CERTIFIABLE CONDITION-BASED MAINTENANCE IN CIVIL AVIATION A REVIEW OF REGULATORY APPROACHES

Robert Meissner, Kai Wicke and Gerko Wende

Institute of Maintenance, Repair and Overhaul
German Aerospace Center (DLR)
Hamburg, Germany

DLR

Content

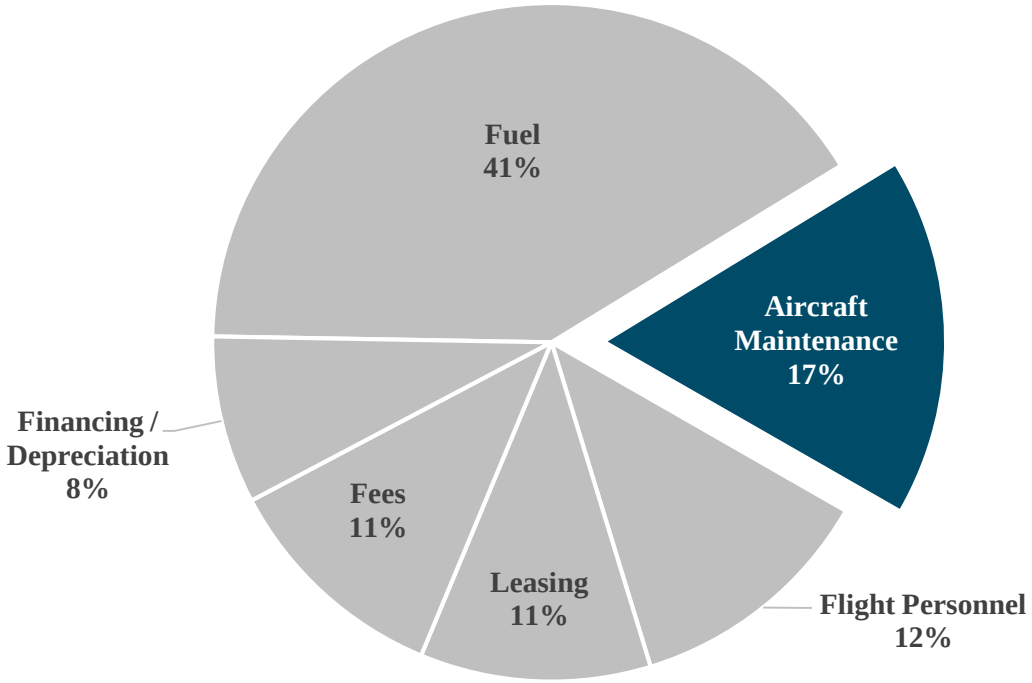
- Scheduled Aircraft Maintenance
- The Need for Regulation
- A Framework Proposal
- Observations & Way Forward

SCHEDULED AIRCRAFT MAINTENANCE

Aircraft maintenance second biggest cost contributor to airline's direct operating cost and major source of aircraft downtimes

Aircraft maintenance cost share

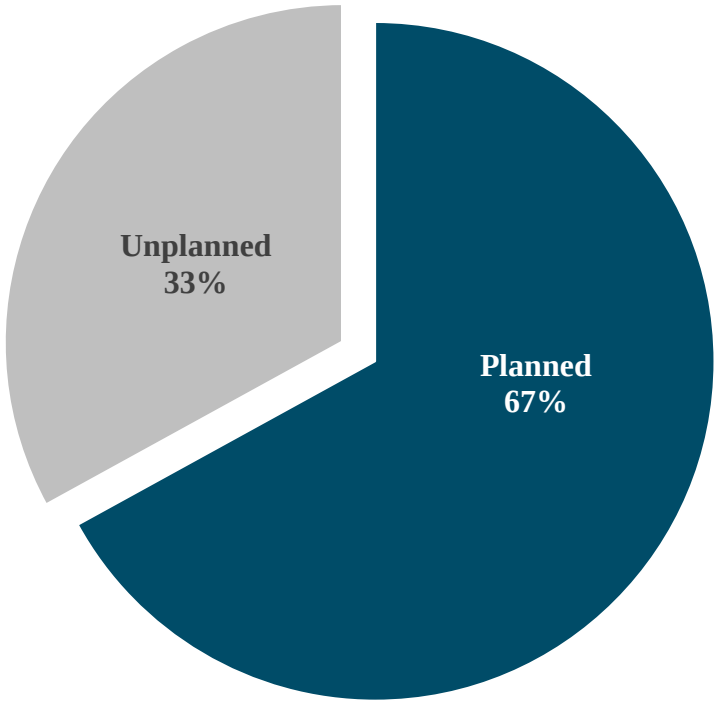
Percentage of Direct Operating Cost



Source: A. Kählert (2017) Specification and Evaluation of Prediction Concepts in Aircraft Maintenance. PhD thesis, TU Darmstadt. URL: https://tuprints.ulb.tu-darmstadt.de/id/eprint/6065

Aircraft unavailability due to maintenance

On the example of an A320, representing narrow-body aircraft

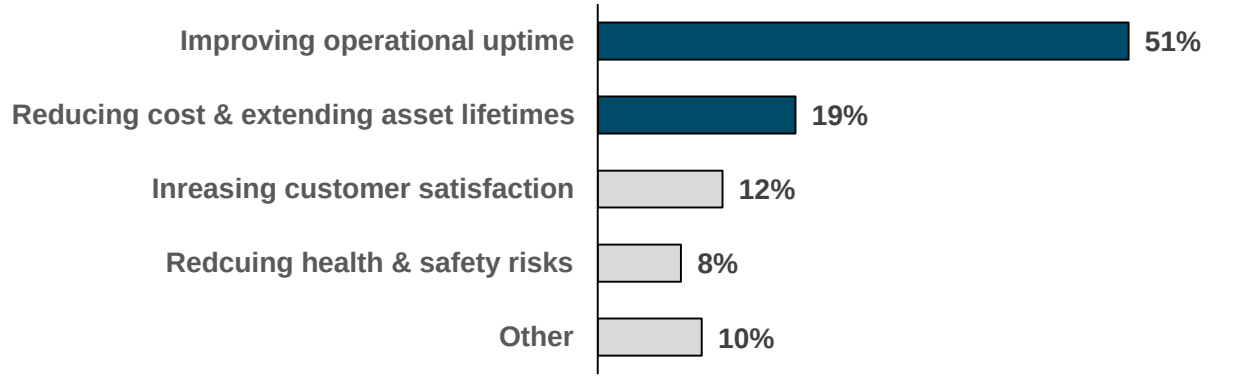


Source: O. Weiss (2018) Maintenance of Tomorrow – The AHM path from Airbus' Perspective. 5th Paperless Aircraft Operations and RFID Conference. URL: www.iata.org

Lack in health management technology adoption as alternative maintenance means despite substantial cost savings potential

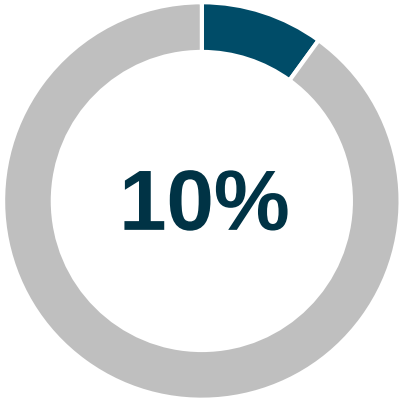
While 60% of companies pursue predictive maintenance concepts ...

Promised benefits from incorporating continued asset health management, N=268



... and stick to the conventional maintenance approach ...

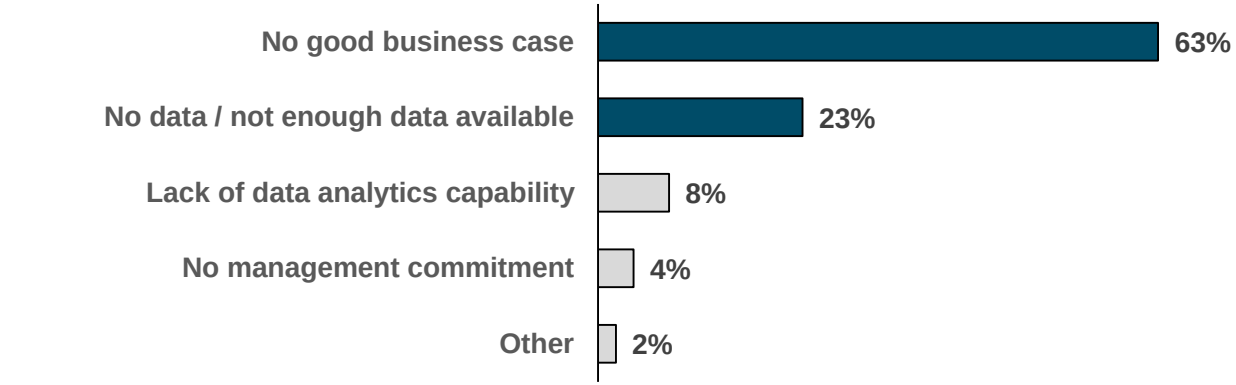
Percentage of findings during scheduled maintenance



Source: O. Weiss (2018) Maintenance of Tomorrow – The AHM path from Airbus' Perspective. 5th Paperless Aircraft Operations and RFID Conference. URL: www.iata.org

... 40% do not see the value of it ...

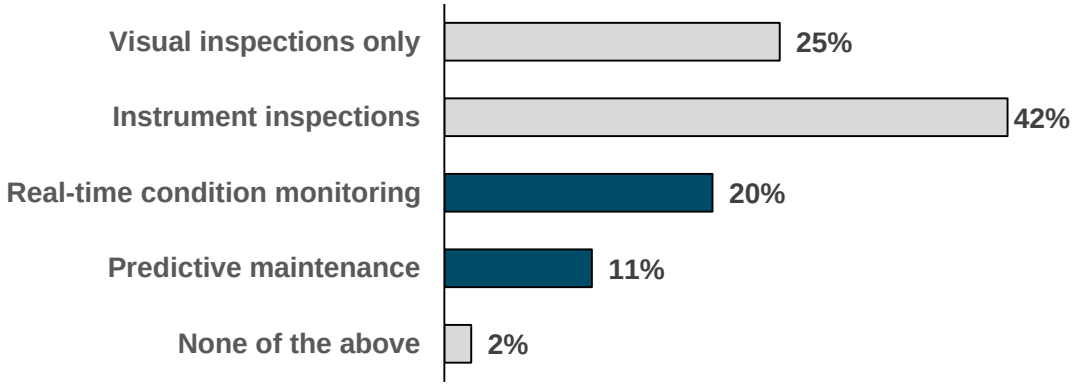
Reasons for companies not to invest in asset health monitoring technologies, N=268



Source: M. Haarman et al. (2018) Predictive Maintenance 4.0 – Beyond the Hype. URL: https://www.pwc.nl/nl/assets/documents/pwc-predictive-maintenance-beyond-the-hype-40.pdf

... leading to a lack of health monitoring maturity.

Technological readiness of companies for predictive maintenance strategies



Source: M. Haarman et al. (2018) Predictive Maintenance 4.0 – Beyond the Hype. URL: https://www.pwc.nl/nl/assets/documents/pwc-predictive-maintenance-beyond-the-hype-40.pdf

THE NEED FOR REGULATION

Regulatory restrictions major source of this slow adoption rate besides technical challenges and lack of viable business cases

*"Integration of AHM within the aircraft maintenance activity must have approval by the **competent aviation authorities certifying the products** [...] AHM implementation for **airworthiness determinations** requires regulatory authority acceptance. [...] **Regulatory guidance material is needed** by AHM actors to drive their effort in a harmonized level across all aviation jurisdictions.*

Source: IATA (2023) From Aircraft Health Monitoring to Aircraft Health Management – White Paper on AHM – Position Updates. URL: www.iata.org/

*"No new maintenance procedure will be approved unless it goes through the **approval steps** that **involve the certification authorities**. This is true for paradigm-shifting technologies involved with PHM, because the basic goal is to **eliminate all regular inspections**. This brings up a **host of issues** that will need to be addressed before these technologies start to be routinely used.*

Source: R. Rajamani (2020) Unsettled Issues Concerning Integrated Vehicle Health Management Systems and Maintenance Credits. SAE Edge Research Report.

*"Current industry efforts on **health management** are made as **an additional monitoring activity** to support or extend the maintenance program implementation. **Regulators**, operators, and manufacturers **still do not recognize certified credit for health management solutions** and offer limited flexibility to drive maintenance based on health indicators or predictions.*

Source: W. Verhagen et al. (2023) Condition-Based Maintenance in Aviation: Challenges and Opportunities. MDPI Aerospace. DOI: 10.3390/aerospace10090762

Developing certifiable integrated aircraft health management (IAHM) solutions require a full end-to-end process consideration

Requirements

One of the more thorough guidelines provided for Health and Usage Monitoring System (HUMS) certification. Three aspects that must be addressed

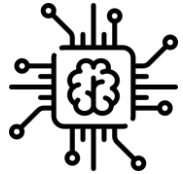
- **Installation** includes all the equipment that is associated with acquiring, storing, processing, and displaying data – including airborne and ground based equipment
- **Credit validation** includes evidence of effectiveness for the developed algorithms, acceptance limits, trend setting data and tests – including the respective demonstration methods
- **Instructions for Continued Airworthiness (ICA)** to ensure continued airworthiness of AHM equipment that could change with time or usage – including information about appropriate maintenance methods

Criticality Determination

Installation Approval

Application Intent

Resultant Criticality



Data Acquisition & Storage

Data Processing & Display

Maintenance Credit

Consideration whether this application is for credit (i.e., it adds to, replaces, or intervenes in maintenance practices or flight operations) to correctly determine the criticality level & establish integrity criteria

Failure Hazard Assessment

Determination of end-to-end criticality and required integrity level – compliance may be achieved & demonstrated by a combination of application qualification & appropriate mitigating actions

Hardware & Software

Consideration of environmental qualification RTCA DO-160 including high intensity radiated fields (HIRF) and lightning for installed hardware – software should follow RTCA DO-178 guidelines

Ground-Based Equipment

Process and display of collected data by airborne means to derive intervention action decisions – integrity and accuracy requirements must be the same as any other part of the IAHM process

Source: FAA (2003) Certification of Transport Category Rotorcraft – Miscellaneous Guidance. AC29-2C MG15. URL: https://www.faa.gov/documentlibrary/media/advisory_circular/ac_29-2c.pdf

Existing guidelines only address partial aspects of the end-to-end cycle – creating blind spots in the development phase





	Application Intent	*Criticality Determination*	*Data Acquisition & Storage*	*Data Processing & Display*	*Instructions for Continued Airworthiness*
Commercial aviation (IAHM) [1]	○	◑	◑	◑	◑
Rotorcraft certification (HUMS) [2]	◑	◕	◕	◕	◑
Maintenance Program Industry Group [3]	◔	◔	○	○	●
Unmanned Aerial Vehicle [4]	●	○	○	◕	○

● Full guidance with extensive discussion ◕ Covered with limited provided guidance ◑ Mentioned, but not discussed ◔ Briefly mentioned ○ Not mentioned at all

Key Messages

- Although the **importance of** a defined **application intent** has been recognized by authorities, **practical guidance** has **only** been developed **in research** thus far.
- While **extensive regulations on the development** & integration **of** airborne (and on-ground) **hardware** have been developed, guidelines for the measurement & **definition of (minimum)** diagnostic & prognostic **performance** are still **lacking**.
- Currently, there is very **limited regulation** with respect to **required skills & training** for the application of AHM-based scheduled maintenance substitution.

Sources: 1. FAA (2022) Operational Authorization of Integrated Aircraft Health Management Systems. AC43-218. URL: https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_43-218_FAA_Web.pdf
2. FAA (2003) Certification of Transport Category Rotorcraft – Miscellaneous Guidance. AC29-2C MG15. URL: https://www.faa.gov/documentlibrary/media/advisory_circular/ac_29-2c.pdf
3. IMRPBP (2018) Aircraft Health Monitoring (AHM) integration in MSG-3. URL: https://www.easa.europa.eu/download/imrbpb/IP%20180%20-%20AHM%20integration%20in%20MSG-3.pdf
4. A. Saxena et al. (2012) Requirements Flowdown for Prognostics and Health Management. In: AIAA Infotech 2012. URL: https://ntrs.nasa.gov/api/citations/20140006575/downloads/20140006575.pdf

A FRAMEWORK PROPOSAL

Open system architecture for condition based maintenance as possible guideline for an end-to-end AHM development process

OSA CBM process steps	Objectives
System Design	• Definition of the **intended application** & determination of **economic viability** of an automated CM system • Identification of all **possible failure modes** of the monitored system & assessment of the **failure criticality**
Data Acquisition	• Definition of **suitable sensor network** to detect respective functional abnormalities • Determination of **sensor qualification requirements** in accordance with identified failure criticality
Data Processing	• Analysis of **expected data quantity**, their **processing needs** and off-board **data transmission frequency** • Determination of **data transmission security** requirements based on underlying failure criticality
State Detection	• Definition of **suitable (fault) alert/alarm levels** based on observable system condition • Derivation of appropriate (preventive) **maintenance measures** to avoid critical failure occurrence
Diagnosis	• Determination of **minimum performance requirements** for a reliable degradation diagnosis
Prognosis	• Determination of **minimum performance requirements** for a reliable failure prognosis • Analysis of inherent projection **uncertainty**
Advisory Generation	• **Presentation of** current and future asset (and fleet) **degradation status** • Derivation of **actionable maintenance measures** to ensure a continued airworthiness among the fleet

Sources: M.G. Thurston (2001) An open standard for Web-based condition based maintenance systems. In: 2001 IEEE Autotestcon Proceedings. IEEE Systems Readiness Technology Conference.
International Organization for Standardization (2003) ISO 13374-1: Condition monitoring and diagnostics of machines – Data processing, communication and presentation – Part 1: General guidelines.

A structured definition of appropriate technology requirements builds the basis of an effective health management development

Step

- System Design
- Data Acquisition
- Data Processing
- State Detection
- Diagnosis
- Prognosis
- Advisory Generation

Identification of intended aircraft health management application	Identification of failure modes of monitored system	Determination of failure criticality for vehicle safety
Identification of relevant stakeholders for the AHM development • Understanding stakeholder needs & objectives • Deriving high-level requirements for AHM performance	**Definition of functions, operating modes & environmental conditions** • Analysis of functional requirements of the monitored system • Identification of environmental factors on the installed AHM hardware	**Analysis of functional failure criticality on overall system safety** • Understanding if failure of monitored system will be mission/flight critical • Definition of mitigating actions – if applicable
Analysis of AHM integration into their maintenance processes • Identification of business case setting and potential profitability for each involved stakeholder • Definition of priority targets for AHM development (e.g., cost vs. performance)	**Analysis of relevant functional failures and their detection means** • Identification of all relevant failure modes & their respective causes • Understanding of fault identification means & degradation progression rates	**Analysis of interaction between AHM and aircraft system in case of failure** • Understanding the effects of a faulty AHM on the aircraft's system reliability • Understanding of AHM behavior in case of a failure of the monitored aircraft system

The analysis of the intended aircraft health management system follows the standard development process of conventional (aircraft) systems[1] & the results with the defined technical requirements are typically consolidated in a ConOps[2] document.

1 | Ref. SAE ARP 4754 & 4761, 2 | Concept of Operations
Source: SAE (2019) Guidelines for Writing IVHM Requirements for Aerospace Systems. ARP6883. URL: https://www.sae.org/standards/content/arp6883/

Development and qualification of a suitable sensor network is essential to acquire reliable condition data of the aircraft system

Step

- System Design
- **Data Acquisition**
- Data Processing
- State Detection
- Diagnosis
- Prognosis
- Advisory Generation

Determination of suitable measurement network

Definition of suitable measurement means for respective failure mode

- Definition of appropriate sensor technology (e.g., accelerometer) based on prior identification of fault detection means

Determination of properties of sensor network & its maintenance needs

- Identification of areas of the monitored system with most severe manifestation of malfunctions
- Definition of regular maintenance or calibration necessities for the chosen sensor

Qualification of sensors according to required AL[1]

Identification of qualification requirements & mitigating actions

- Determine the hardware qualification requirements (e.g., with RTCA DO-160) – depending on the functional failure criticality
- Define mitigating actions – if appropriate

Selection of qualification approach depending on the failure criticality

- Develop a testing plan depending on the functional failure criticality (e.g., seeded fault tests or analytical methods)

Assessment of measurement uncertainties & their causes

Identification of expected measurement uncertainties

- Understanding of interaction between external / system-specific conditions (e.g., humid conditions) and resulting condition measurement inaccuracies

Analysis of uncertainty causes & definition of counter measures

- Understanding of interaction between internal / AHM-specific conditions (e.g., sensor drift) and resulting measurement inaccuracies
- Definition of applicable mitigating action

The defined sensor system network with its functionalities determines the needs for data processing capacities & diagnostic capabilities. AHM systems are qualified as any other airborne equipment – considering environmental qualification, e.g., through RTCA DO-160.

1 | Assurance Level

Sources: International Organization for Standardization (2002) ISO 13373-1: Condition Monitoring And Diagnostics of Machines – Vibration Condition Monitoring – Part 1: General Procedures.
International Organization for Standardization (2018) ISO 17359: Condition Monitoring and Diagnostics of Machines – General Guidelines.
FAA (2003) Certification of Transport Category Rotorcraft – Miscellaneous Guidance. AC29-2C MG15. URL: https://www.faa.gov/documentlibrary/media/advisory_circular/ac_29-2c.pdf

Ensuring secure and reliable on-board data processing and off-board data transmission requires cyber security considerations

Step

- System Design
- Data Acquisition
- **Data Processing**
- State Detection
- Diagnosis
- Prognosis
- Advisory Generation

Definition of data quantities & transmission frequencies	Validation of data processing software according to AL[1]	Determination of appropriate cyber security requirements
Determination of on-board vs off-board data processing capabilities • Defining minimum processing capacity of AHM infrastructure for the amount of data – depending on failure mode criticalities and progression rates of degradation	**Identification of qualification requirements & mitigating actions** • Determine the software qualification requirements (e.g., with RTCA DO-178) – depending on the functional failure criticality • Define mitigating actions – if appropriate	**Identification of hardware qualification requirements for data transmission** • Determine the data transmission hardware qualification requirements (e.g., with RTCA DO-160) – depending on the functional failure criticality
Definition of data transmission frequency & transmission reliability • Dependent on run-time monitoring method (e.g., archived alerts vs. continuous monitoring) and criticality of function • Consideration to be given on operational (e.g., time limited dispatch) and technical constraints (e.g., part of MEL[2])	**Establishing independent verification means for incorporation of COTS[3]** • Determination of compliance with integrity requirements difficult for COTS[3] equipment • Integrity compliance through equivalence, e.g., redundant processing with dissimilar equipment or comparison of COTS[3]-based data output with validated AHM data	**Identification of cyber security threats with respect to failure criticality level** • Determine and evaluate the *Level of Threat* from malicious attacks (e.g., with DO-326) • Define digital protection means (e.g., with DO-355) to verify the integrity of transmitted information & limit potential opportunities for data tampering

Off-board data processing & transmission requirements depend on the necessary condition monitoring sampling rates & the on-board processing capabilities. For the use of COTS[3] equipment, independent verification means are needed to ensure integrity compliance.

1 | Assurance Level, 2 | Minimum Equipment List, 3 | Commercial Off-the-Shelf – hardware & software not qualified to aircraft standards

Sources: FAA (2003) Certification of Transport Category Rotorcraft – Miscellaneous Guidance. AC29-2C MG15. URL: https://www.faa.gov/documentlibrary/media/advisory_circular/ac_29-2c.pdf
EASA (2023) Executive Director Decision 2023/009/R. URL: https://www.easa.europa.eu/en/document-library/agency-decisions/ed-decision-2023009r
SAE (2023) Guidelines for the Development of Architectures for Integrated Vehicle Health Management Systems. ARP6290. URL: https://www.sae.org/standards/content/arp6290/

The effectiveness of (automated) airworthiness decisions heavily depends on the performance of health assessment algorithms

Step

- System Design
- Data Acquisition
- Data Processing
- State Detection
- Diagnosis
- Prognosis
- Advisory Generation

Definition of suitable alert & alarm levels for the system condition

Determination of appropriate warning levels to avoid critical malfunction

- Alerts are produced to indicate possible anomalous behavior & should be applied to every monitored component

Definition of data unavailability limits & resulting intervention procedures

- In case of criticality by missing or latent data, MEL[1] specification may be given for algorithm/AHM validity
- Recommendations on maximum period of unavailability of AHM functions shall be provided through ICA

Determination of required fault diagnosis & failure prognosis performance

Identify human performance benchmark

- If AHM system shall replace existing maintenance task, the validated detection capability shall be as good/better than the legacy maintenance task

Derivation of tolerable algorithm performance from HL[2] requirements

- Demonstrate how the AHM system provides an acceptable defect detection performance
- DAH[3] should establish data analysis minimum standards based on root system criticality and intended use of the data

Definition of appropriate maintenance actions

Determination of maintenance tasks for the monitored system

- Guidance for interpretation of diagnostic information provided by the AHM system
- Necessary maintenance instructions in the event of alarm – including failure-finding, alarm verification tasks

Determination of regular maintenance tasks for the monitoring system

- Definition of scheduled maintenance for the AHM system – including inspections to confirm sensor performance and system functionality

Based on the initially determined functional criticality, appropriate alert levels need to be defined that allow a timely & effective intervention before failure occurrence. The underlying algorithms are typically validated through established precision & accuracy metrics[4].

1 | Minimum Equipment List, 2 | High Level, 3 | Design Approval Holder, 4 | ref. SAE ARP5783

Sources: EASA (2023) Certification Specifications, Acceptable Means of Compliance and Guidance Material for Large Rotorcraft (CS-29).
FAA (2022) Operational Authorization of Integrated Aircraft Health Management Systems. AC43-218. URL: https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_43-218_FAA_Web.pdf

Deriving actionable maintenance decisions require availability of condition monitoring data and appropriate training for personnel

Step

- System Design
- Data Acquisition
- Data Processing
- State Detection
- Diagnosis
- Prognosis
- Advisory Generation

Definition of displayed information for maintenance decision making

Definition of necessary information to display for the derivation of airworthiness decisions

- Personnel responsible for releasing vehicle into service needs provision of necessary AHM data (e.g., indicators & trend data), maintenance recommendations & AHM system Built-In Test data (e.g., detection criteria & thresholds)
- Information necessary for immediate post flight fault diagnosis

Definition of data record keeping procedure for retrospective traceability of maintenance reasons

- AHM data used for airworthiness determinations must be available for inspection by the administrator or any representative
- In the event of an accident or incident, operators need a procedure to safeguard AHM data to prevent manipulation or loss of essential information

Determination of necessary skills & training for maintenance personnel

Determination of AHM-related responsibilities & roles within the maintenance organization

- Necessary system administration functions need to be established – covering procedures such as data transfer and storage, recovery from failed down loads & introduction of hardware/software modifications

Definition of appropriate training and qualification of AHM-related maintenance personnel

- AHM effectiveness relies on properly trained personnel
- Training courses should cover: AHM system installation, necessary AHM maintenance (e.g., sensor calibration), use of AHM system for system monitor – including data transfer, interface with data analysis, response to alerts and alarms & other diagnostic actions – & required data analysis + reporting functions capabilities

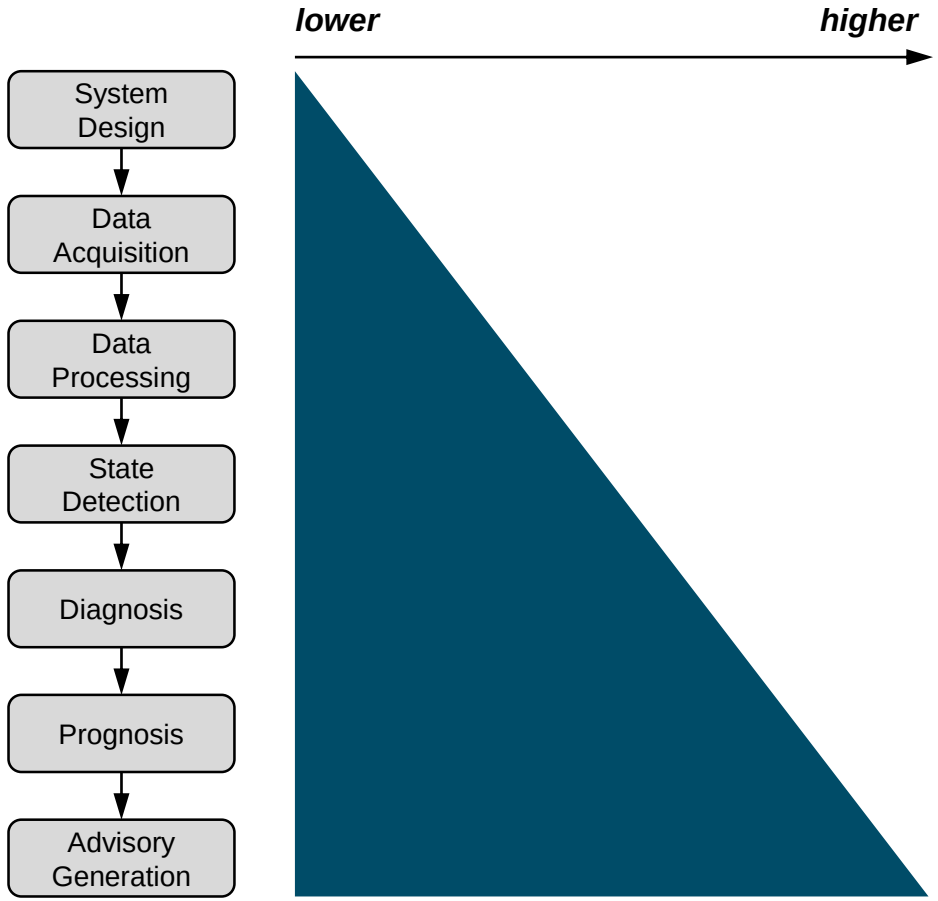
AHM-based maintenance advisories have to be comprehensible by regularly trained personnel. Access to underlying indicators, e.g., trend data, alert criteria, etc., have to be available for release-to-service decisions & need to be safely recorded in case of incidents.

Sources: EASA (2023) Certification Specifications, Acceptable Means of Compliance and Guidance Material for Large Rotorcraft (CS-29).
FAA (2022) Operational Authorization of Integrated Aircraft Health Management Systems. AC43-218. URL: https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_43-218_FAA_Web.pdf
International Organization for Standardization (2003) ISO 13374-1: Condition monitoring and diagnostics of machines – Data processing, communication and presentation – Part 1: General guidelines.

OBSERVATIONS & WAY FORWARD

Despite a substantial body of guidelines, the level of ambiguity increases in later stages of the end-to-end process cycle

Level of ambiguity of existing guidelines



Key Messages

- A **significant number of guiding material** – especially focusing on technical developments – has been developed **by organization such as ISO and SAE**.
- Since **condition monitoring** is well established in **other industries** (e.g., the manufacturing industry) as well, there is plenty of **guidance to be learnt and adopted** from them.
- Although most of the **end-to-end process steps** are at least **referenced** by existing guidance and regulatory initiatives, their **level of ambiguity** substantially **differs** – especially for later stages in the process cycle.
- At the same time, the **highest economic benefit** will be yielded with an **effective advisory generation** system that not only ensure a safe operation but also the avoidance of costly maintenance-induced irregularities.
- Therefore, for any framework to be successful, **not only regulatory concerns** but also **practicalities** for a subsequent **industrialization** and **monetarization** need to be respected.
- Otherwise, it increases the **risk of an impractical regulatory framework** which will hardly allow any viable business case scenario.

Next steps include the representation of a regulatory perspective on the proposed framework and the definition of a pilot use case

Discussion with **industry representatives** about the frameworks practicality

Check

if the framework is compatible with existing aircraft industry development procedures –
evaluate its practicality and viability

Inclusion of **regulatory perspective** about potential safety concerns

Ensure

that the framework is compatible with the regulatory intent and does not violate current safety standards –
include the regulatory perspective

Definition of **pilot use case & application** of the framework for AHM development

Extend

beyond a mere theoretical development concept and apply the framework to a pilot use case and support a regulatory-compliant AHM development process

THANK YOU FOR YOUR ATTENTION

KEY TAKEAWAYS

01 While imperative for the development of effective AHM technologies, regulatory guidelines are still lacking for an end-to-end solution!

02 Many recommended practices have been developed by institutions such as ISO and SAE; however, their ambiguity increases with later stages of the end-to-end process cycle!

03 Despite the importance of a sound understanding of the AHM application’s intent, no document from competent authorities is providing thorough guidance there yet!

Imprint

Topic:	**Certifiable Condition-Based Maintenance in Civil Aviation** A Review of Regulatory Approaches
Date:	2024-09-13
Authors:	Robert Meissner, Kai Wicke, Gerko Wende
Institute:	Institute of Maintenance, Repair and Overhaul, Hamburg, Germany
Image sources:	All images “DLR (CC BY-NC-ND 3.0)” unless otherwise stated