

# Strategic action plan for future CBM adoption



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# Challenges and possible solutions

Condition-based Maintenance is a strategy that follows a process involving the sensing of a given asset, the acquisition and transmission of the data collected with the sensing, the analysis of this data into health diagnostics and prognostics, and the definition of a consequence maintenance plan. This section discusses the challenges and possible solutions for each of these four steps. This discussion is then complemented by looking at the challenges of validating the benefits of CBM, educational needs, the need to build trust and cooperation among stakeholders to develop the CBM concept successfully, and changing regulations and standards. The challenges related to the aviation green transition are discussed in the last sub-section.

## Sensing technology

The generation of data from airborne sensing is critical in a health management system. A CBM strategy makes use of onboard sensors to continuously collect information about the performance and environmental conditions to which an aircraft system or structural element is subjected during aircraft operations. A reliable application of the CBM strategy will depend heavily on the reliability of the sensors being used. It is essential to ensure that the sensors will function steadily for the lifetime of the monitored component. It is recognised that the impact of operational environmental conditions, such as temperature, humidity and, in particular, vibration, can affect the reliability of sensors. Interruption to the generation and transmission of sensor signals can compromise operator awareness of component health degradation. Sensors may fail for reasons other than monitoring of structural systems or elements, and sensor condition monitoring is another health management challenge.

Future aircraft design for maintenance must consider the reliability of sensing technology. In particular, resilient sensing systems need to be considered. Reliability testing and self-diagnostic procedures, such as those considered in ReMAP (deliverable D3.3) should be proposed together with the sensing technology. Anyhow, a recovery plan should be considered in case of sensor failure, reverting to classical maintenance procedures if necessary. The cost of such a recovery (e.g., immediate inspection upon a sensor failure) should be considered while determining if a certain CBM application is beneficial. This means that the sensing technology's reliability will largely impact the feasibility of a CBM application.



Another challenge in relation to detection technology is defining the right technology to use. From the practical experience of the campaign and discussion with other ReMAP partners involved in the Structural Health Management (SHM) test campaign, it became clear that no single detection technology is suitable to address all health management challenges. This is particularly the case for SHM, for which different technology must be considered if the complete SHM hierarchy, i.e. anomaly detection, damage location, damage sizing, and severity analysis, is to be addressed. The sensors to be used and the technology selected will depend on the purpose of the CBM application, the type of component being monitored, the operational conditions to which each component is exposed, and the type of failure mode expected. In fact, depending on the business case and easiness of detecting structural damage, it is believed that 'traditional' periodic NDT checks, like eddy-current surveys, can be the best approach to monitor some structural elements' health state regularly.

It is considered by the industry that wireless sensors do not yet offer a reasonable solution for aircraft health management. Despite being a good solution in terms of the added weight to the aircraft, some hindrances constrain the applicability of this technology in practice. A major concern is the power supply for these sensors. The most attractive positions for wireless sensors are remote regions of aircraft, such as the tip inside wing boxes, for which long cables would be required in the case of wired sensors. However, these are also regions that are difficult to access for the regular replacement of sensor batteries. In addition, these sensors require a monitoring system on their own to track the state of charge of the batteries. Another issue with current technology is that wireless data transmission is still unreliable and not acceptable in the case of military aircraft.

## IT solutions

A CBM strategy covers the use of infrastructure to transmit data from detection technology, store and organise the data, manage its use and flow, and facilitate the use of analytical tools. Standards for the implementation of CBM should consider the IT solution needed to ensure the reliability of the data chain and analysis tools. They shall define, among other things, minimum standards for sampling rates and frequency of data transmission, aspects related to data security during transmission, analysis and storage, and integrity and accuracy requirements for the equipment and ground infrastructure used to process and display the collected data. Requirements regarding data traceability and reproducibility of analysis also have to be considered during the certification phase. This can raise several challenges regarding the long-term storage of huge amounts of aircraft sensor data and the scalability of CBM for large aircraft fleets, involving the analysis of many components. For instance, according to EASA, operators and maintenance providers should retain detailed maintenance records for at least three years (EASA, na). The need for real-time or high-frequency data collection, the amount of data to be used and the efficiency of analysis solutions should be carefully defined according to the criticality of the component to be monitored in order not to compromise the efficiency and scalability of a CBM strategy.

Some of these requirements have been discussed and proposed for the ReMAP project in deliverables D2.1 and D2.2. Based on the ReMAP experience, it has been identified that currently, the IT challenges lie more on the ground phase and not so much on the aircraft and the transmission of this data from the aircraft to a local server. In particular, data (cyber)security and the operator's IT requirements may impose additional requirements regarding data management and the design of the IT infrastructure architecture. Following the distributed concept followed by ReMAP, in which a health management model can visit different aircraft nodes for data analysis, another challenge is the interoperability of data eventually originated by multiple operators, making the data airline agnostic. ReMAP proposed specific requirements and a data catalogue for the solution demonstrated in work package 8 (deliverable D2.5), which was later validated by operating the IT Platform for six months during the project's demonstration phase. Finally, it is relevant to consider specific big data management packages when designing and developing IT solutions and analytical tools for CBM. Here again, we take

learnings from the ReMAP project. Whereas simple (small-data) approaches allowed for fast prototyping of prognostic models, their limitations became apparent after scaling up to allow for continuous real-time monitoring of a full fleet. The efficiency of big-data technologies can facilitate the smooth implementation and scalability of the application of such technologies.

## Health management models

Health management models are mathematical models that, by using sensing data and knowledge about the component behaviour, can diagnose or predict the evolution of the health state of that component. There have been significant advances in the scientific literature in the last years regarding health management models (refer to Lei et al., 2018 for a review paper). The models presented in the literature demonstrate good performance, and the trend is that their accuracy has improved over time. However, when applied to the aviation sector, most of these diagnostic or prognostic techniques are usually tested in synthetic datasets, like the C-MAPPS (Commercial Modular Aero-Propulsion System Simulation) data set generated by NASA containing simulated run-to-failure data for turbofan engines (Frederick et al., 2007; Saxena et al., 2008). The application to real case data sets has been limited in number and scope. It is recognised that it is more challenging to prove the reliability of such methods when the data comes from aircraft operations, subject to different operational conditions and other external factors. There are, however, a few successful industry examples.



As done in ReMAP, the next step is to extend this effort by increasing the accuracy and prognostic horizon of health management models in practice as well. There are four main challenges associated with this effort.

- The first is that, in several cases, there are very few failure or extreme health degradation examples in health data from components of operational aircraft. Following the airworthiness or commercial requirements, the operators frequently replace or repair the components way before the end life or failure status. This makes it hard to develop and train health management models to detect and predict these failures. The solution to this challenge is to have operators securely share data, as proposed with the IFHM solution from ReMAP, and to have OEMs share data from the certification process, if available.

- The second is the lack of publicly available operational aircraft data for model developers to use and exploit. Access to real public datasets can help researchers improve their solutions and address the practical challenges of implementation.

- The third challenge is the lack of physical knowledge about the failure behaviour of the system or structural element. Usually owned by the manufacturer, this knowledge is present in some existing physics-based or model-based health management models. Good examples are some of the Engine Condition Monitoring solutions on the market. However, for commercial reasons, this knowledge is not necessarily shared with operators and third-party model developers, limiting the development of knowledge-based models for health management. It was noted in ReMAP that a purely data-driven approach might not lead to sufficiently reliable health management models. Understanding component physics and failure behaviour may be necessary to improve the suitability of health management models for practical application.

- This last challenge is linked to the value of the sensor data collected to detect and explain health degradation. Most sensors on board aircraft are not intended to monitor the health degradation of associated or related aircraft components. This means that it is not always possible to identify the fault signature in the data obtained by the sensors.

Even when reliable health management models are considered, there is the additional challenge of tracking and explaining the results produced by diagnostic and prognostic models. For example, in the ReMAP project, several prognostic models relying on neural networks were implemented. Even though these models showed reasonable accuracy, it was too difficult to understand from their output exactly which subsystem was affected by what problem. This issue eliminated the opportunity to activate the prognostic model, as the effort to investigate the problem further on-ground outweighed the potential cost-saving. This can be mitigated by extending the models with a set of processes and methods that can enable the human user to understand and trust the results created by what could be seen as a 'black box'. There is a growing interest and literature on Explainable Artificial Intelligence (XAI) that aims to address this challenge (Linardatos et al, 2021).

Finally, it is important to recognise the risks associated with following an approach that relies on data collection over time. For new aircraft or aircraft systems, there may not be sufficient data (if any) that can be used to formulate and train a data-driven health management model. Another example is in case a component modification occurs, compromising the validity of data collected prior to the modification. This, too, happened during the course of the ReMAP project. The systems eligible for prognostics were chosen (amongst others) based on their risk of causing an operational disturbance. Prognostics does not only address problems caused by such systems. The OEM typically introduces a design change (modification) to mitigate the problem. In one case, this modification was introduced just before the predictive maintenance solution under ReMAP was delivered. The increased reliability of the new design almost voided the benefit of the newly developed prognostic algorithm.

Some potential solutions can be followed to overcome this risk. The first is to develop an initial understanding of component behaviour. The operator can, together with the manufacturer, define the 'normal operating' behaviour of the component and monitor deviations from this behaviour to detect degradation. A second approach is using data from the certification process, if available. This data can be used to develop an initial data-based model. This complementary approach can also help to define 'normal functioning' behaviour. In the case of a good knowledge of the new or modified component, a third solution could be to use artificial intelligence (AI) or model-based simulators to generate synthetic data and help the model developer identify potential health degradation patterns.

## Maintenance planning solutions

The last step of a CBM strategy is to define the maintenance action following the health data analysis. A systematic and optimal approach to maintenance action planning is needed to fully exploit a Maintenance Control Center (MCC) strategy's implementation. However, receiving information eventually from a large aircraft fleet involving many aircraft structural systems and elements can be daunting for a human operator in charge of developing maintenance plans. In addition, any decision has to be made in the full context of the operator's Maintenance Planning Programme (MPP) and airworthiness requirements, considering maintenance resource availability and business requisites.

There is a need for IT solutions that can consider all this information to produce optimised and stable maintenance plans. In ReMAP, scheduling algorithms were fed by open tasks, maintenance slot opportunities, and resource availability. However, it became apparent that a human planner today uses an even more versatile set of inputs to base a decision. Automating this process in support of a human decision will facilitate the adoption of CBM as a standard practice. These IT solutions need to be integrated into the operator's IT ecosystem and complemented with a user-friendly interface that can help the maintenance planner read the health management analysis and understand the impact of maintenance planning decisions.

Another identified challenge is coupling the maintenance planning and health degradation analysis with monitoring the aircraft's operational usage. Taking into account the operations of the aircraft can enhance the benefits of a CBM strategy by tailoring the maintenance schedule to each specific aircraft and better understanding the drivers that lead to the degradation of particular components.

## CBM viability

The consideration of CBM solutions will depend on the assessment of two main criteria, safety and a positive business case. The first criterion is strict, relating to ensuring that current safety standards and industry performance are preserved if not improved. For the second criterion, possible reductions in maintenance costs and increased aircraft availability compared to current maintenance practice must be demonstrated to justify investment in a CBM strategy. In other words, the costs and effort of monitoring and detecting a component should not outweigh the added value of performing maintenance based on the health analysis of that component. The costs of a CBM solution include the costs associated with the deployment of the technology, including the sensors and cables, the deployment of the IT infrastructure and data management system, the development and maintenance of the health management and planning models, and the training of the technicians who will use the CBM solution. On the other hand, benefits will come from a lower maintenance demand and consequently a higher aircraft availability. Continuous monitoring of the health condition of aircraft components also leads to greater reliability and eventually to greater component performance efficiency. In addition, a CBM strategy can help to better plan the stock and resources required over time, possibly reducing the costs associated with maintenance support activities.

Despite the previous two criteria, operators may raise two additional concerns when considering the adoption of confidence management strategies. The first one is the fact that implementing a CBM strategy may lead to more false positives or 'no-fault found' (NFF) (i.e. situations where a failure is predicted but not observed once the component is verified), ultimately resulting in a larger number of times an aircraft is grounded. However, a fair comparison has to be made with current practice. It is estimated that 80% of aircraft out-of-service time is due to scheduled maintenance requirements and the implementation of operator-defined maintenance schedules. As of now, from these times, the aircraft is out-of-service for maintenance, 90% of cases result in no change to the condition of the aircraft. In other words, the aircraft is grounded to perform specific maintenance tasks, and no faults are found. Therefore, for a fair comparison with a CBM strategy, interval-based interventions that do not result in actionable outcomes should also be viewed as NFF

events. Following this comparison, the goal should be to adopt a CBM strategy that results in fewer NFF cases compared to an interval-based maintenance strategy. Still, the operator should be prepared to experience NFF occurrences for non-critical systems since no health management model can be perfectly accurate. For critical systems, the challenge would be to eliminate false negatives (i.e. situations where the model predicts a health state but a failure is observed in practice) without compromising accuracy over false positives. In the case the false negatives cannot be reduced to an acceptable level of safety, a backup process has to be in place. Definitions will have to be reconsidered as well, as predicting a future failure under CBM policy is not the same as detecting a fault under today's paradigm. Predicting a future failure, the component could still test within limits by conventional Fault Isolation Procedures. Labelling such a component as NFF would not do justice to the potential value that a prediction can make. This issue was illustrated during the 6-month operational demonstration at the end of the ReMAP project. On two occasions, prognostic models triggered a potential problem with a component. However, upon manual validation of the issue (using the Fault Isolation Manual), the component was still tested within operational limits as per the Component Maintenance Manual, meaning that a preventive removal could not be justified. Consequently, the component had to stay on the aircraft, only to fail a few weeks later.

A second concern is a consideration that the addition of onboard sensors may pose an additional risk to operators. Following the current regulatory framework, a failure or airworthiness issue identified by monitoring the health status of a component may force the operator to preventively ground the aircraft for maintenance. This concern is fair and undermines the attractiveness of a CBM strategy in practice. Part of the benefit of a CBM strategy is limited by the fact that current regulations and industry standards have been defined based on an interval-based strategy paradigm. They do not yet provide the flexibility to extend maintenance intervals or replace inspection tasks with continuous component health management. The aviation industry needs to address this challenge by redefining industry regulations and standards according to continuous health management strategies without compromising safety requirements.



## Education and trust

Future aircraft maintenance engineers must be prepared to deal with the Industry 4.0 transformation in the maintenance, repair and operations industry. This will increase the need for more data science experts to be attracted to the maintenance field. Still, the industry recognises that the preference goes to domain experts, knowledgeable in aircraft technology, sensing technology, and maintenance operations, who are trained to recognise the value of data and able to exploit the power of data. There should be an effort to train future engineers to understand the complex world of maintenance operations and comprehend certification and (continued) airworthiness processes, emphasising the relevance of data-driven analysis and informed decision-making. This includes preparing future maintenance engineers to be able to read and understand probabilistic information resulting from, for example, the use of health management models.

In parallel, there must also be a communication effort to educate current decision-makers and managers to understand the purpose and value of health management strategies. There is a learning curve that needs to be followed. More demonstrative industry examples of health management deployment and validation are needed to showcase the value of CBM solutions. For example, it is essential to explain why the long-term cost reductions and increased aircraft availability resulting from an accurate CBM solution offset the costs deploying the technology and the costs of, in a few cases, diagnostic maintenance too early (i.e., NFF events). That is, CBM believers need to make an effort to show researchers, manufacturers, suppliers, operators, and regulators the value of moving towards a data-driven tail-specific (and model-based) maintenance philosophy. Industry- or governmental-founded research and validation projects, like ReMAP, are needed to accelerate the building of trust within the aviation industry and realise the ACARE vision for aircraft maintenance.

A final point regarding education is the definition of a common language. Many terms are used to define health management solutions and technology. Most of these terms are interchangeable or, even worse, have different meanings when used by different stakeholders. The obvious case is the use of the term CBM, which does not have a standard and industry-accepted definition. This forest of terms and concepts jeopardises the understanding and discussion of health management solutions. Education institutions and aviation standards entities must play an essential role in uniformising the industry terminology.

## Stakeholders collaboration

It was already identified that the need for strong collaboration among all stakeholders in the aviation industry to push CBM forward. This includes researchers, education institutions, OEMs, suppliers, operators, IT providers, and regulators. No CBM solution will fully work without the involvement of multiple stakeholders. The ambition of having a future CBM aircraft will also require combined efforts from manufacturers, first and second-tier suppliers, operators, and regulators. It will be necessary for all partners in the MRO chain to coordinate and communicate to harness the power of CBM.

Furthermore, collaboration is also needed between similar stakeholders. For instance, due to the lack of failure data within the airline fleet, airlines must work together to have enough data to train their health management models. Due to the global scope of the aviation sector, regulators have to work in unity. Manufacturers share similar technology and clients with heterogeneous fleets. And industry IT standards will be needed to facilitate the marketability of IT solutions.

The ReMAP IFHM approach, adopting a distributed IT approach to manage data and health management models, is a good example of how to facilitate this collaboration. Operators, model developers (including manufacturers and suppliers), and IT developers can work together to develop and promote health management models in a trustful ecosystem, generating larger marketability of these solutions by potentially accessing multiple aircraft operators.

Currently, manufacturers are directly competing with operators (and maintenance service providers) in developing after services, including maintenance support. The collaboration will be fostered by generating contexts in which both (or most all) partners benefit from it. This may require new contractual arrangements between parties. For instance, current guarantee and after-sale assistance contracts do not usually foresee using health management solutions to support the maintainability and replaceability of the aircraft parts covered in these contracts. However, both parties will eventually benefit from collaborating in setting up these health management solutions and service thresholds together.

## Regulations and standards

The current industry regulations and standards framework, defined by the MSG-3 task-based methodology to derive requirements for planned maintenance, follow the knowledge and IT technology of the 1980s and 1990s, when current aircraft were designed. This poses a challenge when implementing a CBM strategy. Current industry efforts on health management are made as an additional monitoring activity to support or extend the implementation of the maintenance programme. Regulators, operators and manufacturers still do not recognise certified credit for health management solutions and offer limited flexibility to drive maintenance based on health indicators or predictions.

One of the examples shared during the ReMAP Day discussions shows the impact of not recognising credit to health management solutions. The air filter of the Boeing 737's air cabin environmental monitoring system (ACES) is changed according to a recurring task performed after every 3000 flight hours. This interval was ultimately determined based on the estimated use of the aircraft in a worst-case scenario. The deterioration of the filter condition can eventually be monitored by measuring the pressure and temperature in the system. If a significant deterioration of the monitored parameters is observed, this may indicate that the filter is clogged, and a replacement action can be planned. Assuming the abnormal case in which degradation of the parameters is observed 2400 flight hours after the last filter change, a preventive task is scheduled, and the filter is replaced because the blockage is observed. Still, unless the preventive task is signed as the corresponding periodic maintenance task, the filter must be checked and replaced after 3000 flight hours, only 600 flight hours after the preventive task, because no credit is given for the health management detection.



Still, operators see the value of health management solutions and request more flexibility. In particular, it is recognised that the benefit will come from replacing tasks or escalating intervals. For this reason, regulatory agencies are paying attention to these needs and aviation standards entities have been making an effort to propose new standards and regulations. In particular, the Maintenance Program Industry Group (MPIG) proposed, with Issue Paper 180 [2018] titled "Aircraft Health Management (AHM) integration into MSG-3," a systematic approach to amending the MSG-3 logic by introducing an alternative health management process using acquired data instead of interval-based maintenance tasks. This Issue Paper was later amended by Issue Paper 197 [2021], titled "Amendment to IP180 to clarify system features to be certified by type certification staff," clarifying that the certification process and limiting the scope of health management process proposed to non-safety related tasks. The latter also gives an overview of the Airbus and Boeing positions regarding certification of health management solutions.

These documents and related discussions with regulatory boards had led, for example, to the Federal Aviation Administration (FAA) Notice No. 8900.634 [2022], entitled "OpSpec/MSpec/LOA D302, Integrated Aviation Health Management Program" and published in July 2022, which authorises the application process for integrating health management programs for maintenance credit. The Notice recognises the need for various aviation industry stakeholders to use onboard aircraft systems, ground infrastructure and software solutions to extend certified aircraft maintenance and provides the framework for requesting authorisation for such a process. While an important milestone in defining CBM strategies as a standard practice, the FAA Notice and MPIG issues restrict the domain of health management solutions to still non-critical components. This limits the applicability to most interval-based tasks of the Aircraft Planning Document (issued by the manufacturer or Type Certificate Holder), significantly reducing the applicability to aircraft structural elements and the escalation of most interval-based tasks. Operators must build the confidence to extend this strategy to critical systems or safety-related tasks. This will be done with relevant industry application cases that, on the one hand, can show that the probability of fault detection on specific critical components is not compromised when using a health management strategy and, on the other hand, demonstrate that the reliability of the monitoring system is high enough to be certified. It is also acknowledged that, especially for these safety-related tasks, authorities will always require to have a human in the decision loop. For this reason, processes need to be defined in which health management solutions are seen as decision support tools that provide a way for human decision-makers to manage information, control health degradation better and trace their decision.

Given the complexity of deploying CBM strategies, operators and other stakeholders must be supported with certification and industry guidance material. The material should help standardise the process of deploying this technology, addressing the multiple steps regarding deploying a CBM strategy. It has to be developed by regulatory entities (e.g., Civil Aviation Authorities, ICAO, International Maintenance Review Board Policy Board) in cooperation with aviation standard entities, such as SAE International, MPIG, EUROCAE, and industry representatives from airlines, MROs, DAHs and other relevant stakeholders. The recommendations should refer to [based on Issue Paper 180, 2018]:

- The installation and qualification of the onboard sensing technology, including the hardware, cable and software associated.
- The qualification of off-aircraft (ground) system used to analyse and monitor the health condition of aircraft components.
- The qualification of the data requirement and traceability requirements associated with the health management process.
- The qualification of the monitored parameters and health thresholds considered to define health degradation alerts.
- The qualification of the health degradation parameters estimated to predict future degradation and drive maintenance requirements.
- The qualification of the adapted maintenance procedure and service validation.

The regulatory and industry standards recommendations are further elaborated in ReMAP's deliverable D7.3.

### Green transition

The urgency for a green aviation transition creates a major opportunity for CBM and health management solutions in general. First of all, a CBM strategy can contribute to this transition. It promises to reduce the demand for maintenance, resulting in fewer spare parts being needed, less energy consumed for maintenance, and producing less waste.

But, most of all, CBM can facilitate the transition to new energy. It may reduce the costs of adopting new power sources and monitor the evolution of the degradation of technologies still in an infancy phase. For instance,

- it is not known yet if the use of Sustainable Aviation Fuel (SAF) in current technology will not require a different maintenance program. A health management solution can help monitor the effect of using SAF and facilitate a flexible maintenance program.

- The use of liquid hydrogen will challenge maintenance. It will be hard to maintain components while managing very low temperatures or without using too much energy to control the temperature. Assuming that components may have to be warmed up before maintenance takes place, the maintenance interventions will also be longer. Therefore, human intervention in the maintenance execution has to be reduced. A CBM strategy should help to reduce maintenance needs and execute maintenance when only necessary.

The design of sensorised aircraft, prepared to be monitored and maintained according to a CBM strategy, may also lead to future lightweight aircraft. These lighter aircraft will ultimately be more efficient and consume less fuel to perform the same mission. Developments in SHM will be critical to facilitate this development and contribute to a green transition. However, it must be recognised that there are limits when it comes to weight reduction. Firstly, there are safety design margins that must be respected. Regulations only allow manufacturers to reduce design margins to a level corresponding to the allowable stress (i.e. the maximum stress that the structure is assumed to withstand during its service life).



Secondly, a maximum acceptable weight reduction needs to be determined on a case-by-case basis. This maximum acceptable weight depends, on the one hand, on a commercial trade-off analysis between the investment in the SHM solution and the operational and maintenance benefits of having a lighter and more controlled aircraft. On the other hand, it will also depend on the balance between the weight added with the sensing technology added to the aircraft and the weight reduction achieved. As shared during the ReMAP Day, some industrial applications have considered sensing technologies that weigh around 2 to 5 kilograms of materials, including cables, standby connectors, and sensors. The weight benefits would have to be greater than this to justify investing in an SHM solution to reduce aircraft weight.

It should also be understood that such lightweight aircraft would only be operational in the future, 15 to 20 years from now.

# Next steps

The CBM concept, applied to the aviation industry, is still in the initial development stage. Some isolated efforts exist where key aviation players developed health monitoring systems aiming to improve the corrective tasks in the operators' maintenance program. ReMAP is recognised as a flag project in the way it contributed to developing the CBM concept and extended the analysis to multiple systems and structures. Still, no fault detection credit is given to these health monitoring systems. The industry is still far from considering replacing current time-interval strategies with purely CBM strategies. Even so, ACARE predicts that by 2035 the CBM strategy will be accepted as a standard approach to monitoring the aircraft condition and planning maintenance.

This section highlights some possible steps to contribute to developing and accepting CBM in the aviation industry. The discussion is divided into four parts – aircraft systems, structural health monitoring, planning solutions, and designing a future CBM aircraft. Some of the indicated steps can and should be supported with industry resources. However, to achieve the ACARE vision, the support of international funding agencies will be needed to mature the level of technologies associated with a CBM strategy.

We divided the steps into efforts related to aircraft systems (or PHM), structural health monitoring (SHM), maintenance planning, and the design of an aircraft prepared to foster the adoption of a CBM strategy for a large part of its components. In the last sub-section, we summarise the steps per type of stakeholder in a proposed roadmap.

## Aircraft systems

Despite the relevant effort done by ReMAP by addressing multiple aircraft systems and demonstrating it in an operational environment using operational data, more demonstration exercises are needed to consolidate the trust in CBM strategies. The industry can follow this project by centring its effort on simple cases that can be implemented within the current regulatory framework and standards. For instance,

1. For components that are currently monitored using onboard sensors, the focus should be on using the existing data to prove the earning potential of a CBM strategy. The ambition should be to demonstrate that following such an approach can lead to a higher interval between maintenance interventions. With lower maintenance demand, the operator can benefit from a higher earning potential from higher aircraft availability and operational reliability (i.e., fewer technical disruptions).

2. For most interval-based tasks, there are usually no sensors available. A potential initial approach would be to retrofit sensors that can provide relevant information to develop a CBM strategy.

A few good new demonstration examples from key stakeholders should call other stakeholders' attention, build their trust, and foster the current discussion on changing regulations and industry standards.

In parallel, there should be an attempt to test further the IFHM solution developed in ReMAP. In particular, increase the TRL level of the technology developed to do more in-service tests and demonstrate the benefit of using data from multiple operators. Special attention should be given to federated learning approaches for health models capable of training health monitoring models using data from different datasets to enhance the potential of the distributed approach proposed by ReMAP. This effort will involve many stakeholders, operators, IT developers, manufacturers, and regulatory agencies.



Future steps should also look at deploying CBM solutions for critical aircraft systems. The scope of demonstration exercises for such components is rather limited, eventually being limited to simulation or shop tests. Nevertheless, the industry needs to discuss and analyse how it will be possible also to perform maintenance on critical aircraft systems based on a health management approach. It should also be considered how this effort can be validated and later certificated. This effort will involve low Technical Readiness Levels (TRLs) and should be supported by funding agencies. The involvement of manufacturers and regulatory agencies will be critical to the successful development of this effort.

### Structural health analysis

For SHM, the challenge in the coming years is to move from laboratory tests to life demonstrations. There are a few examples of industry SHM experiments, especially addressing aluminium alloys and joints. Despite being limited in scope, they provide a good reference for future SHM efforts. Furthermore, there was an unprecedented effort made by the ReMAP project to cover the full scope of the SHM hierarchy for composite structures, including the development of health degradation prognostic technologies. With industry tests, the TRLs from these technologies need to be increased in the coming years.

When designing the research efforts and industry tests, the following criteria should be considered:

1. It should be easier to show the added value of investing in sensing technology and developing an SHM strategy if hot spots are selected for these tests. Hot spots could be damage-prone sections of the aircraft structure or elements that require long inspection times and recurrent effort to be maintained (see example below).

2. Primary structural elements are more relevant for an SHM strategy. As defined in the Maintenance Planning Document, the current inspection intervals for these structures assume higher operational demands (e.g. loads) than most operators endure and are, therefore, too conservative for most airlines. Furthermore, some of these intervals were designed based on an optimistic assumption of the human eye's capability to identify small cracks or dents, and the damage is, in practice, later detected. Therefore, these intervals can potentially be extended if the damage detection and propagation are well monitored. In addition, there could be a margin to fail with an SHM strategy. In most cases, these primary structural elements are associated with second elements that can allow the aircraft to still fly for a limited number of flights until repair without necessarily representing a high safety risk. Furthermore, if well monitored, the reparability of the primary element will be much cheaper and easier to perform than repairing it after failure, and it ends up happening following the intervals-based strategy.

For example, aircraft fasteners can be considered hot spots and suitable to be monitored with an SHM strategy. Some fasteners are located at the rear of the galley on the aft pressure bulkhead. These fasteners require regular inspection that takes no more than 15 minutes. However, opening and closing the galley can take 4-5 days, require some functional checks (e.g. power or plumbing) and consume hundreds of labour hours. In addition, there is the risk of introducing damage during disassembly and assembly. An SHM solution applied to these fasteners could avoid unnecessary maintenance checks and reduce the overall inspection time.

A parallel effort should address detection technologies. In addition to identifying and standardising the detection technology to be used in each specific SHM case, future steps must also address sensor reliability. Smart detection technologies, with the potential to self-diagnose sensor failures and adapt to the environment, could be explored in the future.

Efforts should also be made to help develop smarter and lighter structures supported by health management solutions. Initial efforts are already underway in European projects to design tailored sensing technologies to support the development of lighter, quieter and smarter engine nacelles.

Finally, it is important to recognise the current trend to focus on sensing technologies to define aircraft usage better. Some industry stakeholders are investing efforts in improving the way to measure the degradation of structures, replacing flight hours or cycles with close monitoring of relevant usage parameters like loads, vibration, temperature or humidity to tailor inspection intervals accordingly. Although this approach would not facilitate the monitoring of the damage itself and reveal the physics behind the long-term behaviour of structural elements, it can complement CBM strategies and allow an extension of the intervals.

## Maintenance planning

CBM efforts must be complemented with efforts to digitise the maintenance decision process. At least for most operators, current maintenance practices and decision processes are still based on paper documentation and human judgment. Other operators already rely on digital tools to support the management of their fleet maintenance programmes. However, these tools are typically oriented towards data or inventory management. Most of these tools do not produce maintenance plans or manage information from health monitoring solutions to facilitate the development of such plans.

The next steps should focus on developing solutions to optimise maintenance planning for the entire fleet. The tools can help the human decision-maker manage the information overload that can potentially be generated by implementing CBM solutions to monitor multiple aircraft components. Following the ReMAP effort, development can be done in three phases:

1. Development and test in operational environment optimisation solutions that can address the full scope of an operator maintenance program. The solutions should cope with the continuous flow of information, updating the state of the fleet and the availability of maintenance resources to produce optimised schedules in a few minutes.
2. Integrate and process information coming from the health monitoring solutions. Methods should be developed to translate probabilistic diagnostics and prognostics into maintenance tasks and respective fleet maintenance plans.

3. To validate the practicability and reliability of such methods and optimisation tools in industry tests to increase their TRLs.

The development of optimisation tools should be complemented with the effort to develop user interfaces that can help human beings to consolidate and understand all the information regarding the fleet health management and maintenance plan. The users' trust in these tools and a CBM strategy will largely depend on the readability and interpretability of the solutions produced with these digital tools.

## CBM aircraft

Current aircraft was conceptualised with IT knowledge from the 80's and 90's. New design concepts and aircraft capabilities are needed to facilitate the adoption of CBM strategies in the future. However, it is accepted by the industry that the future CBM aircraft will not be fully sensorised. The introduction of a large number of sensors to completely monitor every component of the aircraft would compromise the global reliability of the aircraft and largely increase the aircraft's complexity. Not all aircraft operators will have the size and capacity to deal with such complexity. In fact, the focus should not be so much on the quantity as it should be on the value of the data generated with the sensing technology. Modern aircraft can already generate terabytes of data per flight, but just a small percentage of this data is being collected by airlines.

Each piece of a health management system to be located in the aircraft has to justify its place on the aircraft in terms of its value, costs and requirements. Not all aircraft components will be suitable for a health management approach. Nor is there always a clear business case associated with replacing current interval-based strategies with a CBM strategy. The addition of unnecessary sensors will increase the requirements for data computation and data storage capability to trace all this data eventually for decades. This may require a significant infrastructure (and amount of energy), eventually compromising the profitability of such modification.



Future steps should therefore aim to identify which sensors and parameters need to be measured to facilitate the adoption of CBM strategies for relevant aircraft components. Operators and other stakeholders should work with manufacturers and sensor technology providers to define the sensors required to meet the ACARE vision. Criteria should be defined to identify those that will have the greatest impact on aircraft maintenance and reliability. The aim should be to facilitate a maintenance plan and reduce the need for maintenance (i.e. increase aircraft availability for operations). The signal ratio and frequency with which these parameters are to be downloaded to the ground station outside the aircraft should also be defined. These should be defined based on the criticality of the data to be considered when defining the health management system to be added to the aircraft.

Future CBM aircraft will not be on the market until 2040 or 2050. Therefore, there will be a transition period where two parallel programmes will be followed by operators - the current interval-based and condition-based programmes. During this transition period, health management solutions will continue to cover only a (small) part of the aircraft ecosystem. They will have to be done using sensors that are not necessarily designed for health monitoring or with sensing systems not designed for high reliability. Thus, future research efforts should consider this transitional period, adapted to cope with the two transitional maintenance programmes and regulations. In addition, it should be considered that the expected results of CBM exercises during this transition period may be compromised.

Smarter actuators that can collect and evaluate data at the node before selecting which data to share or possibly predict the health status of the monitoring component should also consider in the design of future aircraft. These can help to streamline the flow of data needed to be transmitted and used for health management performed at the ground stations. A smarter aircraft can facilitate the adoption of CBM strategies with less model developer and operator effort.

## Roadmap

In this sub-section, we summarise the identified steps per group of stakeholders: manufacturers (including original equipment manufacturers, OEM, and second- and third-tier suppliers), sensor developments, operators, research centres and model developers, universities and regulators. It should be mentioned that the research centers and model developers groups also include manufacturers, sensor developments, operators, universities and IT commercial companies that invest on R&D programs related with developing health monitoring models. The steps are divided into short-term steps (Table 1), which reflect ongoing initiatives or efforts that should start in the coming 2-5 years, and long-term steps (Table 2), reflecting efforts that should be taken beyond the 5 years to make CBM a sustainable and accepted strategy for aircraft maintenance. Most of these efforts involve the cooperation between multiple stakeholders. While other efforts, including the study and analysis of CBM strategies for safety-critical components, are associated low TRLs and require the investment from funding agencies to progress and facilitate the ACARE vision for future aircraft maintenance.

## Short-term steps per stakeholder



### Manufacturers (OEM & suppliers)

- Interact with and participate in industry and regulators working groups to discuss the implementation of CBM
- Propose detectability of the fault by introducing a sensor capturing the initiation of the fault already in the design
- Define a smarter usage interval, making use of actual operational loads from sensors
- Make certification data available to operators and model developers to facilitate the adoption of CBM on new or modified components
- Adapt guarantee and after sale assistance contracts to consider and facilitate the use of CBM technologies by operators



### Sensor Developers

- Improve compactness and reliability of electromechanical systems and electronics.
- Provide tailored solutions fitting the OEMs and operators need.



### Operators

- Focus on non-critical systems for demonstration of CBM value and increase 'trust' among stakeholders
- Work closely with the manufacturers to scope, design and verify retrofit solutions for current aircraft
- Interact with and participate in industry and regulators working groups to discuss the implementation of CBM
- Make publicly available (anonymised) operational and reliability data that can foster CBM research
- Collaborate with other operators, sharing components failure data in a secure and non-disclosing manner, to better train health monitoring models
- Identify, together with manufactures, aircraft components that will benefit from a CBM strategy but do not have sensors capable of explain health degradation



### Research centres & Model developers

- Focus on non-critical systems for demonstration of CBM value and increase 'trust' among stakeholders
- Work closely with the manufacturers to scope, design and verify retrofit solutions for current aircraft
- Interact with and participate in industry and regulators working groups to discuss the implementation of CBM
- Make publicly available (anonymised) operational and reliability data that can foster CBM research
- Collaborate with other operators, sharing components failure data in a secure and non-disclosing manner, to better train health monitoring models
- Identify, together with manufactures, aircraft components that will benefit from a CBM strategy but do not have sensors capable of explain health degradation



### Universities

- Develop and offer education programs to prepare maintenance engineers for Industry 4.0
- Develop and offer training programs to support the understanding of health management strategies to practitioners and decision-makers
- Promote the use of a common language
- Create forums to discuss CBM technologies and challenges, and promote interaction between academia, research centers, and industry
- Facilitate the access to public health degradation data (from lab experiments or host data from operators) to foster CBM research



### Regulators

- Participate in the discussion and validation exercises of CBM technologies
- Look critically at the limitations currently holding back CBM implementation and promote discussion to address them
- Adapt current and define new regulations and industry standards to give certified credit to health monitoring solutions in non-critical components

## Long-term steps per stakeholder



### Manufacturers (OEM & suppliers)

- Support the development of CBM demonstration exercises in aircraft critical systems
- Adjust and propose aircraft design requirements according to the CBM solutions to be used to continuously monitor the health degradation
- Propose recovery plan solutions for the case sensors for critical systems fail to generate information
- Equip future aircraft with sensors that bring added value for the adoption of CBM strategies for relevant components
- Develop and propose, together with operators and regulators, CBM-based maintenance strategies for future aircraft (hydrogen, electric)



### Sensor Developers

- Provide tailored solutions fitting the manufacturers and operators needs
- Develop smart detection technologies that can collect and evaluate data before transmitting it
- Improve sensors reliability with self-diagnose sensor failure and that can adapt to the environmental conditions
- Further develop power supply and reliability challenges related with wireless sensors



## Operators

- Develop CBM demonstration exercises on critical systems to validate the CBM value and increase 'trust' among stakeholders
- Propose recovery plan solutions for the case sensors for critical systems fail to generate information
- Develop and propose, together with operators and regulators, CBM-based maintenance strategies for future aircraft (hydrogen, electric)



## Research centres & Model developers

- Develop proofs-of-concept, methods and processes which can contribute to increase "trust" demonstration in critical systems
- Develop fleet health monitoring solutions integrating health monitoring models with maintenance planning optimisation models for an integrated fleet monitoring
- Develop qualification process to continuously validate and deploy new health monitoring modelling updates
- Facilitate the access to public health degradation data (from lab experiments or host data from operators) to foster CBM research



## Universities

- Develop and offer high-skilled education programs to train engineers for specific CBM challenges
- Facilitate the access to public health degradation data (from lab experiments or host data from operators) to foster CBM research



## Regulators

- Support the development of CBM demonstration exercises in aircraft critical systems
- Define regulations and industry standards, including data security, data storage, monitoring accuracy and recovery plans requirements that need to be followed by operators to give credit to health monitoring solutions in critical components
- Develop and propose, together with operators and regulators, CBM-based maintenance strategies for future aircraft (hydrogen, electric)

# Conclusion

This report provides an overview of the industry perspective on the current challenges regarding developing the CBM concept for aviation. In addition, it identifies some of the efforts needed in the future to promote the acceptance and deployment of this concept in practice. The report has been prepared following the findings of the ReMAP project and discussions with project partners, advisory board and other stakeholders. In particular, this report describes some of the considerations and topics discussed during ReMAP Day.

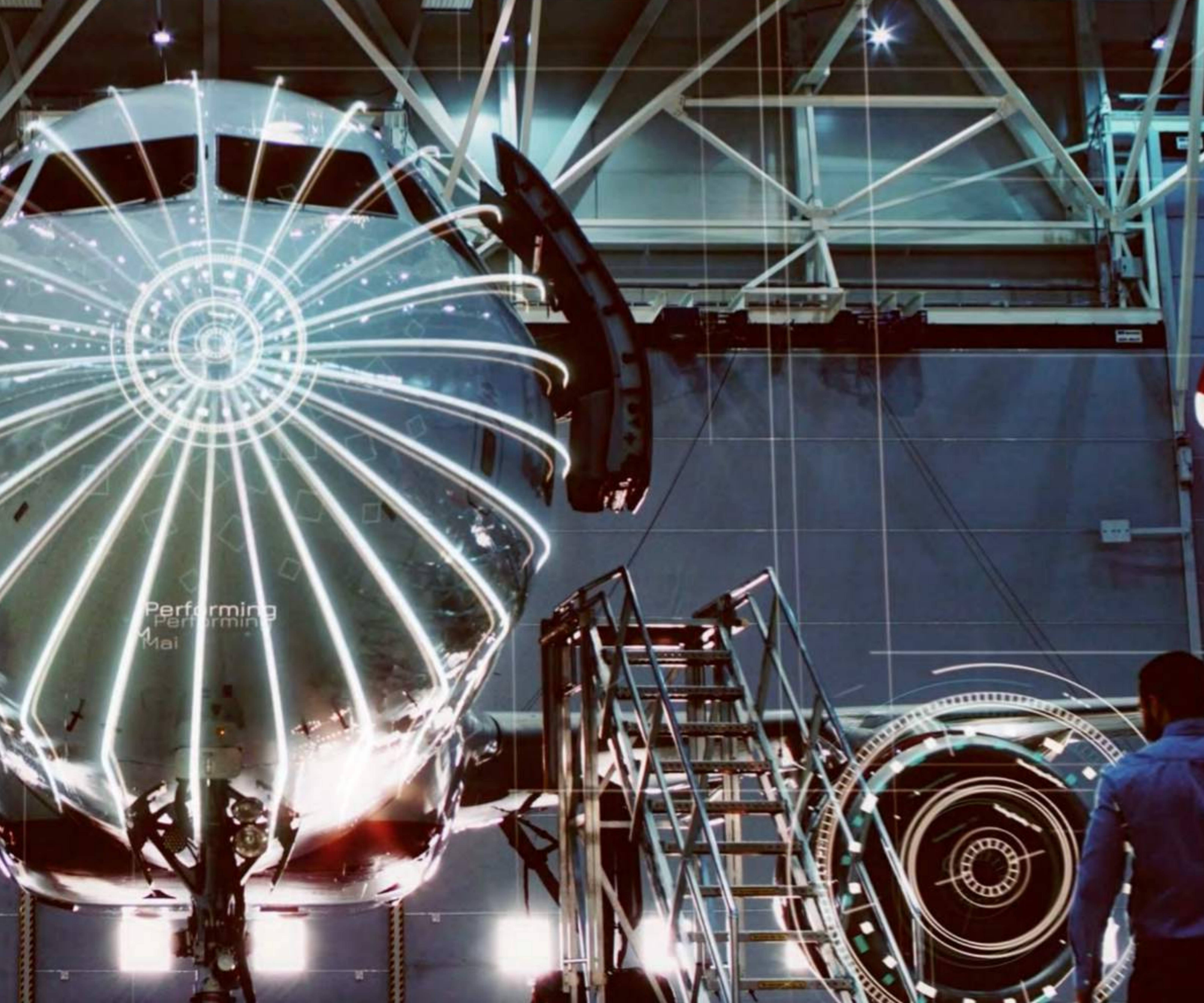
It seems clear to aviation stakeholders that CBM is an attractive concept for aviation and one that needs to be developed further. The ReMAP project has contributed significantly to developing and validating this concept in an operational environment, further raising industry interest in this maintenance concept. Future efforts should be to extend this effort and show the scalability of the concept and its technologies. Although CBM technologies have not yet been given credit for identifying failures and driving the aircraft component maintenance programme, there has been a relevant industry effort to propose standards and adapt regulations to be flexible in implementing CBM strategies. Still, safety and confidence are paramount in this effort, and a learning process must be followed.

It is also recognised that the solution for health management technologies has to be defined case-by-case basis, depending on an attractive business case and proof of reliability. However, stakeholders cannot work alone in this effort. The collaboration of all stakeholders in the maintenance, repair and operations chains is critical for the rapid and successful development of the CBM concept. A bad example, promising overestimated CBM results or presenting doubtful CBM demonstration results, can move the CBM discussion back a few decades. The industry needs some good wins, like the ReMAP project, following an agile approach to scale up these good examples, and intelligently communicating the results to inform stakeholders well.



# References

- Issue Paper 180 (2018) "Aircraft Health Management (AHM) integration in MSG-3", International Maintenance Review Board Policy Board – URL: <https://www.easa.europa.eu/download/imrbpb/IP%20180%20-%20AHM%20integration%20in%20MSG-3.pdf> (accessed August 2022)
- Y Lei, N Li, L Guo, N Li, T Yan, J. Lin (2018) "Machinery health prognostics: A systematic review from data acquisition to RUL prediction", *Mech Syst Signal Process*, 104, pp. 799-834 - <https://doi.org/10.1016/j.ymssp.2017.11.016>
- Frederick, D. K., DeCastro, J. A., and Litt, J. S. (2007) "User's guide for the commercial modular aero-propulsion system simulation (C-MAPSS)," NASA/TM–2007-215026 – URL: <https://ntrs.nasa.gov/api/citations/20070034949/downloads/20070034949.pdf> (accessed August 2022)
- Saxena, A., Goebel, K., Simon, D., and Eklund, N. (2008) "Damage Propagation Modeling for Aircraft Engine Prognostics", 2008 International Conference on Prognostics and Health Management, PHM , pp. 1-9, <https://doi:10.1109/PHM.2008.4711414>
- Linardatos, P.; Papastefanopoulos, V.; Kotsiantis, S.(2012) "Explainable AI: A Review of Machine Learning Interpretability Methods", *Entropy*, 23, 18. <https://doi.org/10.3390/e23010018>
- Issue Paper 197 (2021) " Amendment to IP180 to clarify system features to be certified by type certification staff", International Maintenance Review Board Policy Board – URL: [https://www.easa.europa.eu/sites/default/files/dfu/ip\\_197\\_-\\_amendment\\_to\\_ip180.pdf](https://www.easa.europa.eu/sites/default/files/dfu/ip_197_-_amendment_to_ip180.pdf) (accessed August 2022)
- Notice 8900.634 (2022) "OpSpec/MSpec/LOA D302, Integrated Aircraft Health Management Program", Federal Aviation Authority – URL: 8900.634 - OpSpec/MSpec/LOA D302, Integrated Aircraft Health Management Program – Document Information (faa.gov) (accessed August 2022)



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