From Aircraft Health Monitoring to Aircraft Health Management

White Paper on AHM – Position Updates

Contents

1. Foreword

Managing the technical availability of the aircraft is key in accomplishing your mission, whichever is your stakeholder status vis-à-vis the aircraft asset: Airline Operator, Aircraft OEM, Aircraft MRO or Aircraft Owner/Lessor.
In assessing the potential impact of (un)availability, operators asserted that aircraft dispatch delays can cost $10K (or more) per hour with flight cancellations imposing a financial penalty of $100K (and above) per instance[1].

Reaching consistently the targets set above a 99% benchmark of aircraft technical availability[2] implies a careful steering of the aircraft maintenance with a sharp focus on preserving the capabilities and performance of the asset close to its "as new condition". Hence, the needed enabler for a 24/7 visibility on, awareness of, and action to maintaining the required level of aircraft health.

Accomplishing the above is the main objective and direct result of a robust Aircraft Health Management (AHM).
The AHM means using aircraft and fleet generated data to promptly identify the individual aircraft's needs for maintenance work and trigger an effective and efficient maintenance action. This is an end-to-end comprehensive process, which encompasses aircraft systems, data transfer and electronic processing, data analysis, and subsequent informed decision on improved, re-defined, or alternative methods to maintenance tasks. Such a process includes both "on-board" and "off-board" sequences and its results are highly relevant to planning and executing the aircraft scheduled maintenance program or the ad-hoc required maintenance action. It is a dynamic action-oriented approach and a consequential evolution of the already acknowledged albeit more "passive witnessing" field of Aircraft Health Monitoring.

This White Paper is a quick review of what AHM implies and could possibly empower its adopters to perform, in the not-too-distant future, towards ensuring the economically optimized technical availability of the aircraft.
While there is no substitute (at least not yet) to the aircraft maintenance action requiring the maintenance staff "hands-on" presence for physical accomplishment of an aircraft part replacement or repair, implementing the AHM approach would position the practitioner to make the optimum decision regarding such maintenance action. Predictive maintenance employing health monitoring mechanisms is estimated to enable airlines around $3B per year in maintenance cost savings.

The objective of this White Paper is to: a) familiarise the industry with the technological revolution that the use of data collected from the aircraft can improve the levels of safety and efficiency, b) provide a roadmap to capitalize on this data usage, and c) address challenges and opportunities that this will bring to the industry.

Empirical data indicate that, for the average operator, over 70% of its scheduled maintenance program "fault finding tasks" resulted in "no findings". This maintenance execution fact coupled with utilizing the alternative of AHM-based tasks to enable a condition-based maintenance versus on-wing "manually-driven" preventive maintenance tasks will result in: a) significant cost reductions for the operator, and b) increased aircraft on-time performance and improved dispatch reliability as real time data is either pro-actively or reactively used by operators to address aircraft systems or structural issues before faults could develop into functional failures affecting the aircraft technical availability.

[1] Recently IATA collected estimates and rationale are available on page 65 of "IATA Ground Damage Report" – see https://www.iata.org/en/programs/ops-infra/ground-operations/ground-damage-report/
[2] Comprehensive review available in IATA published "Aircraft Operational Availability" 2nd Edition – 2022 – see https://www.iata.org/contentassets/bf8ca67c8bcd4358b3d004b0d6d0916f/aoa-2nded-2022.pdf

Adopting and operationalizing a refined AHM path will naturally lead civil aviation actors to also explore new ways of guarding the safety level priority in the context of ever-growing complexity of aircraft and their operation.
Critically important for all entities in the aviation ecosystem is that aviation regulatory authorities approving and overseeing the AHM implementation do engage the industry and consider their feedback in designing the safest and most efficient aviation framework. Data and information delivered by AHM will certainly become an integral part of the Condition Based Maintenance approach, a distinct departure from today's scheduled maintenance tasks' intervals.

Recently manifested radical progress factors and technology disruptors like Big Data and Cloud Services, Industrial Internet of Things, Artificial Intelligence and Machine Learning, Industry 4.0, Digital Twins and Digital Threads are all major potential contributors to shape and empower the AHM.

This White Paper is an invitation for all industry stakeholders to consider the AHM ensuing benefits in building the future success of the entities and communities they belong to.
Sharing AHM related ideas, initiatives, experiences, and results would benefit the entire aviation ecosystem and this White Paper is intended to enhance the interest in that direction.

Please note that the present document is an update of the one released by IATA in Feb 2022. Being intended as a summarizing snapshot about its area of focus, the typical White Paper enjoys the freedom of open forays in unsettled areas of the subject addressed, with sometimes challenging facets, themes of reflection or proposed priorities, all without being expected to undergo a cycle of revision tracked document. Notwithstanding such tenets, the update you're about to peruse was considered necessary following the increased pace at which AHM relevant perspectives and milestones evolved since the initial publication of the White Paper.

Looking forward to receiving your feedback at Techops@iata.org.

2. Aircraft Maintenance Milestones

While not always visible to the aircraft operation direct beneficiaries, aircraft maintenance is a constant presence enabling the aircraft asset to deliver along its entire life the expected financial and business values without any hindrance due to aircraft technical status. The recognition of aircraft technical availability key role is unanimous, albeit one should always check the definition of this KPI for a common acceptance basis and interpretation awareness (see reference [1] in Appendix 2 for a detailed discussion).

2.1. Aircraft Maintenance as Means to an End

Airline Operators are aware that aircraft maintenance, notwithstanding its "must have" regulatory status, is just the means to support the desired end outcome of aircraft fleet operational readiness.

The perspective of a "self-healing" aircraft is still a distant one even if some of the edge research in self-diagnostics and self-repair of complex structures is bringing such aircraft of the future out of the Science Fiction realm and closer to aviation attainable goals.
In this context, the first step to ensure the desired technical availability of the aircraft is to set-up an appropriate maintenance activity, which is focused on and supports the airworthiness, technical capability and performance of each aircraft, as demanded by the airline's operations schedule.

While clearly distinct from it, the aircraft technical availability relies first and foremost on the aircraft reliability.

Figure 1: Reliability Bookmarks

The reliability which an operator could achieve for the aircraft (i.e., "individual tail reliability") is lower than, or at best equal to, the aircraft reliability performance intrinsically resulted from the design of the aircraft type and production of the aircraft unit.

The aircraft "built-in" reliability threshold resulted from design and production is the maximum achievable level of reliability in operation. Aircraft maintenance, however diligent and effective, would not result in exceeding that threshold and operators should acknowledge it as a limitation which is out of their control and is dependent on the aircraft design and production.
Only with a well-conceived and implemented Aircraft Maintenance Program (AMP) could the operator eventually achieve that end level of reliability. Airlines are requested by regulation to have a Reliability Program for their fleet by considering several sources of information (e.g., Pilot Reports – PIREPS, Maintenance Reports – MREPS) and operationalizing a Failure Reporting, Analysis and Corrective Action System (FRACAS) type of construct.

Additionally, operational relief mechanisms involving dispatch under Minimum Equipment List (MEL) and Configuration Deviation List (CDL) are, in some circumstances, facilitating a limited technical availability of the aircraft, albeit they are not intended to and could not address a lack of reliability issue.

AHM potentially becomes a key enabler of optimized AMP implementation; its direct impact on securing the aircraft technical availability makes it an important tool for airlines in achieving the desired level of Dispatch Reliability (DR).

2.2. Maintenance Life of the Aircraft

The aircraft "maintenance life" is effectively starting once the production test flight of the aircraft is performed. Life consumption of all critical parts is technically tracked from the Final Assembly Line (FAL) phase during aircraft production and before customer delivery.
The clock and focus on technical, commercial, and regulatory compliance activities with aircraft maintenance relevance is initiated "de jure" at the time of aircraft asset delivery to its first operator, nevertheless it is not necessarily starting from a zero basis at that time.

Exploring the taxonomy of aircraft maintenance types is a multi-layered exercise with numerous categories of maintenance activities being distinguished based on the criteria considered to define them.

A non-exhaustive list of examples would include grouping by:

- location and complexity of activity execution during the aircraft operational life (i.e., line or base maintenance).
- volume of activity committed and its optimization for the timing and duration of execution within the defined maintenance event (i.e., equalized or block maintenance).
- nature of activity in relation to the technical content of the executed maintenance tasks (i.e., preventive or corrective maintenance).
- prior level of eligibility for planning granularity/comprehensiveness which is governing the activity (i.e., scheduled or non-scheduled maintenance).

Each criterion is capturing the dominant feature of that category of maintenance and the very same maintenance task could be simultaneously identified as belonging, for example, to preventive, block and base maintenance.

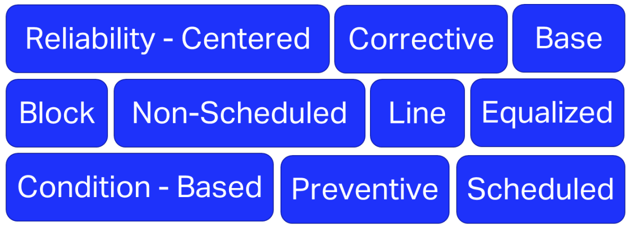

Figure 2: Maintenance Focus Taxonomy Excerpt

The individual airline will always seek to build and adopt the AMP best suited to its own operational profile and fleet; the resulting aircraft maintenance activity planning and execution will account for the specific constraints and conditionalities. This could result in a very tailored packaging of maintenance tasks which accommodates to the best possible level the particular operation. Inherently, with the aircraft asset transiting from one type of operation to another one (which is often the case when the life of the aircraft is split between several operators), accounting for migration from one maintenance program to another could become a non-trivial task. Such transition would often entail the build-up and execution of a bridging program between two AMPs, which translates into a one-time "equalization maintenance check" event at the time of aircraft asset transfer.

Reviewing the frequency of aircraft parts' failure, a series of patterns were identified in the attempt of linking the occurrence of such failures to the operating time (or the relevant use control parameter) of the part. The conclusion was that most functional failures (approx. 89% of them) in a complex machinery like the aircraft occur following a deterioration model which is not "age related" but rather "random" (see reference [13] in Appendix 2 for more details). The emergence of software parts which the configuration of modern aircraft comprises (e.g., currently, the B787 counts around 1400 instances of such parts in its listed configuration) seems to bring no major change to the above conclusion which is based on legacy configuration aircraft (i.e., in-service by 1980).

While the conclusion drawn constitutes an important element which the AHM must consider, the corelations unveiled by a continuous and detailed monitoring of parameters could be an AHM opportunity to pursue when attempting to better explore the previously observed randomness.

2.3. Evolution of Aircraft Maintenance Concept

In its history beginning phase, aircraft maintenance was mainly of corrective type – fix the equipment once it has broken and failed to fulfil its intended function - with the addition of some servicing maintenance actions (e.g., cleaning and lubrication) and limited restoration of condition to "as if new" when the need to recover evident loss of performance was identified.

This approach evolved later to include scheduled restoration, overhaul or replacement of equipment and parts. The intent of such maintenance actions was preventive in nature with the scope of increasing reliability of subject equipment and parts, and it was based on the belief that the more maintenance the aircraft undergoes the better its reliability will be.
This view resulted from across-the-board application of the "bathtub model" of failure and its assumed wear-out zone while, at the same time, ignoring the failure rate injected into otherwise stable operating systems by unnecessary maintenance actions.

The Maintenance Steering Group (MSG) became the aerospace industry driving force to introduce the systemic engineering approach to aircraft scheduled maintenance development. This formalized a decision logic flow which was repeatedly refined and was reflected in the successive standards document MSG-1/ -2/ -3 with a notable mechanism for periodic revisions of MSG-3.

Figure 3: Driving Factors in Scheduling Maintenance

The major step in this evolution was to recognize that performance of maintenance should be targeting function preservation at the aircraft level rather than focusing on the component failure per se. This evolution resulted in MSG-3 delivery to enforce:

- the system level and top-down approach for function identification, instead of a component level and bottom-up approach.
- the consequence-driven approach, starting with the failure identification as "hidden" or "evident" to the flight crew and "safety" or "non-safety" categorization to ensure specific controls are used to address the risk of failure.
- the function preservation instead of failure prevention, to ensure the system function and the availability of protective devices.
- the task-oriented approach instead of a maintenance process-oriented approach in preparation of the aircraft maintenance programme.

This evolution history started with embracing three types of maintenance processes:

Hard Time (HT) defined as the preventive process in which known deterioration of a system or component is limited to an acceptable level by the maintenance actions which are carried out at periods related to time in service or other corresponding control parameter (e.g., calendar time, number of cycles, number of landings). The prescribed actions restore the system or component utility margin to the applicable control parameter limitation. Examples: overhaul the landing gear; discard the cartridge of the engine fire extinguishing bottle; discard cabin crew protective breathing equipment.

On Condition (OC) defined as the preventive process that requires a system or component be inspected periodically or checked against some appropriate physical standard to determine if it can continue in service between the periodic maintenance actions. The standard ensures that the unit is removed from service or undergoes the necessary maintenance action before failure in service. Examples: Lubrication tasks, Operational Checks, General Visual Inspections.

Condition Monitoring (CM) defined as the process for systems or components that have neither HT nor OC maintenance as their primary maintenance process. It is accomplished by appropriate means available to an operator for finding and solving problem areas. This is not a preventive process, and the system or component are permitted to remain in service without preventive maintenance until a functional failure occurs. The CM is often abusively equated with "run-to-failure" or "fit and forget" philosophy, ignoring that many components maintained under such a process are removed before their failure in service if related repair costs would justify removal. Examples: maintenance of Passenger Convenience Items or Non-Essential Equipment and Furnishings.

It should be noted that in-shop maintenance practice for off-wing components may be following what is sometimes referred to as "**soft-time intervals**" philosophy which, for example in the case of an engine, retains in essence the "on-condition" maintenance practice and minimizes the impact of additional module disassembly.

While in general these maintenance processes are not driving the aircraft maintenance concept anymore (exceptions may be encountered for legacy fleets), it is worth emphasizing that (contrary to what a linguistic semantics misguided understanding may be) CM is not linked to achieving OC maintenance.

Another misleading association is to assume any commonality between CM and CBM.

Condition Based Maintenance (CBM) is a type of maintenance activity that determines the condition and remaining useful life of the component/equipment and consists in maintenance performed based on evidence of need in order to maximize the utilization of economic life of that component/equipment. The CBM, through its application and integration of appropriate processes, technologies, knowledge-based and prognosis capabilities, represents a major evolution of the OC type of maintenance; enabling the optimal failure management strategies depending on system reliability characteristics and the intended operating context, it essentially corresponds to completed AHM implementation.

Avoiding confusions associated with various interpretations is benefiting also from the evolution of MSG standards: the MSG-3 departed from the HT, OC and CM concepts which were central to the MSG-2.

A notable evolution in the decision logic established for developing the aircraft scheduled maintenance is to accommodate the AHM implementation as predicated by MSG-3 Rev 2022.1 which includes the optional level of analysis adopted through IP-180 (see section 4 for details). The Maintenance Program Industry Group (MPIG) is already engaged in drafting the future MSG-X logic to significantly transform the framework under which the new aircraft types scheduled maintenance programs are developed; this new approach will include, interalia, the Integrated Aircraft Health Management (IAHM) path.

Takeaway

- Aircraft maintenance shall be strictly supporting the technical availability of the aircraft asset for safe flight operation and integrate the airline operator specific elements in the process of doing so in an effective and efficient way.

- Implementation of AHM is a logic step to consider in the evolution of aircraft maintenance concepts, especially as they apply to the new level of technology defining the recently certificated aircraft types; the corresponding new paradigm is expected with the advent of MSG-X methodology.

3. The AHM Paradigm

Engaging into AHM implementation is conditional to having both the DAH/OEM and the Operator successfully reach the necessary readiness level and assume the AHM specificities consistent with their roles as recognized and endorsed by the Regulator. The multi-layered essence of this required three-legged construct is summarized in the figure below.

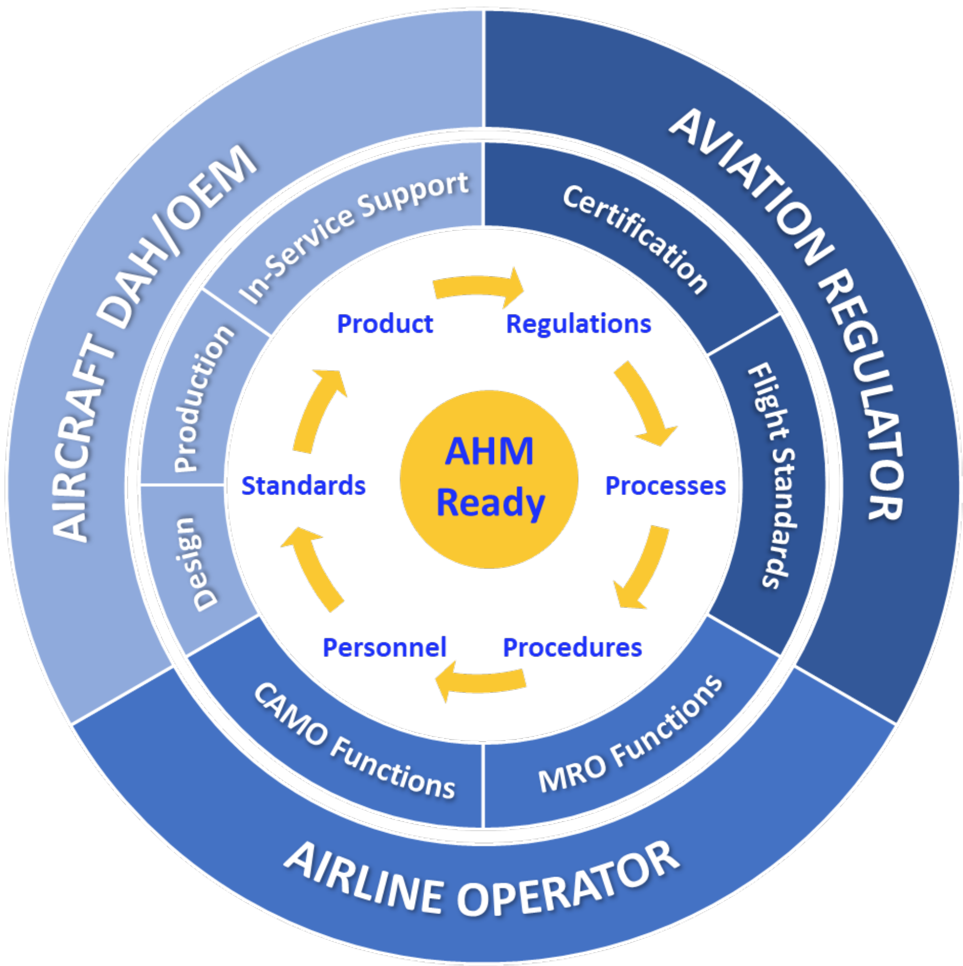

Figure 4: Layered Setup of AHM Readiness

Although robust addressing of safety remains the main driver, commercial considerations (e.g., costs and contractual agreements) do have their role in some of the intra and inter layer connections implied in the above figure.

While building the AHM readiness requires each stakeholder to explore and master new elements, a previous exploit in aviation – consisting of the ETOPS/EDTO implementation - is a valuable procedural model to follow.

Several tenets worth be reminded for their relevance to the AHM paradigm:

- With a fundamental role in aircraft airworthiness and, thus, essential to aircraft flight safety, the aircraft maintenance actions must be executed whenever necessary and shall always encompass the sufficient level of detail. Thus, the maintenance action must meet both the necessity criterion and the sufficiency criterion.

- The AHM purpose is to produce the aircraft accurate health indicator which would constitute the evidence of maintenance need and guide the granularity of work to be performed based on the condition and actual use controlling parameter of the equipment instead of a specified calendar time or generic use limits.

- The key enabler in pursuing any maintenance credits for AHM is to identify and address the product certification and operational authorization precursors in a way commensurate to the AHM use case.

- Implementation of AHM requires a capability level not only for the initial qualification phase (e.g., aircraft type certification and production certification; airline infrastructure, processes, procedures, and personnel) but also for the continued preservation of such qualification (e.g., in-service experience/data driven revisions/updates).

- In the present context of sustainable design/production/operation technological level, the portability between maintenance systems with and without AHM over the operational life of the aircraft asset should be ensured; for now, AHM should be viewed and developed as "the option" and not "the obligation" of airline operators.

- Exploring the concept of certification of "AHM dependent product design" is a possible future direction envisaged by OEMs. Considering the contextualized operational reality has a clear potential for "overdesign" avoidance while still ensuring safety margins for system operational performance. One of the most innovative approaches would be to consider certification of aircraft systems with AHM based performance seeking controls; this would be a pragmatic approach to trimming the control of aircraft systems operation based on their actual condition, as captured by AHM, in view of safely delivering the performance the system is capable of at the time of operation.

3.1. Defining Vocabulary

The aircraft maintenance concepts, even when new and somehow disruptive approaches were adopted, have always provided to practitioners a cohesive evolution from one construct to the next and AHM is no exception. There is however a certain level of on-going dynamics regarding the definition, acceptance and use of some of the terminology or categorization involved in the emergence of AHM and related activities. This could generate overlapping, duplication, or misalignments (even apparent contradictions) which the industry and regulatory stakeholders are called upon limiting; flexibility is desired and would benefit AHM implementations, but vagueness and/or lacking consistency would hamper progress in AHM use.

Often enough, a close scrutiny of the wording used and the associated definitions may indicate more of a marketing or trademark motivation rather than a substantial conceptual differentiation.

While a definitive coining of the AHM vocabulary is out of scope and would be an unattainable pursuit for this paper, there are a few elements to highlight in support of a common understanding basis:

Aircraft Health Management (AHM) is the unified capability of using health monitoring of aircraft structure and systems (including propulsion system) to control the scheduling of aircraft needed maintenance actions; could be resumed to the process stages of **S**ense, **A**cquire, **T**ransfer, **A**nalyse and **A**ct (SATAA).

Aircraft Health Monitoring is the technique of monitoring the output of a single or multiple condition indicators during aircraft operation and consequent use of their output to diagnose faulty states and predict future degradation of the equipment; could be resumed to the process stages of **S**ense, **A**cquire, **T**ransfer and **A**nalyse (SATA).

Fault vs Failure implies distinguishing between the anomaly identified in a component or system without impact on the required functional output of the item or system and (i.e., vs) the inability of a component or system to perform its functional role within previously specified limits.

Potential to Failure (P to F) is the interval (expressed in functional use control parameter units), counted from the presence of a defined identifiable condition at its earliest point of detection/diagnosis, at the end of which the degradation process triggered by the condition leads to a functional loss of the component or system; it is a value which once predicted remains constant for the entire degradation period.

Remaining Useful Life (RUL) is the remaining segment of the P to F at the time of discussion; it is a value which decreases from the P to F value (if the time of discussion coincides with the origin of P to F) to zero (if the time of discussion coincides with the functional loss).

Failure Mode vs Failure Cause vs Failure Effect implies distinguishing between the way in which a component/system can fail and (i.e., vs) the why the component/system has failed in the observed mode and (i.e., vs) the result/consequence which the failure of the component/system generates.

Condition Indicator vs Health Indicator implies distinguishing between the result produced by an algorithm that combines one or more features of a component or system and which is representative of the state of that component or system and (i.e., vs) the result of one or more condition indicator values cumulated to signal the need for a maintenance action.

Predictive Maintenance is the maintenance process with the objective to answer "what and when" will happen with the asset which will require maintenance. It consists in the prediction of future events based on historical and real-time collected data; it employs sophisticated data analytics and automated maintenance workflow elements with possible AI tools.

Prescriptive Maintenance is the maintenance process elevating the prediction capabilities (see the predictive maintenance process discussed above) by adding adaptation and optimization capabilities which enable it to not only predict "what and when" for the event which will happen but also recommend "how" to resolve the event; it employs sophisticated data analytics and automated maintenance workflow elements including AI tools.

3.2. Searching Optimization of Aircraft Technical Availability

Statistics indicate that, depending on the aircraft type and use category/destination/market, somewhere between two thirds and four fifths of maintenance generated unavailability originate from planned maintenance with the rest coming from unplanned maintenance activity. In general, due to operational considerations, from the airline perspective the aircraft asset unavailability "unit cost" ends by being much higher for non-operating time due to unplanned aircraft maintenance rather than planned aircraft maintenance.

The planned maintenance activity would benefit from AHM implementation through its inherent optimization since maintenance resources would be focused on evidence of need provided by health indicators of the aircraft asset. In essence, introducing AHM in the equation of the rationale driving the content of scheduled maintenance, the planned maintenance can be optimized and implicitly the related unavailability can be contained to its feasible minimum.

Additionally, one of the main strengths of an AHM proposed approach and a major source of attracting the active interest of airline operators, is to transform many unpredictable maintenance events into predictable ones and properly plan for them. The capability of additionally reducing operational interruptions from unplanned maintenance events is particularly appealing to airlines.

AHM should provide visibility and knowledge of the aircraft actual usage with a sufficient level of detail and supporting data.
Usage monitoring information comprising data regarding operational regimes, functional parameters and operational environment would generate a refined actual usage identification spectrum of the aircraft structure, systems and components.
The potential consequence would reach from improving the accounting of the maintenance control parameter triggering the execution of a maintenance task up to influencing the decision if the life limit of an LLP was attained or not.
The above-mentioned potential consequence is recognized as an opportunity already explored by engine DAHs with the concept of Usage Based Lifing (UBL), leading to avoidance of premature retirement for LLP replacement of engines still eligible for continuing their "green-time" run.
This would compensate for the unintended over-conservative effect of design and certification assumptions in the case of a low severity usage.
The reversed situation could also happen, whereby AHM outcome safely compensates an under-conservative assumption in the case of higher than design-assumed usage severity.

3.3. Securing the Benefits

Quantifying the value of AHM is a fundamental step for each stakeholder category before engaging on the AHM path and there are different weights attached to individual benefits depending on the stakeholder identity (e.g., airline, OEM, MRO) and business model.
The assessment should consider the potential safety, operational and economic benefits in relationship to the cost of accessing or directly managing the increased complexity of the maintenance process and the analytics necessary to support that process.

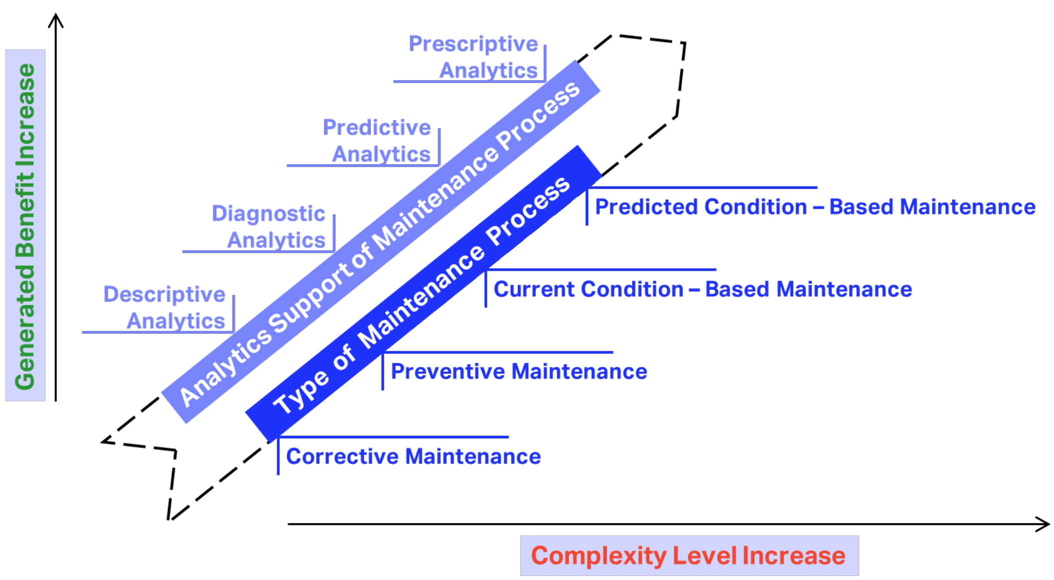

Figure 5: Benefits and Complexity

Enabling a constantly actualized characterization of the in-service condition of an aircraft system or component with the real (or almost real) time continuous collection of data which the AHM entails, could become a significant benefit in the aircraft operational safety equation. The potential of having a continuous monitoring versus a discrete interval snapshot visibility, would enable moving the maintenance action promptitude and its time horizon on a different coordinate with ensuing benefits to aircraft safety.

The AHM benefit pool comprises the categories of short-term ones – e.g., visibility and understanding of a system/component deterioration enables to optimize the timing and the level of maintenance action to avoid operational disruptions, and long-term ones – e.g., prioritize, relying on AHM, the component restoration or repair for an economic optimum regarding maintenance cost.

When deciding on any particular AHM implementation, four questions will be asked from start by the airline considering it:

- Does AHM solve some of the issues the airline is faced with, and would it bring new opportunities to airline's operation?
- Is AHM technically feasible given an airline's organizational context and resources?
- Would AHM be a sustainable all around the clock operation for the airline to engage-in?
- What is the level of regulatory involvement needed for approval and oversight, and could that be secured by the stakeholders concerned?

Integrating the AHM basis in aircraft maintenance would unlock a broad range of benefits including higher productivity, decrease in maintenance turn times, lower costs, increased quality of the process and would deliver finally a better technical availability and enhanced dispatch reliability of the aircraft. Optimization of expensed resources on maintenance, considering labour and parts costs, would be better supported with AHM.

It shall be recognised, nevertheless, that tailoring AHM for implementation on a targeted platform aircraft must consider what is practical to implement versus attempting by default to apply AHM across the board for all equipment / components which are part of the aircraft configuration.

AHM suitability relies essentially on the measured condition of aircraft systems, equipment or components and their actual values of usage control parameters. Aircraft design configuration technical elements or airline operational procedures inability to deliver such information would rule out AHM applicability.

Based on the typical use of classic scheduled maintenance tasks for all aircraft systems (i.e., including propulsion systems) it is asserted that up to 90% of those tasks result in "no finding". This statistic would lead to the rather staggering conclusion that 90% of aircraft ground time for systems scheduled maintenance does not change the condition of the aircraft. Is that a waste of labour and material resources?
Additionally, it is asserted that more than 60% of the systems' functional failures (i.e., considering the total across all FECs) had no scheduled maintenance tasks selected through the typical maintenance program development process.
If such a high percentage persists despite the typical continuous improvement which a maintenance program undergoes through its associated reliability program, a rethinking of the whole approach to scheduled maintenance maybe necessary.

The potential to improve, through a robust implementation of AHM, the maintenance elements generating the above outcomes is a strong motivator for action.

Takeaway

- The willingness to optimize maintenance and shed ineffective use of labour and material resources resulted from the typical scheduled maintenance development is a strong incentive for AHM implementation.
- While there are up-front costs involved by AHM implementation, and all categories of stakeholders should assume their share, in general "the potential gain is worth the pain".
- Individual scrutiny for feasibility and sustainability should be applied to each AHM use case.
- The AHM future requires a high level of automation with data science developed processing analytics and algorithms running in an AI/ML setting made possible by AHM ready aircraft products and components.

4. Industry Action Steps

Like most developments in civil aviation, the exploration of AHM concept emerged from the aviation industry push to refine what and how to perform for aircraft maintenance once the asset commenced its service life.
While airlines are the ultimate enabler and user of the AHM implementation, hence their active role in building a coherent and fit for purpose sustainable construct, developing the AHM path could neither be envisaged as the effort of a single category of stakeholders (see considerations presented in section 3) nor outside of a wide-reaching harmonization of players.
IATA is at the forefront of advocating and pursuing such harmonization and several of the status relevant elements are summarized in sections 4 and 5.

This section is presenting some of the aviation industry debated elements and the successfully undertaken steps by entities participating in forums like the (IATA) Technical Operations Working Group (TOWG) / ex - Engineering and Maintenance Group (EMG), Maintenance Programs Industry Group (MPIG), and SAE International. Significant follow-up steps are needed and expected from the industry to improve and implement the AHM approach promoted by the forums mentioned above.

4.1. Recognizing Foundations

The AHM consists fundamentally in looping the aircraft health data through the process stages of **S**ense, **A**cquire, **T**ransfer, **A**nalyse and **A**ct (SATAA). The loop starts at the aircraft asset level with the physical sensing of one or more parameters and eventually ends at the aircraft asset level with the physical execution of a maintenance action.

Each one of the above stages is essential by itself and the AHM would be as robust as the weakest link of the SATAA chain. For each stage there is a primary role assumed by one stakeholder, but the success of that stage delivery will always depend on (at least one) secondary role fulfilled by another stakeholder (e.g., for **S** the aircraft configuration must physically have the sensing capability – thus, the DAH/OEM is a primary stakeholder – but that capability/part must be properly operated/maintained – thus, the Airline is a secondary stakeholder).

The degree of accuracy between the actual real condition/state of the asset and the one perceived or predicted is at the core of AHM and the agreement/disagreement of the two is reflected in the Uncertainty Matrix.

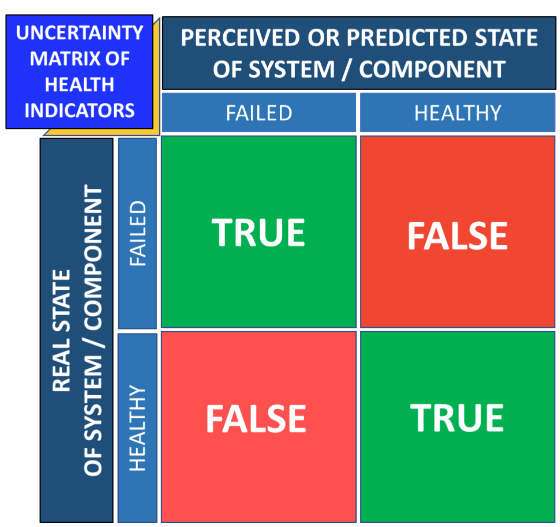

Figure 6: Uncertainty Matrix of Reality and Perception

Considering that a Health Indicator is positive when indicating a failure, the resulting errors in diagnosing the system/component emerge as a False Positive (when the healthy system is perceived as failed) or a False Negative (when the failed system is perceived as healthy) and would affect the predictive capability of AHM.
Parsing the uncertainty starts at the Sense (S) stage but extends to the Analyse (A) stage depending thus on the sensor as much as on the predicting algorithm or modelling of the system/component. Additionally, the intermediate phases of data transfer and storage could also inadvertently add uncertainty or anomalies through data-corruption elements; this must be addressed in the more general context of AHM implementation and includes relevant cybersecurity considerations.
The AHM with a robust predictive capability performance will generate a "TRUE" outcome subsequent to a successfully executed diagnostics (process which corresponds to "perceived") or prognostics (process which corresponds to "predicted").

AHM is relying on data reflecting the set of parameters of interest originating from the aircraft/systems.
The capability of processing the data and run it through algorithms which model the aircraft/systems supports the predictive performance of AHM bridging from "Normal" to "Remaining Useful Life (RUL)".

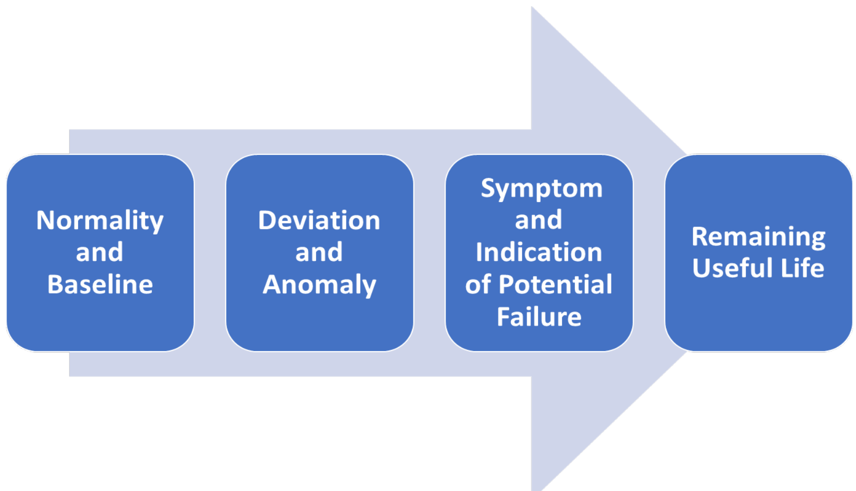

Figure 7: Steps Marking the Life-Cycle

Data generation and collection rates, latency of data availability and securing data quality (through appropriate procedures for data cleansing and wrangling) are all raising several specific issues which must be addressed in each one of the steps depicted above.

Some fundamental elements considered in the life cycle suggested process should be:

- There is a certain variability of normality in operation from one asset to the next; establishing the baseline of normal functioning must be calibrated for the asset and it may also drift with usage in service.
- Any excursion of a parameter from its baseline is a deviation but not all qualify as anomalies; the context of the deviation must be available for such a qualification to be made; having an anomaly detection system does not equate with having a diagnostics system.
- The aircraft/systems modelling would identify which anomalies are symptoms representative of an incipient failure and based on the potential to failure (P to F) the RUL could be predicted.

- The predicted RUL depends on the type of terminal event it accounts for (i.e., RUL to avoid damage; RUL for economic repairability; RUL for loss of function) and is always affected by an uncertainty distribution curve of its estimation.

The modelling of the aircraft/systems could be derived from engineering applied laws of physics or could be a data-driven model; each of the two has pros and cons and adoption of one or the other is conditional to specifics of the business case.

4.2. Developing Capabilities

The adoption of AHM should not be contemplated as a panacea to aircraft maintenance and it would always depend on the capabilities of the solution proposed. Pondering applicability and effectiveness for maintenance tasks will be the deciding criteria since measuring loss of performance, deterioration and condition with the aircraft in-service is sometimes technically challenging and it could be cost prohibitive.

The table below summarizes the general discussion regarding the evolution of AHM capability sophistication and its expected integration level with the aircraft asset. The table is an adapted partial excerpt from a more detailed matrix and classification criteria proposed by SAE International (check reference [12] in Appendix 2).

AHM Capability and Integration Levels						
	From NIL to HIGH →					
Description of Operational Approach	Service actions and findings linked to scheduled maintenance or resulting from Flight Deck Effect (FDE) info relayed by the Flight Crew (PIREP)	Maintenance Technicians gain added diagnostic insight using automated scanners to extract aircraft operating parameters and diagnostic codes	Maintenance Technicians gain real-time aircraft data via remote monitoring of aircraft to capture issues in a more comprehensive and timely available way	Flight Crew and Maintenance Technicians are provided with component health status (Green/Yellow/Red) before problem occurs; limited Condition-Based Maintenance	Flight Crew and Maintenance Technicians are provided with systems or aircraft level health indicators before problems occur and action is guided by reliable Remaining Useful Life (RUL) estimates . Condition-Based Maintenance (CBM)	Self-adaptive control and optimization to extend aircraft operation and enhance safety in presence of potential or actual failures
Aircraft Asset Capability	Only manual Diagnostic Tools and no Condition-Based services	On-Board Diagnostics available	On-Board and Remote Data available	Component-level Health Predictors	Aircraft-level Health Management	Aircraft Health Management integrated into aircraft controls
Essential Characteristic of AHM	Limited to On-Aircraft warning indicators	Enhanced Diagnostics using Scan Tools	Telematics providing Real-Time Data	Component-level Proactive Alerts	Integrated Aircraft Health Management	Self-Adaptive Aircraft Health Management

Figure 8: Integration and Capability Milestones

The accuracy of prediction is time-horizon dependent and only predicting with a reasonable variance would be of interest to aircraft maintenance practitioners.

When discussing the capability of enacting AHM, a clear understanding and distinction between the diagnostic phase (as representing a classification problem) and the prognostics/predictive phase (as representing a regression problem) should be made.
Although any reliable prediction is dependent on the accurate/detailed diagnostics which precedes it, the latter is not ensuring the existence of AHM in the true acceptance of the concept.

The role of modelling the component/system/aircraft to enable the in-service data-driven informed and credible prognostics is essential to AHM.

The DAH/OEM models with first principles basis already passed the certification scrutiny and were used to explore all corners of the aircraft flight envelope but they may not be available to operators.
Although the alternative of a post EIS data-driven model exists for the operators, we should note that data-driven / data-derived models are merely a representation of their training data set; addressing a novelty in the operation mode when triggered by airline business priorities (e.g., new flight profiles or flight environments) could be challenging such a model and its inherent extrapolation limits.

Another important feature of the AHM capability discussion is the level of automation.
This permeates each step of AHM: starting from parameter sensing and data collection, following with the in-flight real-time transmission to ground (rather than post landing download/transfer/access) continuing with the processing and maintenance decision support systems which involve AI and ML techniques.

Automation is in fact the condition for viable scalability of AHM; ensuring a reliable, unaltered, and secure data flow compliant with cybersecurity standards is paramount to the integrity and credibility of the AHM program. Given the big data which the AHM handles and relies on, extended automation is the only way forward and a complete automation is very likely to follow.

4.3. Creating Standards

The body of standardization work with AHM significance comprises on one hand provisions focused directly on the design and integration of its functional elements as well as their subsequent operational use and on the other hand provisions indirectly touching on features met by it.
In one category the bar is set by MPIG and SAE while the other category benefits from deliveries of RTCA and EUROCAE.
While MPIG is engaged in drafting a future MSG-X framework where a transformative approach will consider the IAHM path from the initial stages of designing a new aircraft type scheduled maintenance program, the present MSG-3 methodology is already moving to accommodate AHM driven elements applicable to today's in-service fleet.

Given its impact on the aircraft maintenance activity practitioners at the aircraft in-service level, which is where AHM should make the difference, the synthesis of what is entailed by opening MSG-3 to AHM is mentioned below (check references [4], [5] in Appendix 2 for more details).

The traditional MSG-3 logic flow which consists of two levels of analysis of the aircraft systems to select an applicable and effective maintenance task is enhanced with a third level, entirely optional, to be applied for identifying an alternate with AHM basis in eligible cases resulted from the previous logic flow level.

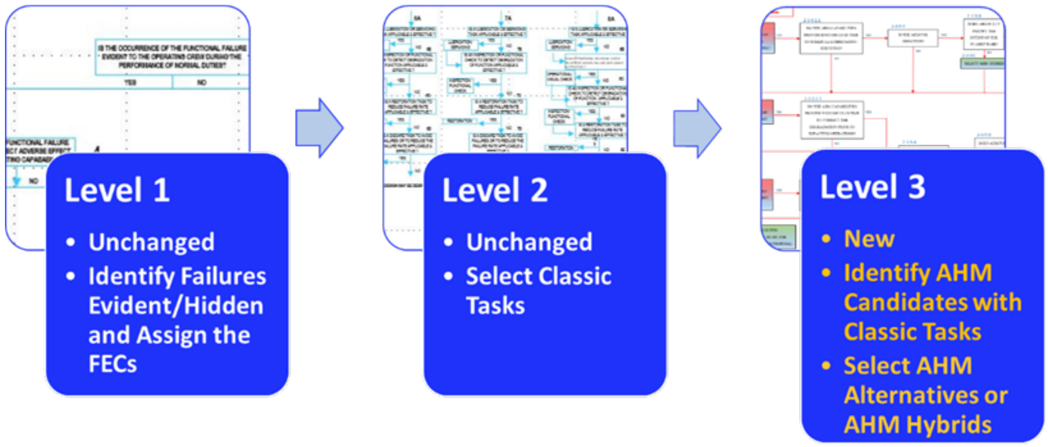

Figure 9: Levels of Analysis in MSG-3 Logic

To enable the execution of analysis at Level 3 the amount of additional work involves extensive preparatory material to address AHM linked details, parameters, interfaces, functional description, P to F and software certification elements. The systems/components part of the aircraft certificated configuration added for AHM purposes generate themselves the dedicated MSI analysis.
The possible outcomes could lead to a full replacement of the classic task (in the case of the "alternative" selection) or to a partial replacement of the classic task (in the case of "hybrid" selection) or to the confirmation that no applicable and effective replacement would be possible on AHM basis.

The above resumes the discussion of what is conducive in the end to the MRBR with its potential enhancement considering AHM capabilities.

It is important to note that whereby the AHM path may not be found applicable and effective within the MRBR framework, the stakeholder (DAH) may still develop and offer AHM options outside the MRBR. As part of the AMP the airline operator may decide to use such options or even pursue to develop them.

The SAE Aerospace Council Technical Committees with AHM related focus (i.e. AISCSHM for aerospace structures, HM-1 for systems and E-32 for propulsion) released several materials to address standardized metrics, recommended practices and design requirements linked to the design approach and integration of vehicle health management systems (see references [7] to [12] in Appendix 2).

Takeaway

- Aviation industry started its evolution towards AHM capability and integration, and is envisaging a breakthrough in this journey by future pervasive availability of remote data and use of health-ready components/systems to enable reliable prognosis and prediction of their RUL.

- The industry incremental transition to AHM will be conducive to partial validation of recommended practices and standards through legacy fleet retrofits before a new clean-sheet design of a complete AHM-ready aircraft type/model will emerge.

5. Regulatory Balancing Act

The role of Aviation Regulators in the AHM construct is covering all the typical aviation industry certification, authorization, and oversight activities which ensure the operation of a safe and reliable civil aviation ecosystem. The opportunity which Regulators have for adopting an effective risk-based framework and guidance for AHM implementation is dependent on the timely harmonization between regulatory systems and the industry stakeholders leading the AHM evolution.

The involvement of Academia and Research Institutions in defining the new path to aircraft maintenance should not be neglected and it is encouraging to notice active research grants aimed to building such necessary bridges for an effective Regulatory action (see reference [16] in Appendix 2).

IATA is at the forefront of advocating and pursuing such harmonization and, given its status of non-commercial and impartial airline industry association, is an active partner for AHM focused proceedings conducted by aviation regulatory bodies present in the International Maintenance Review Board Policy Board (IMRBPB), ICAO Airworthiness Panel (AIRP) and Maintenance Management Team (MMT).

This section is presenting some of the regulatory debated elements and highlights considerations which the Regulators are called to ponder on in a timely manner as part of their AHM focused work with and provision of guidance to industry entities.

5.1. Addressing Necessity

Integration of AHM within the aircraft maintenance activity must have direct or indirect approval/acceptance by the competent aviation authorities certifying /authorizing / licensing and overseeing the products, organizations, personnel, processes and procedures involved.

While the required effective correlation between the typical “Certification / Initial Airworthiness” and “Flight Standards / Continuing Airworthiness” parts of the regulatory house is not a novelty facing aviation authorities, the details of a commensurate and risk-based action with AHM focus are sometimes challenging the customary conventions.
This brings the opportunity of a data driven questioning each time a legacy approach to aircraft maintenance would be prone to AHM based evolution.
Providing the SATAA core of AHM with some specific additional regulatory boundaries and guidance is an incremental process for which the successful previous aviation exploit of developing and implementing ETOPS/EDTO is a valuable procedural precedent.

The AHM construct is encompassing many widely recognized initiatives and functioning programs like: Aircraft Health Monitoring, Engine Health Monitoring, Structural Health Monitoring, Aircraft Condition Monitoring System, Engine Condition Monitoring, Rotorcraft Health and Usage Monitoring System.
This legacy of achievements is spanning over a few decades and that should facilitate a robust and timely differentiation between added value regulatory intervention and ineffective or over-bureaucratic regulatory red tape.

A true AHM implementation involves crediting the right actors for executing decisional mechanisms that support the aircraft safe operation as effective as the legacy processes and procedures which they constitute an alternative to.

5.2. Solving the AHM Puzzle

There are numerous questions to answer in the context of defining and implementing the AHM path and they concern both the readiness of the present regulatory construct for the approach in general and options for addressing the individual solutions in particular.

It is important to raise the issues and ask the questions to incite the exploratory work with the Regulators even when acknowledged that a definitive answer would not be practicable at the level of "one size fits all" generic discussion.

The issues are mainly emerging from reviews and analysis of:

- Suitability and readiness of the legacy regulation for certification and continued airworthiness regarding AHM implications, including the performant and secure data acquisition-transmission-analysis-storage.

- Eligibility or non-suitability of the AHM sequence to supplement, provide alternatives to or supersede partially or completely the aircraft maintenance tasks.

- Consequences/impact of AHM on allocation of initial and continuing airworthiness responsibilities between the DAH / OEM and the Airline Operator (including Engineering/CAMO and Maintenance/MRO related activities).

- The architecture of the AHM approach and its on-board / off-board aircraft partitioning.

- Building AHM with resources (i.e., products, services, personnel) residing within or external to aircraft Technical Operations organizational layers (e.g., Engineering, Maintenance and Supply Chain/Material Management) and even outside of customary aviation domain organizational layers.

- Addressing the transfer/portability of the aircraft asset maintenance between an AHM solution and a non-AHM (legacy) one: both in a temporary scenario requiring continuity/recovery of maintenance operations (like a short-time unavailability of the AHM solution employed by the operator) and in a permanent transition (like an aircraft asset transfer to another airline) from an "AHM operator" to a "non-AHM" one.

Figure 10: Pieces of the Puzzle

Depending on the acceptance of AHM as an "evolutionary" step or viewing it as a "revolutionary" change in aircraft maintenance, a series of AHM specific or technical aviation broader subjects enter the regulatory focused discussion spectrum.

Airline/Operator or DAH/OEM discussion is an area of recognition that, while there are independent individual stakeholder attributes in AHM, the sought outcome can be achieved only by discharging the obligations of both categories mentioned; the airline could pursue an AHM approach only to a limited extent if the aircraft structure/system/component is not designed and manufactured at a certain "AHM ready" level; the transfer of AHM work execution between the two stakeholders' camps could take place but regulatory responsibility transfer needs clarification.

On-Board or Off-Board debate is due to the limited integration by the aircraft platform of the needed data processing and analysis which leads to the decision on the maintenance action; while AHM use of certified aircraft (i.e. on-board) resources would be a somewhat trivial step since "green-light" was given to the entire aircraft configuration via the aircraft certification process, the typical SATAA is still involving today major ground-based contribution in advance of the maintenance action itself; future technical developments may shift much of that and regulatory provisions should accommodate all scenarios.

Qualify or Certify discussion acknowledges that, while many of the technical elements supporting the data collection and analysis are part of aircraft configuration and are certified as such via the aircraft certification process, the data analysis may be the result of non-aviation traditional resources which lack an aviation certification; ground-based hardware and software involved in data analysis is in general "imported" to aviation; more parts of the maintenance action decision making reside with data analysts who are not (and should not be) necessarily certified/licensed maintenance personnel.

Aviation Source or COTS Source is linked to the previous theme by recognizing that, while there may be a need of verifiable status and traceability elements, a form of "qualification" construct should suffice and be accepted by Regulators; there are clear cases when a risk-based rationale would indicate that a strict aviation "certification" process is not justified and its replacement with a "qualification" commensurate to the case would deliver the same safety benefits.

Relying on AHM implementation for airworthiness determinations or maintenance program adjustments requires regulatory authority acceptance and authorization. The required maintenance credits for the related AHM parts would be integral to the process. If operators use data for monitoring self-imposed tasks that have no influence on airworthiness, such express authorization may not be required.

For example, it is envisioned that for US-based operators, the FAA will grant maintenance program AHM authorization through Ops Spec D302 "Integrated Aircraft Health Management (IAHM) Program". The provision is mentioned in the Advisory Circular (AC) 43-218 "Operational Authorization of Integrated Aircraft Health Management Systems". This publication sanctioned by the FAA, may provide a template for other national regulatory authorities to emulate.

Another example of a recent development with relevance to AHM path is the FAA (AIR-621, AED) released generic "Issue Paper on Qualification of a Structural Health Monitoring System for Detection of Damage in Structure" available to interested applicants in connection with AC 25.571-1D.

Examples of regulatory recognition of AHM precursors relevant to the AMP exist also in the form of references to Aircraft Health Monitoring and Engine Health Monitoring in the Part-M and Part-CAMO issued by EASA.

The regulatory issues linked to AHM should be considered in a timely manner by Civil Aviation Authorities. Such entities must instigate the establishment of an AHM approach governed by uniform ICAO-originated standards to eliminate variability and ensure harmonization and consistency among national rulemaking, processes, procedures, and regulation mechanisms.

While the aviation regulatory provisions are not called upon governing the commercial aspects of the developments they regulate, and nor should they attempt doing that, there are contextual elements regarding ownership and intellectual propriety rights regarding data produced and exchanged for AHM purposes as well as the regarding algorithms to process that data.

The Civil Aviation Authorities should be aware of such aspects and consider if they are recognized and agreed to in a way that would not impede on the implementation and accountabilities of AHM stakeholders.

5.3. Opening Regulation to Impending Reality

The latest revisions of International MRB Policy Standard (IMPS, Issue 02, Oct 2022) and Operator/Manufacturer Scheduled Maintenance (MSG-3, Rev 2022.1) documents incorporate a mechanism by which MRBR content could capture AHM capabilities of the aircraft type it supports.
While this constitutes a remarkable step grounded in a "crawl-walk-run" pragmatic view on AHM integration in the daily dealings of aircraft maintenance, it is articulated as an addition to the existing structure of analysis (see Figure 9) and consequently it is limited by the present view on initiating the aircraft scheduled maintenance program.

The opportunity to evolve towards a novel structural basis, in which the MRBR document will be generated following the ISC-MRB duopoly work during certification and operational life of future aircraft types, is undoubtedly here. Seizing this opportunity implies, interalia, robust consideration of the following:

- Unlocking a "maintenance continuum" through the 24/7 monitoring of the aircraft should not be perceived as or become the potential for increasing maintenance burden on operators, but rather be the tool to secure unprecedent level of safe technical availability of the aircraft asset; on long-run, this AHM sustainability condition requires that CAA – AOC Holder – TC Holder act synchronously to elevate the aviation ecosystem to a new aircraft maintenance paradigm.

- A future aircraft "clean-sheet-design" would likely have the technical maturity to directly embrace nose-to-tail CBM product capabilities; such a scenario would make today's MSG-3 "classic maintenance tasks" approach and their Level1/2 supporting analysis irrelevant in their present format; additionally, and as a direct consequence, the AHM related Level3 would become untenable as presently adopted.

- The traditional understanding of "operating crew during the performance of normal duties" as the flight crew on-board the aircraft, becomes a debatable criterion to characterize the functional failure as evident or hidden for the future autonomous (i.e., uncrewed) aircraft; remotely operating crew for RPAS would have a different set of "normal duties" compared to today's flight crew; additional, the AHM would make a functional failure (actual or impending) evident to technical personnel in charge with managing the aircraft health.

- Central to the concept of aircraft certification is the classification of failure conditions (Minor-Major-Hazardous-Catastrophic) by assessing the severity of the effects of failure on aircraft, occupants, and flight crew. The consideration of effects on environmental integrity and ecological damage, including people on-ground, may become significantly important for future certification and operation (e.g., control of aircraft emissions; Parts Departing Aircraft); such extended considerations may add to the applicability angle to the AHM implementation potential benefits.

- Scalability of AHM to global aircraft fleets relies on major roles for AI and ML; in this context defining the AI certification specifics for AHM (if any) is fundamentally important and the first steps undertaken by Regulators (see reference [17] in Appendix 2) need a vigorous and timely continuation.

5.4. Practical Considerations

There are several practical questions and considerations relevant to the search of comprehensive AHM regulatory provisions having pervasive performance-based flexibility that would nurture and not stifle the aviation progress in this field.

Can AHM be applied today?
While the answer is "yes", certain items should be considered:

- Cooperation of the operator with the regulatory authority and the OEM should be envisaged on a case-by-case basis; the use of AHM for the same specific system/component may involve different regulatory oversight for different operators.

- Creating an AHM path to address non-safety related tasks will be less contentious and have a higher timely approval rate compared to safety related tasks.

Will a 3rd party provider recognize and credit the AHM capability?
In answering there are several elements to consider:

- The service provider has made a commitment given a known MTBR/MTBF rate. A component removed earlier (under the AHM system advice/alert) will result in NFF as the part will likely be deemed serviceable when tested.

- Earlier removal of parts will result in providing spare part (inventory) levels to support the early removals with additional levels of investment for spare parts earlier in various commercial full support programs.

- Trust on the algorithms supporting AHM by all parties. A provider needs to be convinced that predictions are accurate and will not result in additional costs.

- Reasoning of early removal based on AHM. Repair providers should be informed on any monitored parameters that led to an early removal by AHM. This will establish the logic behind an early removal of a part and promote the trust between the parties involved.

- Substantiation that the early removal of a part due to AHM results in lower costs to repair the part. The hypothesis is that a component operated to failure will have significant higher costs to repair and overhaul vs a part that is removed earlier (and most likely would have not encountered any major or catastrophic failure as when operated to fail).

With all the above, we should point out that:

- Spare parts levels may have to be provided earlier in a program to support AHM + early removals.

- Repair costs from early removals should be lower than when components "fly-to-fail" (when catastrophic results may occur).
- Trust needs to be built between all the various parties involved in an AHM solution.

Will AHM need to be certified?

Currently AHM can be used on a case-by-case basis for one system by one operator, one OEM and one authority. Any deviation will need a similar approval/acceptance process. In the future, we envision that AHM capable aircraft will allow for a simple process to enable the function and ensure a smooth transition between AHM and the traditional approach.

IATA is of the opinion that when AHM data are used already to feed various aircraft systems on board, there should be no need to recertify such systems. In cases of data not used by any aircraft system, maybe further discussion and evaluation should be implemented to ensure proper use of AHM.

What happens if AHM triggers a removal in a line ops environment? Will the airline have the time to react and avoid a delay/cancellation?

Certain thresholds of monitored parameter limitations should be established to avoid certain reactions that may lead to disruption of operations following an AHM indication.

Can AHM parameters and outputs be used by MRO shops in certain repairs of parts?

The vision is that the reasoning behind the early (i.e., AHM based) component removal will be used by the MRO shop to develop certain repairs for each case behind the early removal. Linking the "reason to remove" with the "repair" will allow faster turnaround times.

How can AHM use cases be disseminated?

For existing aircraft platforms and because AHM is not institutionalized, an industry sharing site would assist all industry stakeholders to take advantage of these new technologies.

Various tools may allow sharing of experiences that almost always will need to involve the collaboration between operators and OEMs (while MROs may also play a significant role) under the auspices of authorities.

Parties involved may evaluate how to share their experiences while protecting any potential IP rights.

Takeaway

- A risk-based approach should timely drive the rationale to determine if AHM specific regulatory provisions need to be established. Regulators should be transparent and closely engage with Aviation Industry stakeholders to validate the need and to draft such provisions, as applicable.
- Regulatory guidance material is needed by AHM actors to drive their effort in a harmonized and level playing field across all aviation jurisdictions. Regulators should closely cooperate with Aviation Industry stakeholders when drafting such guidance.

- The development pace of the AHM path by Industry should instil a sense of urgency for Regulators in addressing the above.

- The future place of AHM in aircraft certification and maintenance of next generation of aircraft may require a thorough revision of the present-day regulations and standards. Regulatory provisions must enable the novel technologies in aviation to realize their full potential.

6. AHM Roadmap

The AHM concept surpassed the phase of its brainstorming beginnings and, without denying the "in-flux" status for some of its features, is reaching a maturity level justifying the dynamics of implementation phase.
This section presents several considerations relevant to mapping the implementation road of AHM.

6.1. Starting Points

The aviation industry has enacted in the last decades several successful aircraft structure and systems monitoring programs which are considered, in a significant measure, precursors of the integrated AHM pursued today.

Monitoring of physical parameters like pressures, temperatures, vibration, mechanical loads, electric loads/currents in a time series data flow which covers transitory as well as stabilized operation of aircraft systems/components is enabling operators to estimate degradation or detect a fault before a functional failure would generate operational disruptions to require unscheduled maintenance corrective action.

The main purpose of such monitoring programs was to enable a functional mechanism of notifications and alerts which were tailored for triggering actions to improve the operator dispatch reliability or optimize the cost of maintenance and repairs.
By far and large they were not used as the sole source to determine aircraft system condition for safe operation and its compliance with type design specifications. Such airworthiness determination was not permitted in the absence of simultaneously using another accepted practice as well (e.g., visual check or functional check).

There is however a limited number of one-off cases when aircraft health monitoring techniques were given the maintenance credit required to alter/replace a traditional industry-accepted practice.

Nevertheless, the sizeable experience gathered by exercising the SATAA specific steps in the type of programs mentioned above (see also section 5) is of significant transferable value to the integrated AHM model.

Starting from the basis of a sufficiently mature AHM foundation in both technological feasibility dimension and economic sustainability dimension, we should consider the approach of:

- an incremental iterative development which could be accommodated by MSG revisions prioritizing the preservation of exiting steps in logic analysis and building only the Minimum Viable Product (MVP) for AHM addition;
- a transformative review of the MSG framework (as already considered by MPIG in exploratory studies undertaken by its MSG-X dedicated Task Force).

Realistic accounting of the aircraft type certification cycle and operational life expectancy of the typical aircraft asset would strongly indicate that the two approaches should rather coexist as AHM development strategies; such coexistence would span over the next two decades as a minimum.

The implementation potential of AHM in maintenance of the aircraft global fleet, understood as the percentage of total in-service fleet which integrates at least some level of CBM in the applicable AMPs, could be realistically estimated to reach a single-digit percentage around mid of this decade and grow to a double-digit percentage by end of the decade.

Figure 11: Coexisting Strategic Paths

However, a large aircraft type operating in commercial passenger service, under a maintenance program entirely built on the CBM concept operationalized through AHM, would likely emerge only as a new aircraft concept designed from scratch with an integrated AHM system; such outcome implies concurrence of all main stakeholders and reaching the required level of comfort by OEMs, Regulators and Airlines will take aviation beyond the first third horizon of 21st century.

6.2. Validation Gates and Criteria

The validation gates and criteria must be set considering the requirements for design approval (residing with the DAH) and the operational authorization (residing with the Airline/Operator), all in a manner acceptable to the Regulator.

In meeting both categories of requirements it should be made clear that the definition of the set of requirements in each category should be tailored to the content and complexity of the AHM implementation envisaged.

A typical example of such tailoring would be the use for AHM purpose of data and information identical in origin(source)/form/format with the one already employed in the control and oversight (including the FDE) of the aircraft system/equipment; this was already covered by certification of the aircraft design and, thus, additional design approval expectation based on its off-aircraft use for AHM could be questioned by the applicant.

Obviously that any AHM dedicated system/component which is part of the aircraft certificated configuration will be submitted to the aircraft certification process specifics to the extent applicable to the said AHM dedicated system/component.

The importance of an incremental progress towards establishing the AHM cannot be underestimated.
This incremental approach is particularly important for the operational authorization as well as the AHM induction of "legacy aircraft types".

A clean-sheet design aircraft would give the opportunity of integrating the AHM readiness in the initially certificated configuration.

6.3. Pursuing Implementation

The considerations presented in this section sketch a roadmap of what a successful implementation of AHM in the airline industry should entail in the short, medium, and long-time horizon.

AHM Successful Implementation Steps

Prerequisites	Maturity Timeline	Milestones
➢ Established regulatory criteria for authorizing operators for AHM use as alternative to maintenance tasks ➢ Established industry standards for inclusion of AHM alternatives in aircraft maintenance programs ➢ OEM established policy and procedures with industry and regulatory acceptance for creating AHM alternatives to maintenance tasks ➢ Airline built cases of readiness (infrastructure & personnel) to execute AHM alternatives to maintenance tasks	Short Term	➢ OEMs launching with preferred operators "one-off" pilot tests of AHM alternative to non-safety tasks for selected aircraft type/engine/system ➢ Operators using AHM in maintenance tasks which are airline "self-induced" and have no influence on airworthiness ➢ Several regulatory auhorities are adopting provisions and guidance for AHM use in aircraft maintenance
➢ Regulatory readiness to aprove and oversee transition of AHM alternatives scope from non-safety to safety related and airworthiness determination tasks ➢ Industry availability and use of consistently proven robust modeling (data or primary principles driven) of aircraft / systems / components to enable AHM based predictive maintenance action ➢ Significant number of airlines with required capabilities (both technical & business) to implement all non-aircraft based links of the AHM chain	Medium Term	➢ OEMs providing to any eligible operator of the aircraft type/model the AHM alternative & support limited and tailored to non-safety tasks ➢ OEMs launching "one-off" pilot tests of AHM alternative to safety related maintenance tasks ➢ Regulatory acceptance of operators' aircraft maintenance programs incorporting AHM alternatives to non-safety related tasks
➢ Succesful completion with regulatory endorsement of multiple IAHM pilot projects for aircraft systems & components ➢ Robust IAHM related regulatory base for design approval and operational authorization in several national regulations with at least one leading high profile authority involved (e.g. EASA, FAA) ➢ Aircraft and engine OEMs enacting IAHM capabilities and cascading them into business requirements to first tier providers ➢ Several major airlines committed to and prioritizing the IAHM operation	Long Term	➢ New TC for "clean sheet design" aircraft with complete IAHM capability ➢ Aircraft launch operator with complete IAHM reliance for the type fleet ops ➢ OEMs providing the IAHM alternative & support to any eligible operator of the aircraft type/model ➢ Airline industry wide acceptance of & engagement in IAHM ops with portable processes & procedures

Figure 12: Steps to Take for AHM Implementation

While each timing stage comprises identifiable prerequisites, which are a must in order to access the milestone deliveries, quantifying the timeline of each one of the three time-horizons is inherently a challenging forecast.

Such challenge is additionally compounded by the context in which the aviation industry in general, and the airline world in particular, started the 2020s decade with two years of unprecedented crisis during which existential priorities took their toll on AHM envisaged steps by each stakeholder category and individual entity.

The good news would be that completing the short-term prerequisites is almost accomplished and checking the respective stage milestone achievements was already started by AHM early adopters in each stakeholder category.

It is worth reminding some successful use cases and completed actions focused on implementation of AHM elements:

- Airline identification and prediction for aircraft defect management performed in-house or with OEM support (e.g. bleed air valves, flap skew sensors, filter condition monitoring, hydraulic level monitoring)
- AMOC issued to AD provisions on the basis of AHM procedures, with appropriate end to end definition (including constraints, mitigating measures and analysis algorithm) to replace fixed periodicity requirements for SDI maintenance action (e.g., engine HPT borescope inspection, pressure bulkhead NDT)
- Proposal of revised PPH to support the AHM implementation in the aircraft type MRBR per MSG-3 Rev 2022.1
- Dynamics of incorporating user's lessons learnt to finely tune the Level 3 logic flow (see IMRBPB adoption in May 2023 of IP211 "Level 3 Analysis – AHM Effectiveness Determination")
- First revision of the MRBR of a large commercial aircraft to include AHM tasks (revision released Aug 2023)

While AHM is mainly contemplated as an alternative at this time, its addressing could take place on applicability basis at operator level via customized solutions or at the fleet-wide global level via appropriate DAH involvement; with the former having the potential of a more agile time-response to adoption of AHM, the latter will always be a guarantee for the AHM adoption coverage.

Takeaway

- Airlines have a significant experience with AHM type of actions scoped to improve their individual aircraft operational reliability or to optimize the cost of individual aircraft maintenance and repairs.
- Incremental steps in adopting AHM should be timely progressed to the benefit of all stakeholders before the advent of the next clean-sheet design aircraft.
- The active sharing of experience and examples between AHM stakeholders should be incessantly pursued in all eligible fora with the view of a timely progress in this field benefitting Industry and Regulators alike to fast-track the implementation of AHM.

7. Conclusions

A significant body of knowledge and experience emerged from years of aircraft health and trend monitoring used to enhance aircraft dispatch reliability (DR) rates. The span of successful use cases, encompassing aircraft systems (including propulsion systems) and aircraft structure, constitutes a solid basis and strong motivator for developing the AHM path. This would be an alternative applicable to many of the aircraft maintenance tasks and lead to a change in the typical form and significance of executed maintenance action content, thresholds and periodicity.

Introduction of the AHM option alternative, as an opportunity and not as an obligation, is needed to attain the scale of economics potentially offered by the concept of aircraft "Maintenance of Tomorrow" in which true aircraft Condition-Based Maintenance (CBM) would rely on the implementation of both predictive and prescriptive analytics capabilities.

There are aircraft certification aspects and continued airworthiness elements which must be addressed to fully realize the attainable benefits of AHM. They require a phased and simultaneous timely evolution of the deliverables by aviation industry and regulatory entities alike. This can be achieved with a prompt recognition of and commitment to a realistic sense of urgency by all stakeholders involved in the AHM related work.

Providing an AHM option in MSG-3 methodology commenced with Rev 2022.1, and should boost the timely motivation for implementation of new policies, derivative procedures, and technology benefiting all air transport industry stakeholders. This may precipitate a methodological upgrade establishing the basis of a future MSG-X task development methodology construct.

Using AHM data and analysis capabilities to define alternative means to accomplish a "classic" preventive maintenance task is the next practicable opportunity to further enhance aircraft availability. The approach would also require an appropriately revised set of criteria in the traditional area of No Fault Found (NFF) categorization used by maintenance providers, since operators would employ AHM prediction to remove aircraft components prior to their actual in-service failure.

The AHM approach impact on the technical operation's commercial practices and supply chains must be considered as well. Such considerations will potentially reshape the terms of performance agreements both at the product (e.g., aircraft, engines) and component levels, and also trigger a reconsideration of how spare parts inventories are defined and maintained to support aircraft fleet operations. The regular use of AHM may require that supply chain activity governing framework, as defined in Product Support and Assurance Agreement (PSAA), Supplier Product Support Agreement (SPSA), Supplier Support Conditions (SSC) documents or equivalent, is adequately revised.

Benefiting from automation prone sequences of AHM, including prognostics' active reliance on artificial intelligence (AI) and machine learning (ML) techniques coupled with digital twinning of aircraft assets, constitute a priority for viably achieving AHM scalability. The necessary level of digital transformation inherently requires addressing the data ownership and cybersecurity concerns; they are altogether topics of a different important discussion.

Appendix 1 – Abbreviations

Abbreviation	Source Terminology
AD	Airworthiness Directive
AED	Aircraft Evaluation Division (FAA)
AHM	Aircraft Health Management, Aircraft Health Monitoring
AI	Artificial Intelligence
AIR	Aircraft Certification Service (FAA)
AIRP	Airworthiness Panel (ICAO)
AISCSHM	Aerospace Industry Steering Committee on Structural Health Monitoring
AMOC	Alternative Means Of Compliance
AMP	Aircraft Maintenance Program
CAMO	Continuing Airworthiness Management Organization
CBM	Condition Based Maintenance
CDL	Configuration Deviation List
CM	Condition Monitoring
COTS	Commercial (available) Off-The-Shelf
DAH	Design Approval Holder
DR	Dispatch Reliability
EASA	European Union Aviation Safety Agency
EDTO	Extended Diversion Time Operations
EIS	Entry Into Service
EMG	Engineering and Maintenance Group (IATA; it became TOWG as of 2021)
ETOPS	Extended Range Twin-Engine Operations
EUROCAE	European Organisation for Civil Aviation Equipment
FAA	Federal Aviation Administration
FDE	Flight-Deck Effect
FEC	Failure Effect Category
FRACAS	Failure Reporting, Analysis and Corrective Action System
FTOPS	Flight and Technical Operations (IATA)
HPT	High Pressure Turbine
HT	Hard Time
IATA	International Air Transport Association
IAHM	Integrated Aircraft Health Management
ICAO	International Civil Aviation Organization
IMRBPB	International Maintenance Review Board Policy Board
IP	Issue Paper / Intellectual Propriety
KPI	Key Performance Indicator

LLP	Life Limited Part
MEL	Minimum Equipment List
ML	Machine Learning
MMT	Maintenance Management Team
MPIG	Maintenance Program Industry Group
MRBR	Maintenance Review Board Report
MREPS	Maintenance Reports
MRO	Maintenance, Repair and Overhaul
MSI	Maintenance Significant Item
MSG	Maintenance Steering Group
MVP	Minimum Viable Product
NDT	Non-Destructive Test
NFF	No Fault Found
OC	On Condition
OEM	Original Equipment Manufacturer
PIREPS	Pilot Reports
PPH	Policy and Procedures Handbook
PSSA	Product Support and Assurance Agreement
P to F	Potential to Failure
RTCA	(ex) Radio Technical Comission for Aeronautics
RUL	Remaining Useful Life
SAE (International)	(ex) Society of Automotive Engineers
SATAA	Sense, Acquire, Transfer, Analyze and Act
SDI	Special Detailed Inspection
SPSA	Supplier Product Support Agreement
SSC	Supplier Support Conditions
TC	Type Certificate
TOWG	Technical Operations Working Group (IATA; former EMG)
UBL	Usage-Based Lifing

Appendix 2 - Suggested Readings

[1] "Aircraft Operational Availability" – 2nd Edition, 2022 – International Air Transport Association (IATA)

[2] Proceedings of "5th Paperless Aircraft Operations and RFID Conference" – 2018 – IATA

[3] Proceedings of "14th Maintenance Cost Conference" – 2018 – IATA

[4] "ATA MSG-3 Operator/Manufacturer Scheduled Maintenance Vol 1 – Fixed Wing Aircraft" – Revision 2022.1- Airlines for America

[5] "IP180 - Aircraft Health Monitoring Integration in MSG-3" – 2018 – International MRB Policy Board

[6] "AC 43-218 - Operational Authorization of Integrated Aircraft Health Management Systems" – 2022 - FAA

[7] "ARP6803 - IVHM Concepts, Technology and Implementation Overview" – 2016 – SAE International

[8] "ARP5987 - A Process for Utilizing Aerospace Propulsion Health Management Systems for Maintenance Credit" – 2018 - SAE International

[9] "ARP6461 - Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft" – Rev A - 2021 – SAE International

[10]"ARP6407 – IVHM Design Guidelines" – 2019 - SAE International

[11]"ARP6883 – Guidelines for Writing IVHM Requirements for Aerospace Systems" – 2019 - SAE International

[12] "JA6268 – Design & Run-Time Information Exchange for Health-Ready Components" – 2023 – SAE International

[13] "Aerospace Predictive Maintenance: Fundamental Concepts" – Charles E. Dibsdale – SAE International 2020

[14] "Reliability-centred Maintenance" – Second Edition, 1997 – John Moubray

[15] "Aeronautical Design Standard Handbook ADS-79E-HDBK - Condition Based Maintenance for US Army Aircraft" – Dec 2015

[16] "Real-time Condition-based Maintenance for Adaptive Aircraft Maintenance Planning (ReMAP)" – European Comission EU Horizon 2020 Programme: Societal Challenges – Smart, Green and Integrated Transport

[17]"Artificial Intelligence Roadmap 2.0, Human-centric approach to AI in aviation" – 2023 - EASA

Appendix 3 - Acknowledgements

This document is an update to the White Paper released by IATA in Feb 2022 and it incorporates some perspectives which surfaced during the last 20 months of re-energized involvement from main players in the AHM arena.
The overall content reflects elements encountered during the IATA Flight and Technical Operations (FTO) engagement on the AHM subject since late 2015.

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- Maintenance Programs Industry Group (MPIG);
- SAE Committees for:
  - Aerospace Propulsion Systems Health Management,
  - Integrated Vehicle Health Management,
  - Aerospace Industry Steering on Structural Health;
- International MRB Policy Board (IMRBPB);
- Maintenance Management Team (MMT), and
- ICAO Airworthiness Panel

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