$D_{14} = 0$
15	$D_{15} = MTTD + T_L + T_{Check} + T_{technical-delay} + T_{admin-delay} + T_{logistic-delay}$
15-B (28)	$D_{28} = MTTD + T_L + T_{Check} + T_{technical-delay} + T_{admin-delay} + T_{logistic-delay} + T_{no-stock}$
16	$D_{16} = 0$
17	$D_{17} = 0$
18	$D_{18} = MTTD$
19	$D_{19} = MTTD$
20	$D_{20} = MTTD$
21	$D_{21} = MTTD$
22	$D_{22} = 0$