

Article

Condition-Based Maintenance in Aviation: Challenges and Opportunities

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Abstract: Condition-Based Maintenance (CBM) is a policy that uses information about the health condition of systems and structures to identify optimal maintenance interventions over time, increasing the efficiency of maintenance operations. Despite CBM being a well-established concept in academic research, the practical uptake in aviation needs to catch up to expectations. This research aims to identify challenges, limitations, solution directions, and policy implications related to adopting CBM in aviation. We use a generalizable and holistic assessment framework to achieve this aim, following a process-oriented view of CBM development as an aircraft lifecycle management policy. Based on various inputs from industry and academia, we identified several major sets of challenges and suggested three primary solution categories. These address data quantity and quality, CBM implementation, and the integration of CBM with future technologies, highlighting future research and practice directions.

Keywords: condition-based maintenance; integrated vehicle health management; structural health monitoring; prognostics and health management; maintenance planning

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1. Introduction

Aviation comprises a range of economic activities, with one of the major elements being constituted by the Maintenance, Repair, and Overhaul (MRO) market, which is estimated to have an annual turnover of \$78.5 billion [1] and represents about 11% of an airline's cost outlay [2]. Given its impact on airline cost and profitability, there is substantial interest in efficiency improvements in aircraft MRO. At the same time, a variety of technological innovations in this area have reached a stage of maturity that may spur the uptake of novel strategies and policies, consequently helping to address the required drive for efficiency in aircraft maintenance. A primary example is Condition-Based Maintenance (CBM), a maintenance policy that can be defined as “preventive maintenance which includes assessment of physical conditions, analysis and the possible ensuing maintenance actions” [3] or “a maintenance program that recommends maintenance actions based on the information collected through condition monitoring” [4]. CBM and its constituent technologies help identify and prevent unscheduled maintenance, facilitate

substituting maintenance tasks or extension of task intervals, and enable the optimization of maintenance schedules at the fleet level [5,6].

CBM is expected to become the dominant policy in aviation [7]. However, while elements of CBM have been present for decades in the aviation industry, CBM has not yet seen the broad-scale adoption implied by ACARE's vision [7]. Why not, and how can future adoption be facilitated in the current aviation landscape through appropriate policy settings? To address these questions, it is required to form a detailed yet *holistic* understanding of CBM, comprising all elements relevant to CBM uptake. However, the vast majority of CBM research to date has a technological orientation, focusing on developing models, algorithms, and methods to perform detection, diagnosis, and/or prognosis of failures. Another substantial set of literature addresses the planning, decision support, and decision-making aspects of CBM: if a diagnosis or prediction is available, how can an organization use this information to plan and execute an associated maintenance intervention [8–10]? Subsequent questions revolve around the cost-benefit analysis, implementation, and industry process adaptation, regulation, and standardization of CBM. Unfortunately, there is a relative paucity of research considering a priori assessment and subsequent implementation of CBM. Available models are fairly generic and high-level and are prone to display an insufficient understanding of which tasks have the highest potential to benefit from CBM and how, in practice, maintenance procedures have to be adapted to allow for CBM. As noted by Atamuradov et al. [11] and Ingemarsdotter et al. [12], implementation of CBM remains a challenge, with a variety of authors highlighting a need to understand implementation challenges beyond technological aspects [12]. Prior work by Atamuradov et al. [11] has highlighted CBM implementation steps and associated challenges in more detail, as has work by [13]. However, the former primarily focuses on identifying and evaluating technological alternatives, whereas the latter focuses exclusively on the process industry. In both works, a systematic model or framework to identify CBM challenges in implementation needs to be included. Ingemarsdotter et al. [12] address this gap by proposing a structured integrated framework to perform a broad analysis of challenges and solutions in a set of three CBM cases. However, this research is restricted by the fact that its dataset is limited to three cases, each in relatively early implementation phases. Furthermore, the proposed integrated framework predominantly focuses on Internet-of-Things development rather than directly representing CBM implementation processes. It is, therefore, not exhaustive in its analysis.

This research/paper aims to address the scale of issues raised above through the following novel contributions:

- Challenges and opportunities for CBM in aviation are assessed across an aircraft lifecycle perspective, using input from the Horizon 2020 Real-time Condition-Based Maintenance for Adaptive Aircraft Maintenance Planning (ReMAP) project, a 4-year European research project that ran from 2018 to 2022 and focused on CBM in aviation (Real-time Condition-Based Maintenance for Adaptive Aircraft Maintenance Planning project—<https://h2020-remap.eu>, accessed on 14 July 2023). The scale of this project and its activities have enabled several advances and novel considerations in the discussion of CBM, moving this research beyond the current state of the art and leading into a discussion of policy implications;
- The assessment is performed using a generalizable and holistic assessment framework of CBM developed based on the framework proposed by Ingemarsdotter et al. [12].

The remainder of this paper is structured as follows. In Section 2, the theoretical context is further discussed, including a more detailed definition of CBM, its main characteristics, and implementation process representations. Section 3 discusses the research method in more detail, including an adaptation of an earlier framework [12] in Section 3.2. This is followed by its application in Section 4. Here, the framework is applied to identify challenges for CBM in aviation across aircraft lifecycles. Section 4.2 identifies policy

implications, opportunities, and solution directions. Finally, the main conclusions of the research, as well as recommendations for future research, are given in Section 5.

2. Theoretical Context

To place the current research in the context of the academic and practical state of the art, Section 2.1 discusses Condition-Based Maintenance (CBM) in more detail. In Section 2.2., existing process representations for CBM implementation are discussed.

2.1. Definition and Characteristics of CBM

In the literature, Condition-Based Maintenance (CBM) is typically defined as a maintenance strategy or policy while sometimes being positioned as a preventive maintenance approach. Multiple definitions exist, including those highlighted in the introduction. Despite having similar definitions and comprising a number of shared elements, there is frequently contradiction in the terminology adopted and overlap between different concepts.

Following the experience from the Horizon 2020 Real-time Condition-Based Maintenance for Adaptive Aircraft Maintenance Planning (ReMAP) project and input from several industry stakeholders and academics, we propose a definition of CBM for aviation, presented in Figure 1. The definition considers CBM as a policy that contemplates the lifecycle management of the asset as part of a fleet of aircraft. The goal is to maximize the availability of the aircraft for operations considering the best moment to perform maintenance. Three main elements define CBM:

- **Condition/Health Monitoring** involves the direct and indirect collection of information regarding the health state of the asset. This information can be gathered using signals from sensors installed onboard the aircraft or resorting to 'off-board' *Non-destructive Tests* (NDT), such as visual inspection, acoustic emissions, or liquid penetrant testing. These data can be generated for continuous or periodic monitoring purposes, producing condition indicators describing the health state of the asset;
- **Aircraft Health Management (AHM)**, also called *Integrated Aircraft Health Management* (IAHM), is the process of utilizing aircraft condition monitoring data, operational data, and associated event data to infer the health state and predict the health degradation of the asset over time. Health management approaches in aviation are typically subdivided into systems and structures applications. The former is expressed in the field of Prognostics and Health Management (PHM), which includes methods for failure detection and subsequent prognostics. Structural applications are embodied in Structural Health Monitoring (SHM), which covers damage detection, identification, and prognostics. Despite having different names and incidences, both concepts refer to the capability of using single or multiple health condition indicators and physics or data-driven techniques to diagnose faulty states and estimate the *Remaining Useful Life* (RUL) of the system or structural element, respectively. In some applications, AHM is also extended to include a prescriptive layer suggesting the best moment to perform maintenance on the specific component being monitored;
- **Maintenance planning** is the process of scheduling aircraft maintenance on the basis of health assessment and prediction, availability of the resources available to perform maintenance, and the goal of maximizing fleet availability. This element includes the identification of (1) which maintenance action(s) may be required, (2) when these action(s) may be required, (3) and which resources are necessary for the planning and execution of the action(s) at hand. Two important aspects of this process are the combination of distinct requirements for different maintenance actions and satisfying task grouping constraints to produce efficient maintenance schedules for a fleet of aircraft. The resulting maintenance schedule(s) and plan(s) ultimately result in aircraft availability. When aircraft have been maintained and are back in service, aircraft utilization under various conditions and within various environments yields inputs to condition monitoring, closing the loop.

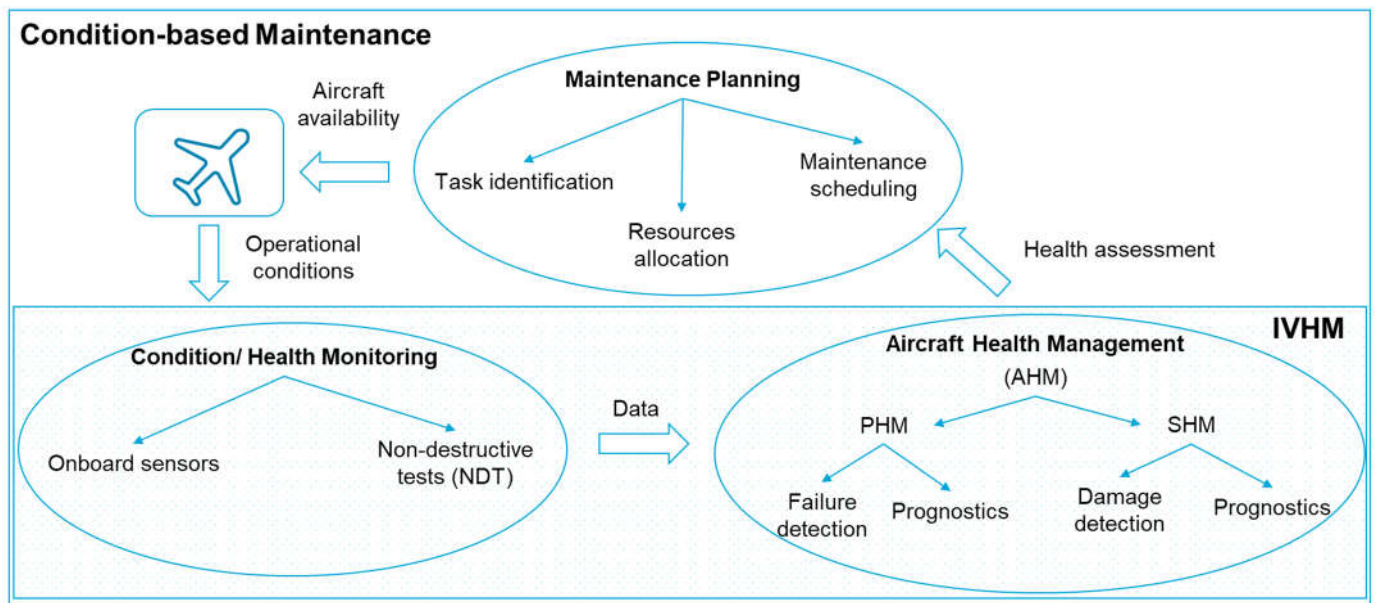


Figure 1. Definition of the Condition-Based Maintenance (CBM) concept.

Several stakeholders also refer to the concept of Integrated Vehicle Health Management (IVHM) [14], which overlaps to a large extent with the concept of CBM. However, IVHM can be seen as integrating condition monitoring and aircraft health management. The result of these approaches is to yield health assessments, vital inputs for maintenance planning.

CBM, as defined above, is a comprehensive policy involving multiple stages and associated research fields. Despite this, most research studies on CBM tend to focus on a single element or, at best, a few elements in conjunction. In fact, the majority of extant literature focuses on the development of Prognostics and Health Management (PHM) as well as Structural Health and Management (SHM) frameworks and methods, intending to provide accurate and early health and Remaining Useful Life (RUL) estimations for different systems and structures [15–19]. A second work stream considers maintenance policy optimization and “is usually based on cost, reliability, or availability” [12]. Several researchers have developed maintenance scheduling and planning approaches in the aviation domain to utilize the predictions resulting from CBM (prognostics) models. This covers applications in many fields, including line maintenance planning [20,21], reduction in unscheduled and scheduled maintenance activities [22], maintenance planning for a fleet of aircraft [5,6,8,23], and the development of entire decision-making support systems for aircraft Condition-Based Maintenance [8]. A third stream of research assesses the (potential) impact of CBM through cost-benefit analysis [22,24–26]). Several studies have provided empirical findings pointing out that CBM reduces asset downtime and total maintenance costs compared to other maintenance strategies [4,27], especially when predicted failures can be turned into scheduled maintenance and clustered with existing activities. However, these findings are established after implementation, leading to a set of research that aims to enable an a-priori assessment of CBM costs and benefits. This considers various potential benefits of CBM, including prevention of unscheduled maintenance, maintenance task replacement, and task interval extensions. While in some research, the effect of incorrect predictions is not assessed [25], other approaches explicitly consider variation in performance as expressed in error metrics or prognostic parameters [22,24,26].

A separate stream of research that considers the implementation of CBM and associated methodologies and process representations can be identified. This type of work builds on the previously covered elements to ask the question: how can CBM solutions be designed and implemented? This is further discussed in Section 2.2.

2.2. CBM Implementation Process Representations

The study of methods and approaches to facilitate CBM implementation has historically taken somewhat of a backseat when compared to the development of detection, diagnostics, and prognostics models, as well as subsequent decision support models. This is reflected in early considerations of CBM implementation, where Jardine et al. [4] identified three key steps for every CBM program: (1) data acquisition, (2) data processing, and (3) maintenance decision-making. Data acquisition relates to “the process of collecting and storing useful information, such as process and event data, preferably in a centrally accessible system” [13]. Data processing covers data cleaning and the subsequent manipulation of data (e.g., labelling, normalization, feature selection) before the processed data are fed into specific models or algorithms. These models are typically set up to perform detection, diagnosis and/or prognosis.

Similar steps are identified as part of the Open System Architecture for Condition-Based Maintenance (OSA-CBM), “a standard architecture for moving information in a condition-based maintenance system”. OSA-CBM comprises six functional blocks and the associated interfaces, including the specification of the inputs and outputs. The six blocks comprise (1) data acquisition; (2) data manipulation; (3) state detection; (4) health assessment; (5) prognostics assessment; and (6) advisory generation. Together, the steps describe “a standardized information delivery system for condition-based monitoring” [28].

Atamuradov et al. [11] offer another representation of the PHM implementation process, where the main steps are “data acquisition, data pre-processing, detection, diagnostics and prognostics, decision making and finally human-machine interface (HMI) [development]”. The latter is a distinct difference from the previously discussed PHM implementation process representations, placing more emphasis on how information is presented to decision-makers.

As noted in [11], the former CBM implementation aspects typically “involve mathematical interpretations, assumptions and approximations [which] make PHM hard to understand and implement in real-world applications, especially by maintenance practitioners in the industry”. A similar issue is noted by Van de Kerckhof et al. [13], who note that asset owners in the process industry struggle to set up and execute systematic CBM approaches and highlight that studying technical factors alone may be insufficient. Finally, Ingemarsdotter et al. [12] propose an integrated framework to analyze challenges and solutions in a set of three CBM implementation cases. However, limitations include the narrow scope of the application and the early stage of CBM implementation for the considered applications. Furthermore, the integrated framework adapts and combines two existing frameworks primarily focused on Internet-of-Thing (IoT) applications rather than CBM.

From the previous discussions, a number of limitations in the state of the art can be identified:

- While CBM and its constituent elements have been well-studied (as also covered by a number of reviews focusing on PHM and SHM e.g., [4]), very few papers comprehensively cover all elements of the definition of CBM as presented in Figure 1. Existing research work has the tendency to be focused on technical, decision-making, or economical aspects;
- A dedicated, up-to-date, multi-stakeholder review of CBM for the application domain of aviation is missing in the state of the art. Available reviews typical consider aviation as one of multiple domains. In doing so, challenges and opportunities specific to the domain are not given sufficient attention. In addition, available reviews—as well as many application studies—are purely academic in nature; that is, they encompass an ‘outsider’ perspective on CBM but do not actively involve input from industrial stakeholders such as airlines, maintenance, repair and overhaul (MRO) companies, primes, suppliers, and legislators.

3. Method

To address these shortcomings, a two-step approach is followed here:

1. To ensure a systematic and comprehensive review of all elements of CBM as defined previously, a structured review framework is required to guide analysis and discussion. Several frameworks have been considered, including generic strategic frameworks such as SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) [29] and PEST (Political, Economic, Sociological, Technological) and its variants [30], as well as Porter's five forces framework [31]. In addition, a recent framework developed specifically for reviewing CBM [12] has been considered. The latter has been selected as a starting point. Its characteristics are discussed in more detail in Section 3.1. However, its existing caveats (as briefly mentioned in Section 2.2 and further substantiated in Section 3.2) require adaptation of the framework. To this end, framework adaptations include a more detailed specification of the context layer, inclusion of economic evaluation considerations, and a representation of product lifecycle aspects. This is further discussed in Section 3.2;
2. The adapted framework is applied towards a systematic review of CBM in aviation, highlighting challenges and opportunities and discussing policy implications, in Section 4.

3.1. Integrated Framework for IoT and CBM Assessment

Ingemarsdotter et al.'s integrated framework [12] has been developed by combining and adapting two earlier frameworks, namely, the new technology stack [32], which describes IoT artefacts as a three-layered technology stack, and the work system framework [33], which describes the system needed to produce a product or a service. The integrated framework is visualized in Figure 2, including examples of the core elements:

3. **Information:** products and systems typically generate data; when viewed in context with other data, the result is considered information [34]. In the framework, information is represented as entities that are "used, created, captured, transmitted, stored, retrieved, manipulated, updated, displayed, and/or deleted by processes and activities" [33].;
4. **Participants:** participants are actors in the work system, producing the actual work. This element is one of two representations of the human elements and their contributions;
5. **Technologies:** technologies "include both tools that are used by work system participants and automated agents; that is, hardware/software configurations that perform totally automated activities" [33];
6. **Activities:** activities are actions that "occur in a work system to produce products/services for its customers" [33].;
7. **Product/Service:** product(s) and/or service(s) "consist of information, physical things, and/or actions produced by a work system for the benefit and use of its customers" [33]. The integrated framework extends this element by introducing the layered technology stack framework, including a service layer, cloud layer, connectivity layer, and product layer;
8. **Customers:** customers are "recipients of a work system's products/services for purposes other than performing work activities within the work system" [33];
9. **Context:** context refers to issues of relevance towards a work system, including environmental considerations (such as organizational, cultural, competitive, technical, regulatory, and demographic factors), infrastructure (resources that are used by the work system but are managed outside of the system), and strategies.

A critical aspect in the integrated framework is formed by the so-called alignment types, as numbered 1–6 in Figure 2. These types describe the interactions between the major work system elements, focusing on how elements align with each other to produce the desired outcome. The six alignment types are further described in Table 1.

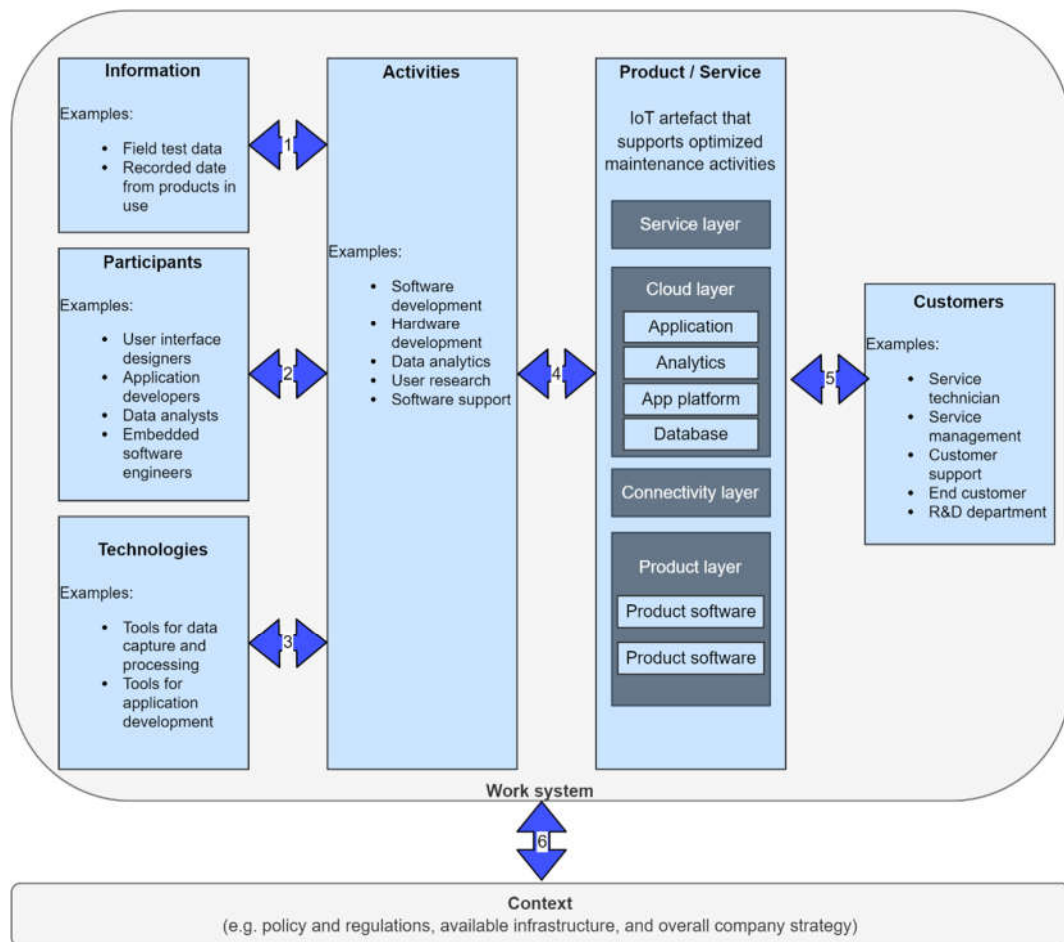


Figure 2. Integrated framework for CBM implementation review [12].

Table 1. Alignment types in the integrated framework [12].

Alignment Type	Explanation
1. Information—Activities	The information that goes into the activities provides satisfactory input to the participants to perform the activities needed to produce the product/service
2. Participants—Activities	The participants are able and willing to perform the activities need to produce the product/service
3. Technologies—Activities	The technologies available to the participants enable them to perform the activities needed to produce the product/service
4. Activities—Product/Service	The activities are well-coordinated and aligned towards the goals of delivering a consistent product/service
5. Customer—Product/Service	The product/service satisfies the needs of all relevant customers, and the customers are able and willing to use the product/service as intended
6. Work System—Context	The surrounding context supports the goal of the work system

3.2. Integrated Framework Adaptations

Several shortcomings can be identified with respect to the integrated framework:

- The integrated framework lacks a clear substantiation of the context layer. In particular, legislative constraints and several resource considerations (especially regarding workforce characteristics) are not clearly identified, while these are quite relevant for policy uptake in general and in aviation in particular;
- The integrated framework lacks attention towards the economic assessment of policies. In other words, requirements and constraints posed by policy assessment,

including associated metrics and performance, are not addressed. This includes considerations of potential commercial revenue and resource requirements. Furthermore, vital questions regarding CBM adoption cannot readily be assessed, for instance, which components are best to equip with novel technology first and which to maintain using legacy policies;

- There is no clear mechanism for translating findings regarding alignment (or misalignment) into implementation and through-life management requirements;
- There is no clear representation of product or service lifecycle considerations; how can a new policy be adopted and applied over time?

The integrated framework is adapted to address these shortcomings and is given in Figure 3. The adaptations include:

- Identifying relevant context, including **cost-benefit assessment, resources, and regulations**, responding to the issues mentioned in the first and second bullet points above. These points are explored in more detail relative to CBM in aviation in Section 4;
- A feedback loop from customers towards the prior elements to represent requirements flow down: in an aviation context, customers—especially launch customers—will play a major role in the definition and refinement of maintenance programs, as per the dominant MSG-3 maintenance program development logic. The associated requirements flow down influences CBM design and implementation across products and services, the enabling activities, information, participants, and technologies. The framework has been extended through a (simple) visual indication of feedback loops (via the directed arrows).;
- Representation of product and service lifecycle considerations: extending on the integrated framework, product and service lifecycles are represented through three main phases, namely, design and development, implementation and operations, and support and phase-out. These phases allow for an explicit consideration of the long-term adoption and evolution of CBM policy for an aircraft lifecycle as well as associated process requirements, which may cover periods of 20+ years (depending on aircraft type). Aircraft configurations, as well as associated maintenance programs, are typically subject to significant updates and revisions during these timeframes, necessitating a representation in the framework.

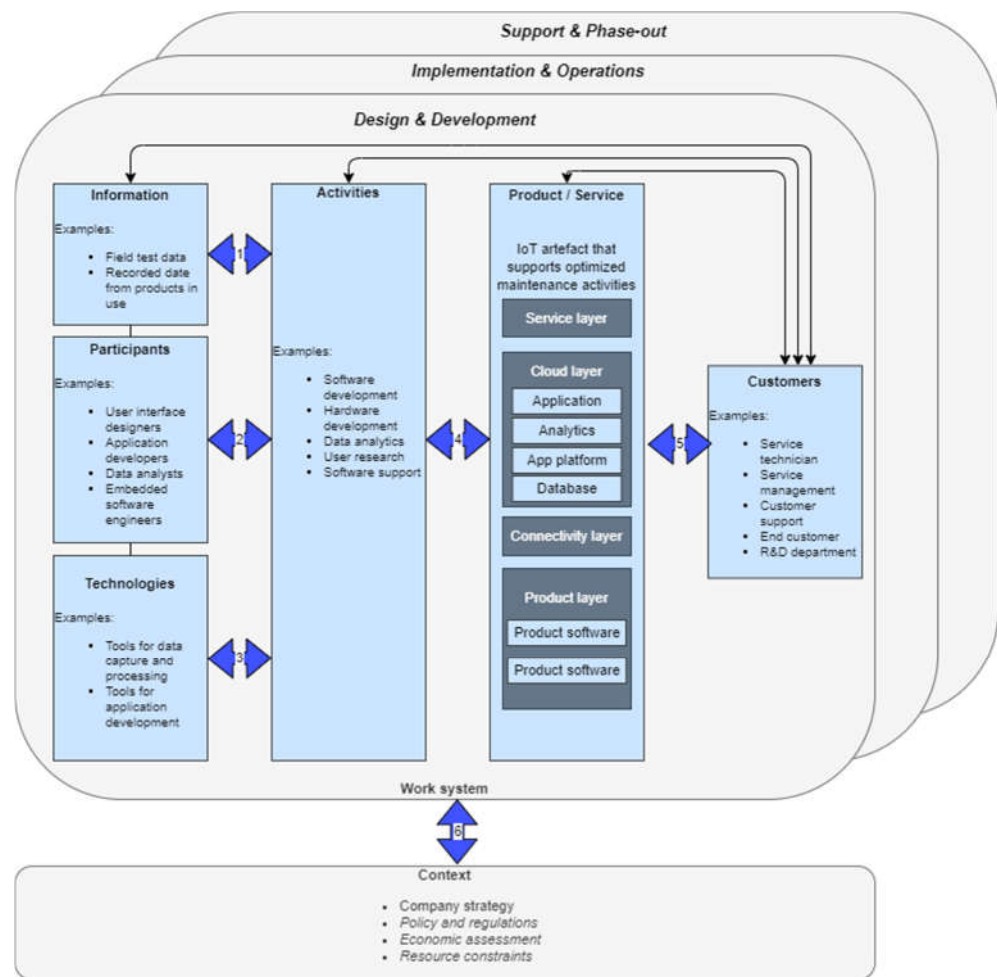


Figure 3. Adaptations (italicized) to the integrated framework proposed by Ingemarsdotter et al. [12].

4. Application to CBM in Aviation: Limitations, Challenges, Policy Implications, and Opportunities

In this section, the adapted integrated framework is applied to identify the limitations and challenges facing CBM. Furthermore, policy implications and opportunities for introducing and implementing CBM in aviation are considered. To ‘instantiate’ the framework, findings from various panel discussions, expert interviews, and stakeholder workshops held at the 1st International Conference for Condition-Based Maintenance in Aerospace (ICCBMA) held at Delft, The Netherlands, on 24–25 May 2022 (<https://cbmacademy.eu/>, accessed on 14 July 2023), and the resulting public deliverable D9.4 “Strategic action plan for future CBM adoption” of the Horizon 2020 Real-time Condition-Based Maintenance for Adaptive Aircraft Maintenance Planning (ReMAP) project have been adopted. Both the conference and the deliverable included input from all categories of primary stakeholders in the aviation ecosystem, including manufacturers/primes, vendors, airlines, MROs, aviation authorities, and academia. As such, a multi-stakeholder perspective on CBM in aviation is provided.

The adapted integrated framework is applied to identify limitations and challenges across the six alignment types. Overall findings are shown in Figure 4 and discussed in more detail in the subsections below.

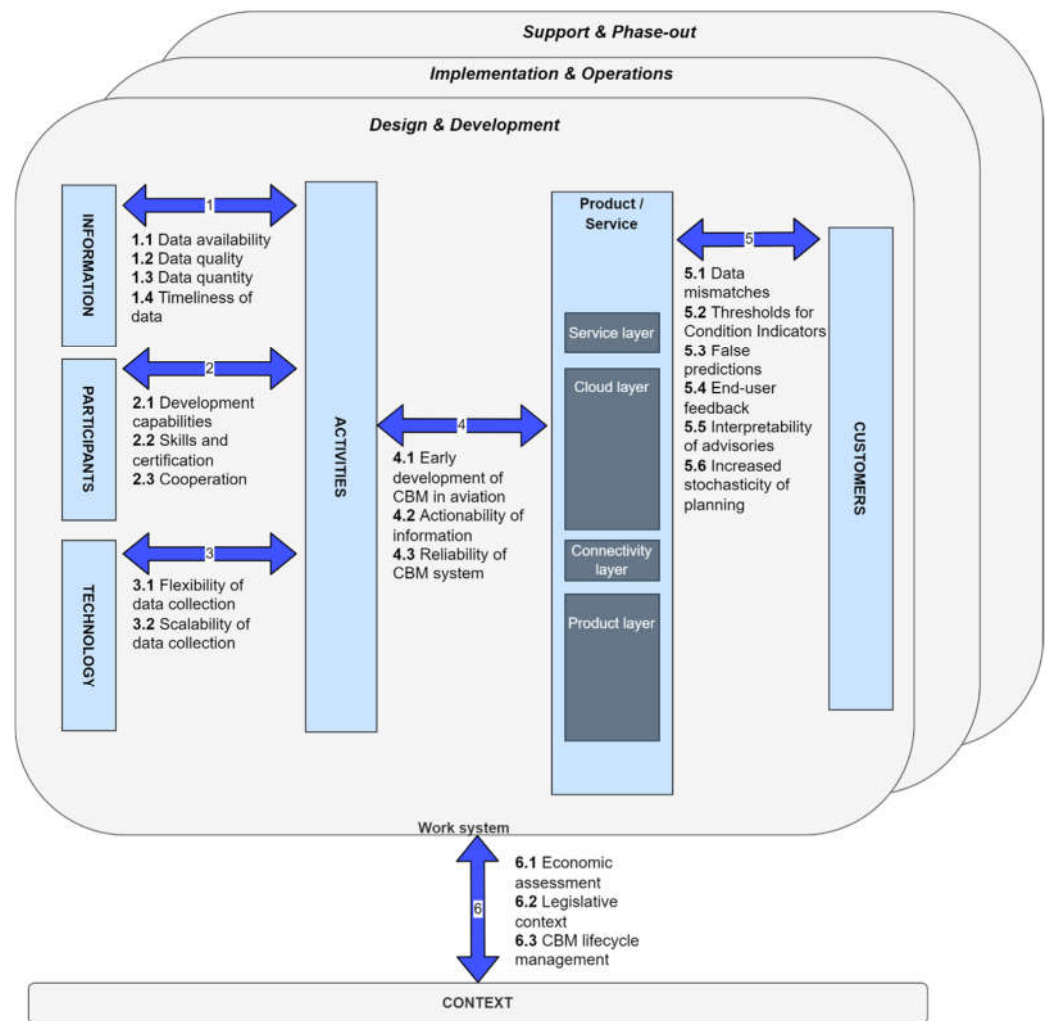


Figure 4. Alignment findings.

4.1. Alignment of Information—Activities

In the context of CBM for aviation, the main challenges for this alignment type center on the availability, quality, quantity, and timeliness of data for use in detection, diagnostics, and prognostics.

4.1.1. Data Availability

Not all data relevant for CBM purposes in aviation are guaranteed to be available. This is particularly the case for SHM where the sensorization of even critical or damage prone aircraft structures is far from being standard. Structures are rather periodically inspected whereas a CBM paradigm calls for continuous or on demand monitoring. Moreover, no single sensing technology is suitable to address all challenges, but rather different technologies must be considered if the complete SHM hierarchy, i.e., anomaly detection, damage location, damage sizing, and severity analysis, is to be covered. 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 [18]. For PHM, typically—even though new(er) aircraft types have an increased number of sensors and associated capture and storage systems available—not all possible parameters can be captured and stored. Airlines have some opportunity to select which sensors and associated data to prioritize, but flexibility is limited. Furthermore, the data captured during a flight may not be transferred at regular and consistent intervals, let alone automatically, due to limitations in data

gathering, transfer, and storage capabilities at various locations in airline networks; outstations, in particular, may not have sufficient provisions for data transfer (e.g., by not having wireless capacities such as gatelink) or the time and personnel required to facilitate data transfer and storage (e.g., when working with short turn-around times). Further complicating this issue is that the communication and storage of data, when talking about terabytes of data per flight, can be extremely expensive. Beyond the sensor data, it is also imperative to capture operations and maintenance (event) data, such as fault messages, EICAS (Engine Indicating and Crew Alerting System)/ECAM (Electronic Centralized Aircraft Monitor) warnings, failures, repair, restoration, overhaul tasks, etc. In addition, while considering usage parameters, environmental conditions and quality of maintenance execution may be used to meaningfully improve predictions [35], these data are usually not captured systematically, nor is it easy to capture given that it may come from different data providers.

4.1.2. Data Quality

Even if data are consistently captured and stored, they may be subject to limitations, such as reliability, completeness, accuracy, and time resolution. A reliable application of a CBM policy 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 recognized that the impact of operational environmental conditions, such as temperature, humidity, and, in particular, vibration, can affect the reliability of sensors. Interruption in generating and transmitting sensor signals can compromise operator awareness of component health degradation. Sensors may fail for reasons other than monitoring structural systems or elements, and sensor condition monitoring is another health management challenge. Resilient sensing systems need to be considered. 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. Beyond reliability, it must be kept in mind that most sensors are not placed in aircraft to monitor the health of related components; they usually serve other purposes, e.g., control. Accuracy and incompleteness often relate to operations and maintenance data limitations, where a human element may be in play, resulting in, for instance, missing or providing incorrect data entry following maintenance interventions [12]. In addition, uncertainty in labeling data exists; sometimes, the aircraft does not clearly identify the origin of a fault. Often, the exact timing of the origin of a fault (or even failure) is uncertain. Configuration changes in the aircraft are well documented (e.g., replacements), but the start date of a fault often remains unknown. Finally, the quality of data may be enhanced by considering data standardization and fusion, an issue explored in more detail in Section 5.

4.1.3. Data Quantity

Aviation data quantity issues usually involve scale. On the one hand, processing and analyzing large datasets can be highly challenging, especially when considering workforce capabilities (see Section 4.1.2). On the other hand, due to existing maintenance policies and corrective mechanisms in the aviation system, the potential of CBM in aviation applications is challenged by the fact that failure events tend to be rare for most non-safety-critical components and exceedingly rare for safety-critical components. Therefore, CBM in aviation usually deals with unbalanced data: a vast number of data can be available, but most of them relate to nominal operations and healthy states and will not have much predictive value. Valuable and rich in information degradation data are usually scarce. In addition, aircraft operate in very diverse environments. With this variety in mind, it is often difficult to assess if anomalies are due to faults or different operations.

4.1.4. Timeliness of Data

For detection, diagnosis, and prognosis using CBM, it is possible to use online and offline methods. The former delivers (near) real-time assessment and/or prediction, whereas the latter introduces a time lag in handling and processing data for CBM purposes. Fast-developing faults may present a challenge in terms of accurate and fast detection and prediction.

4.2. Alignment of Participants—Activities

As noted in [12], typical “challenges within this alignment type relate to a lack of time, resources, and experience in the organization needed to meet CBM-specific requirements”. For the aviation domain, relevant participants in the work system would include internal R&D department(s) as well as external parties. These normally include the Original Equipment Manufacturer (OEM), the type certificate holder, the design organization, and—in many instances—directly providing services to operators. Additionally, suppliers (especially tier 1 suppliers with sufficient critical mass for R&D activities) are also involved in this space. Furthermore, it is not uncommon for contractors specialized in CBM development to be involved [13]. Legislators also require time, resources, and experience to evaluate CBM implementation and compliance in the industry. Taking these stakeholders into account, the following challenges for aviation CBM can be discerned:

10. In-house development capabilities may be limited. Only OEMs, some tier 1 suppliers and the largest in-house MRO providers in the industry have sufficient R&D capacity to develop CBM solutions at scale;
11. CBM development requires particular skills and certifications, many of which are not formally laid down anywhere. MROs, operators, and OEMs are developing these skill sets over time, but few formal guidelines or programs exist to identify and address skills and certification requirements;
12. CBM development requires cooperation across multiple elements of the aviation system. In particular, operations and maintenance departments are involved in CBM development, but not every organization has access to the supporting expertise in these departments. This may be due to internal reasons (e.g., the existence of silos between departments) or external reasons (e.g., being an independent MRO provider without access to operations).

4.3. Alignment of Technology—Activities

For CBM in aviation, the challenges in this alignment type closely match the findings of Ingemarsdotter et al. [12], who note that the flexibility and scalability of data collection and CBM development are problematic. This is mirrored by the findings of the ReMAP project and the dedicated stakeholder panels, and workshops, where efficiency and scalability relative to the design and development of IT solutions and analytical tools for CBM were observed as crucial issues, with big data approaches playing a potential role. With respect to the scalability of data and CBM development, potential roadblocks exist when scaling up the development of CBM development to cover multiple systems and the hierarchy from individual components to systems to systems-of-systems. This involves technological considerations, such as the availability and consistent use of a development platform. Another challenge is the interoperability of data eventually originated by multiple operators, making the data airline agnostic.

As noted previously, airlines have some opportunity to select which sensors and associated data to prioritize, capture, and record. However, this opportunity is limited in volume and frequency: only a subset of available sensors can be selected by the airline, with the others being set by the OEM for operational purposes. In terms of frequency, changing the parameters to be captured is limited because, following any parameter change, data have to be captured for sufficiently long periods of time before being useful for predictions. In addition, when considering real-time acquisition (sensor data

acquisition and pre-processing), transfer (e.g., via Aircraft Communications Addressing and Reporting System (ACARS) or satellite communications), and processing (e.g., using big data technologies), activities may be constrained by bottlenecks in onboard capacity, costs of data transfer, or processing power availability. Finally, these forms of data have to be augmented by data coming from maintenance and operations (e.g., maintenance logs), where increased digitalization provides a pathway forward.

4.4. Alignment of Activities—Product/Service

Several challenges are present in terms of activities—product/service alignment when considering CBM in aviation. As indicated through stakeholder input, a major priority lies in increasing the accuracy and prognostic horizon of health management models in practice. There are four main challenges associated with this effort, namely:

13. In several cases, there are very few failures 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;
14. The lack of publicly available operational aircraft data for model developers to use and exploit. Access to real public datasets can help researchers and digital solutions developers improve their solutions and address the practical challenges of implementation;
15. A lack of physical knowledge about the failure behavior 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 behavior may be necessary to improve the suitability of health management models for practical application;
16. The value of the sensor data collected to detect and explain health degradation. As noted previously, 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.

Beyond these considerations, a major issue relates to the early development stage of many CBM initiatives currently in the market. Organizations may not have fixed processes, roles, and responsibilities to consistently and effectively deliver and maintain CBM solutions. This can be compounded by user issues. The human is, for most operators, the consolidator and analyst of all the information that may lead to feasible maintenance plans. This has the potential to introduce discrepancies in how CBM solutions are used and maintained. This also relates to the previously highlighted issue of data overload. To cope with this, there is a need for an automated approach to process all the data involved in a CBM context, optimizing the maintenance activities for the entire fleet. On the one hand, this is virtually impossible to manage by humans without the support of artificial intelligence, and, on the other hand, a very complex problem to be solved. Current literature is limited in providing a comprehensive and efficient automated method to optimize maintenance activities for a fleet of aircraft under a CBM context.

Complicating the previous considerations is the fact that for critical tasks, the outcome of a CBM product must be guaranteed to be actioned. How is this safeguarded in CBM? How can CBM output be aligned with the correct (corrective) action? I.e., how to make sure CBM is integrated with the maintenance process. Simply having a system that a user should look at once in a while will not work.

From a systems perspective, other issues to consider relating to reliability. How to guarantee the reliability of the CBM system is up to spec to meet safety targets? What are fallback measures when CBM fails? Will organizations switch back to a non-CBM policy, or will all affected aircraft be grounded until the issue is resolved? Recent aviation history has notable examples of where the reliance on technology and automation has introduced major safety consequences and subsequent economic repercussions.

4.5. Alignment of Customer—Product/Service

Customers for CBM in aviation would, at minimum, comprise a range of departments in an airline and/or MRO organization. In particular, the scheduling and planning department, the Maintenance Control Center (MCC), the Operational Control Center (OCC), and the Licensed Aircraft Maintenance Engineers (LAME) may use and interact with CBM solutions. Any developed CBM solution may be vulnerable to the following misalignments.

First of all, potential mismatches may exist in the data and/or meta-data collected and used by CBM developers in CBM solutions and their usability for end-users. For instance, data labelling is crucial to enable training, validation, and retraining of CBM algorithms, but an end-user may find particular labels (if visible to them) irrelevant or distracting. This is one example of what Ingmarsdotter et al. [12] note as a core challenge, namely, "... to translate the needs of the service personnel to the data engineers", and, arguably, vice-versa. Other aspects that are particularly relevant for CBM in aviation include the following:

17. **The use of thresholds for condition indicators:** various detection and diagnostic algorithms use thresholds to inform subsequent decision-making, especially in military applications. If these thresholds are set by developers but are not interpretable by end-users, there is a risk of rote acceptance or neglect of advisories generated by a CBM system;
18. **False positives and false negatives:** most CBM models and algorithms deal with a probabilistic assessment of the health condition of a component and will occasionally get it wrong. False predictions—either false positives or negatives—may reduce acceptance of CBM solutions for end-users;
19. **Feedback loop from end-users:** as noted by Van de Kerkhof et al. [13], CBM solutions require the continuous collection of high-quality data, which involves time from engineers (both licensed aircraft maintenance engineers (LAMEs) and engineers in the supporting MRO organization). However, these engineers may not feel the motivation to record data accurately, given that they may not see the benefit directly from the additional efforts they put into recording these data;
20. **Explainability of advisories:** even when reliable health management models are considered, the additional challenge is to track and explain the results produced by diagnostic and prognostic models. 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 (e.g., [36]);
21. **Increased stochasticity in maintenance planning:** when moving from an inspection-based regime to CBM, one unintended consequence may be that the variability in maintenance intervals increases as fixed intervals are replaced by predictions. This can complicate maintenance planning, especially if CBM is adopted at an increased scale. The maintenance planners must consider the health prognostics of all components being monitored in the fleet to plan the required maintenance actions and keep the aircraft airworthy while respecting flight schedule requirements and maintenance resource limitations. Overall, there is a paradigm change from static and deterministic intervals to probabilistic results subject to error and uncertainty. How will

the current customers (planners) deal with the product output of an entirely new nature?

4.6. Alignment of Context

The alignment of any CBM solution with its context covers several dimensions. Here, in line with the adaptations provided to the integrated framework in Section 3.2, the focus is on three aspects: the economic assessment, the legislative context and lifecycle considerations for CBM in aviation.

4.6.1. Economic Assessment of CBM in Aviation

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.

Economic assessment of CBM requires clear economic Key Performance Indicators (KPIs) relevant for airlines and MROs, and a clear understanding of the potential scope of CBM and its benefits and costs. Some estimates indicate that CBM may lead to cost savings of up to 700 million euro per year for the European aviation sector alone [37]. While several research efforts exist relative to the economic assessment of CBM, most focus on frameworks and models for cost-benefit analysis. Given this, the focus here is on deepening the discussion of relevant KPIs and understanding the scope of CBM.

As a starting point, the concept of Fleet Earning Potential (FEP) expresses the earnings that a fleet can generate. In this context, it can be assumed that the main commercial activity of an aircraft is to perform revenue flights. Ideally, an airline would deploy its aircraft for flights at all times. In that hypothetical situation, a maximum FEP is achieved because all aircraft of the fleet are exploiting their revenue capacity to the fullest by flying continuously. However, it is not possible to schedule an airline network where the fleet is continuously flying in practice. Several factors require the airline to plan ground-time alongside its planned flights (e.g., fueling, passenger boarding, and maintenance). To capture this, the number (or duration) of flights an airline can schedule, given the required reservation for ground-time, is denoted as the *mission capacity of the fleet*, which is the first performance indicator for FEP. The second performance indicator is *operational unreliability*. Several factors influence operational unreliability. These factors include weather, air traffic control, and the aircraft's technical state, which is controlled through maintenance. Lastly, since earnings are expressed as revenue minus cost, we need to consider the cost of performing commercial activities. Here again, maintenance (typically around 10% of total airline cost) is important. Hence, *cost* is the third and last factor for FEP.

To understand the impact of maintenance on FEP, the relative (time) distribution of a fleet's activities during airline ownership is represented in Figure 5. The left graph represents a widebody fleet; the right graph represents a narrow-body fleet. The top bar represents the normalized total duration during which the fleet is owned by the airline. This duration is denoted as *total asset ownership*. The bottom bar shows the relative time the fleet spends flying. Various factors influencing the FEP are given in this figure, with orange blocks representing activities that are (partly) affected by aircraft maintenance. At the bottom, the Realized Flight Operations (RFO) effectively express the realized FEP.

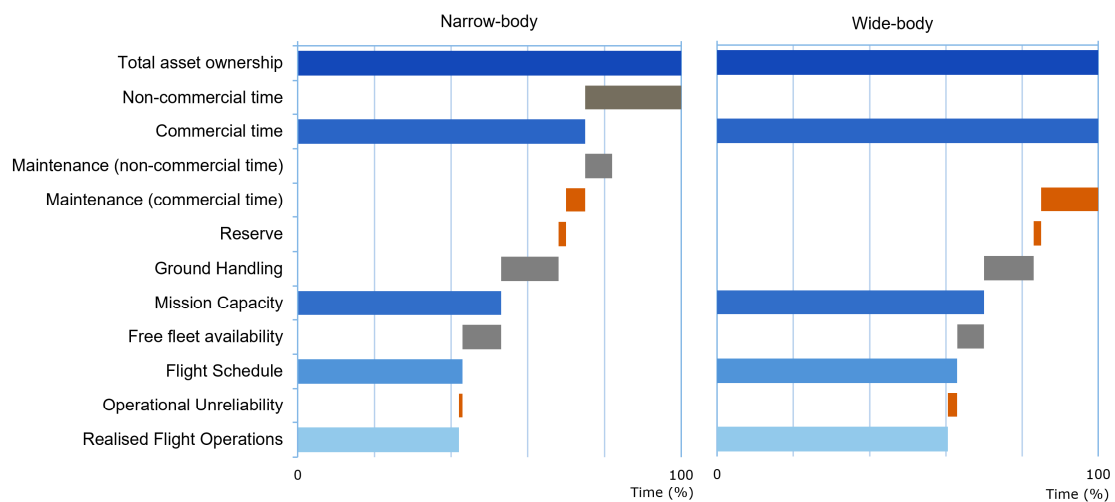


Figure 5. Relative decomposition of fleet activities expressed in time (duration). (Left), narrow-body fleet; (Right), widebody fleet. Orange blocks represent activities that are (partly) affected by aircraft maintenance, whereas blue and grey blocks represent ownership and operational allocations. The figure represents scaled values.

Figure 6 can be used as a basis to illustrate how maintenance decisions can influence mission capacity and operational unreliability. In the context of maintenance, the objective is to determine a strategy where the ground-time due to maintenance (buffers) is as short as possible. Three ways can be identified. Firstly, consider the **quantity**, which is the total number of tasks that need to be performed. Substitution of certain tasks by onboard CBM technology will reduce the total quantity of tasks and, thereby, the required ground-time. The second driver is **efficiency**. By anticipating future maintenance needs using CBM, tasks can be executed in parallel such that the same maintenance demand requires less ground-time. The third and last driver is **timing** as influenced by CBM policy. Execution of tasks in non-commercial time (arrow A in Figure 6), execution of maintenance during ground handling (arrow B), and preventive mitigation of failures (arrow C) are examples where optimized timing of maintenance can contribute to a higher FEP.

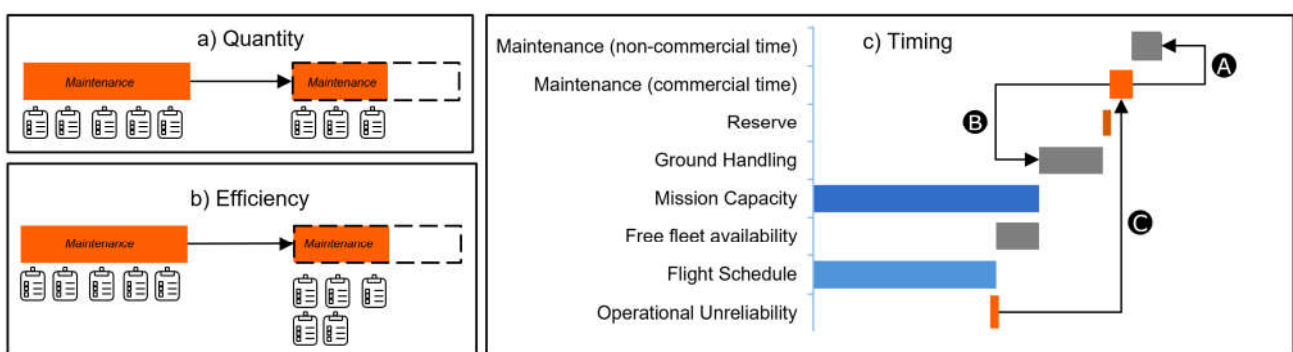


Figure 6. Graphical illustration of three ways to influence FEP by adopting CBM as maintenance policy, with coloured blocks representing the same factors as in Figure 5. (a) Quantity, fewer tasks require less ground-time. (b) Efficiency, parallel execution of tasks requires less ground-time. (c) Timing, execution of maintenance during other types of ground-time increases the mission capacity (arrow A-B); shifting corrective tasks to more convenient maintenance slots reduces operational unreliability (arrow C).

Having set out these KPIs, there is a need for them to be integrated at fleet and aircraft level for economic assessment of CBM. Various research works have used optimization and simulation approaches to study the economics of CBM [22,24,26]. However, challenges concerning the economic assessment of CBM remain. Besides a lack of

unambiguous, widely accepted KPIs for assessing CBM performance and performing cost-benefit analysis of CBM solutions in aviation, ways to identify and assess future opportunities regarding quantity, efficiency, and timing of tasks driven by CBM policy are limited, though several researchers in the scheduling and planning domains have investigated efficiency and timing of CBM [22,24]. These limitations relate to insufficient insight into the reliability (over time) of CBM models, as well as the rigidity of some aspects of the current maintenance program development and implementation approach, where so-called maintenance 'credits' for CBM-derived decisions are not yet adopted.

4.6.2. Legislative Context of CBM in Aviation

The adoption of CBM in aviation has to fit with the general structure of commercial airline maintenance. The MSG-3 approach (Maintenance Steering Group) developed by Airlines for America [38] describes the full methodology to design a maintenance program. This current industry regulations and standards framework, defined by the MSG-3 task-based methodology to derive requirements for planned maintenance, follows 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 maintenance program implementation. Regulators, operators, and manufacturers still do not recognize *certified credit* for health management solutions and offer limited flexibility to drive maintenance based on health indicators or predictions. Still, operators see the value of health management solutions and request more flexibility. In particular, it is recognized 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 [39] 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 [40], titled "Amendment to IP180 to clarify system features to be certified by type certification staff", clarifying the certification process and limiting the scope of the 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 have led, for example, to the Federal Aviation Administration (FAA) Notice No. 8900.634, entitled "Op-Spec/MSpec/LOA D302, Integrated Aviation Health Management Program" and published in July 2022, which authorizes the application process for integrating health management programs for maintenance credit. The Notice recognizes 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 authorization 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 performed 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 decisions.

4.6.3. Lifecycle Considerations for CBM in Aviation

Several lifecycle considerations are particularly relevant for CBM applications in aviation, given the long timespan of the assets (aircraft, engines, landing gears, and other major components). In particular, one issue is how to handle successful CBM applications. Paradoxically, a CBM application that is initially successful may yield suboptimal or even incorrect results later in its life. An initially successful CBM application may lead to fewer failures over time, leading to fewer event data to keep the underlying models and/or algorithms up to date. Due to changes in operational utilization, environmental conditions, or simply accruing age, the assumptions underlying the initial trained CBM application may change over time. Retraining may become difficult as event data are lacking. A second and related issue is how long to keep old data. Data from past years may have lost relevance to current asset use and subsequent CBM application, but literature and practice lack clear markers for identifying when data are outdated. Another consideration is the traceability of data for (post hoc) safety assessment, where data have to be stored and kept for sufficient time to allow for inspection by safety authorities in case of an incident or accident. A final but crucial issue in contemporary aviation is data ownership. As asset ownership over time may change, the associated data may become fragmented. If data are transferred across owners, which data are included and on which basis? It can be argued that aircraft-related data, such as sensor data, onboard system messages, and flight data, may be transferable across the aircraft lifecycle. Still, ownership of detailed event data beyond maintenance certification requirements (such as detailed shop findings) may be kept to the original owner(s) as this reflects on commercial performance. In a wider sense, this is also noted by Van de Kerkhof et al. [13], who mentioned that “data sharing is required [for successful CBM] though organizational incentives to do so are misaligned”.

Another challenge relates to the consistency and traceability of aircraft configuration management over time, especially given that components and systems may switch between multiple aircraft and operators over the life of an aircraft under existing spare parts pooling arrangements. Associated with this, how can the entry of new aircraft into a fleet or the phase-out of aircraft to or from different operators be handled?

Beyond this, the CBM solution has to be sufficiently flexible to move in sync with any changes to data formats, IT/ERP platforms, data exchange standards, human-machine interface requirements, and so on. As experience with legacy systems and migration to new platforms show, this poses a challenge in its own right.

Finally, it is important to recognize 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.

5. CBM Policy Implications: Future Opportunities and Solution Directions

The preceding section highlighted current limitations and challenges for CBM in aviation. The current limitations and challenges for CBM in aviation, highlighted in the preceding section, together with the stakeholders' belief that CBM will become a dominant policy in the future, promoting more efficient and sustainable practices, make CBM a fruitful field of research and development in aviation. In this section, the research opportunities and solution directions that need to be explored to support the future development of CBM are addressed.

22. Data quantity and quality:

23. Sharing data and information between airlines to increase the number of failures in the datasets used to train CBM algorithms. Given the confidentiality and protection of the data, this can be overcome with the use of federated analytics [41]. Federated analytics is a technique used to train machine learning (ML) models across many clients by collecting the data into a central node, ensuring that only the client has a copy of their data. This technique is used, e.g., by developers of mobile applications. Synthetic datasets development using data augmentation for Machine Learning methods is an interesting future direction as well [42–45]. This way, the problem of degradation data scarcity could be effectively alleviated and hybrid, real, and synthetic data could be used to design diagnostic/prognostic methodologies;
24. To help resolve the paucity of failure data, lab tests can be considered to generate data that can be used to develop CBM algorithms for safety-critical components that exceedingly rarely fail.
25. **CBM development:**
26. To address the risks posed by a lack of data—posed both by new and modified components—and its flow-on effect towards CBM development, multiple initiatives can be employed. The first is to develop an initial understanding of component behavior. The operator can, together with the manufacturer, define the ‘normal operating’ behavior of the component and monitor deviations from this behavior to detect degradation. A second approach is using data from the certification process, if available. These data can be used to develop an initial data-based model. This complementary approach can also help to define ‘normal functioning’ behavior. 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 future health degradation patterns. The challenge lies in developing trustworthy models to generate the synthetic data. Once more, the data collected during the certification process can be relevant to increase the reliability of such models;
27. Collaboration is required between similar stakeholders. Due to the global scope of the aviation sector, regulators have to work in unity. Manufacturers share similar technology and clients with heterogeneous fleets. Industry IT standards will be needed to facilitate the marketability of IT solutions;
28. 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 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;
29. The previous two points already identified the need for strong collaboration among stakeholders in the aviation industry to push CBM forward. This perspective can be extended to include researchers, education institutions, OEMs, suppliers, operators, IT providers, and regulators. No CBM solution will fully work without the involvement of multiple stakeholders.
30. **CBM assessment:**
31. A full assessment of CBM policies will require a well-defined set of metrics and their consistent use for assessment purposes. In particular, ‘traditional’ accuracy metrics (such as Root Mean Square Error (RMSE) for RUL predictions) have to be translated into meaningful economic metrics for operators and MROs to work with. As part of this, an integration of predictions with decision support (in particular relative to maintenance planning optimization) is a must;

32. To enable a fair comparison with a CBM policy, interval-based interventions that do not result in actionable outcomes should be viewed as No Fault Found (NFF) events. Following this comparison, the goal should be to adopt a CBM policy that results in fewer NFF cases compared to an interval-based maintenance policy. 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 cost-efficient *backup* process has to be in place;
33. Definitions will have to be reconsidered as well, as *predicting* a future failure under a CBM policy is not the same as *detecting* a fault under today's paradigm. For instance, within ReMAP's demonstration phase, 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.
34. **Usability and acceptance of CBM:**
35. To help transform black-box CBM algorithms into white-box, interpretable, and acceptable algorithms, the use of explainable AI [46] should be considered. This can help both the acceptance of the solutions and the trust on CBM policies;
36. The maintenance planning decision process can be helped by the development of optimization tools while dealing with increasing information resulting from the adoption of CBM. These solutions need to produce fast, flexible, but also stable maintenance schedules when reacting to predictive information from many components in a fleet of aircraft. The use of machine learning (ML) techniques, such as deep reinforcement learning [9,10], are promising solutions.
37. **Workforce considerations:**
38. The automation aspects of CBM may help to address workforce constraints faced by MROs pre- and post-COVID. In tandem with this, the successful adoption of CBM may require the progressive replacement of part of the ageing MRO technician population by data-oriented experts to support the required technological development and lifecycle management. 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 recognizes that the preference goes to domain experts, knowledgeable in aircraft technology, sensing technology, and maintenance operations, who are trained to recognize 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, emphasizing 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;
39. A final point regarding education is the definition of a common language. Many terms are used to define health management solutions and technology, as highlighted previously. 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 jeopardizes the understanding and discussion of health management solutions. Education institutions and aviation standards entities must play an essential role in uniformizing the industry terminology. The concept of CBM as introduced in Figure 1 is one small step to facilitate this process.
40. **CBM and future technology:**

41. A potential path forward for CBM technology is to consider wireless sensors. However, 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;
42. CBM has the potential to facilitate the transition to new energy sources for aircraft propulsion. It may reduce the costs of adopting new power sources and monitor the evolution of the degradation of technologies still in the infancy phase. For instance, it is not yet known if sustainable Aviation Fuel (SAF) use in current technology will require a different maintenance program. A health management solution can help monitor the effect of using SAF and facilitate a flexible maintenance program;
43. Looking further, the potential use of liquid hydrogen for aircraft propulsion 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 reduce maintenance needs and execute maintenance when necessary.

6. Conclusions and Recommendations

This research identified challenges and solution directions related to adopting CBM in aviation. To achieve this aim, an adapted integrated framework has been applied to identify CBM implementation and lifecycle management challenges relevant to aviation and suggest potential solutions. This paper consequently contributes to the existing state of the art by providing a holistic assessment of CBM in aviation, facilitated through an adapted integrated framework providing a systematic approach towards identifying CBM challenges and potential solutions. Based on a variety of inputs from academia and industry, this assessment highlights short-, medium-, and long-term challenges and potential solutions from a CBM lifecycle perspective. Challenges surrounding data, development, implementation, adoption, and evaluation have been discussed, with potential solutions involving alignment of definitions, identification, and uptake of collaboration mechanisms, developing the contributing elements of assessment and subsequent business cases for CBM, upskilling of workforce, and ensuring alignment with future technologies.

Recommendations for future research include extending the adapted integrated framework to study CBM implementation and lifecycle management in other transport domains. Furthermore, further assessment and validation of the adoption and success of CBM in aviation will have to be performed as this policy is progressively rolled out in the sector.

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Abbreviations

ACARS	Aircraft Communications Addressing and Reporting System
ACARE	Advisory Council for Aviation Research and Innovation in Europe
AHM	Aircraft Health Management
CBM	Condition-Based Maintenance
EICAS	Engine Indicating and Crew Alerting System
ECAM	Electronic Centralized Aircraft Monitor
ERP	Enterprise Resource Planning
FAA	Federal Aviation Authority
FEP	Fleet Earning Potential
HMI	Human-Machine Interfaces
IAHM	Integrated Aircraft Health Management
ICCBMA	International Conference for Condition-Based Maintenance in Aerospace
IoT	Internet-of-Things
IT	Information Technology
IVHM	Integrated Vehicle Health Management
KPI	Key Performance Indicator
LAME	Licensed Aircraft Maintenance Engineers
MCC	Maintenance Control Center
MPIG	Maintenance Program Industry Group
MRO	Maintenance, Repair and Overhaul
MSG-3	Maintenance Steering Group – 3
NDT	Non-Destructive Testing / Tests
OCC	Operational Control Center
OEM	Original Equipment Manufacturer
PEST	Political, Economic, Sociological, Technological
PHM	Prognostics and Health Management
RFO	Realized Flight Operations
ReMAP	Real-time Condition-Based Maintenance for Adaptive Aircraft Maintenance Planning
RMSE	Root Mean Square Error
RUL	Remaining Useful Life
SAF	Sustainable Aircraft Fuels
SHM	Structural Health Monitoring
SWOT	Strengths, Weaknesses, Opportunities, Threats
XAI	eXplainable Artificial Intelligence

References

- Berger, J. MRO Industry Forecast & Trends. IATA Maintenance Cost Conference, Geneva, Switzerland, 5 October 2023. Accessed online: https://www.iata.org/contentassets/3f8981eb437e4e16808639bc9d19d5c7/mcc202_day01_0930-1015_mro-forecast-and-mkt-trends_alton_berger.pdf (accessed on 01 July 2023).
- IATA, Airline Maintenance Cost Executive Commentary (FY2020 Data). Available online: https://www.iata.org/contentassets/bf8ca67c8bcd4358b3d004b0d6d0916f/fy2020-mctg-report_public.pdf (accessed on 27 February 2023).
- British Standards Institution, 2017. BSI Standards Publication BS EN 13306:2017 Maintenance—Maintenance Terminology. Available online: www.bsigroup.com (accessed on 14 June 2023).
- Jardine, A.K.S.; Lin, D.; Banjevic, D. A review on machinery diagnostics and prognostics implementing condition-based maintenance. *Mech. Syst. Signal Process.* **2006**, *20*, 1483–1510. <https://doi.org/10.1016/j.ymsp.2005.09.012>.

5. Feng, Q.; Bi, X.; Zhao, X.; Chen, Y.; Sun, B. Heuristic hybrid game approach for fleet condition-based maintenance planning. *Reliab. Eng. Syst. Saf.* **2017**, *157*, 166–176. <https://doi.org/10.1016/j.res.2016.09.005>.
6. Li, Z.; Guo, J.; Zhou, R. Maintenance scheduling optimization based on reliability and prognostics information. Annual Reliability and Maintainability Symposium (RAMS), Tucson, AZ, USA, 25–28 January 2016; pp. 1–5. <https://doi.org/10.1109/rams.2016.7448069>.
7. European Commission, Directorate-General for Mobility and Transport, Directorate-General for Research and Innovation, Flightpath 2050: Europe’s vision for aviation: Maintaining global leadership and serving society’s needs, Publications Office, 2011. Available online: <https://data.europa.eu/doi/10.2777/50266> (accessed on 12 July 2023).
8. Lin, L.; Luo, B.; Zhong, S. Multi-objective decision-making model based on CBM for an aircraft fleet with reliability constraint. *Int. J. Prod. Res.* **2018**, *56*, 4831–4848. <https://doi.org/10.1080/00207543.2018.1467574>.
9. Tseremoglou, I.; Santos, B.F. Condition-Based Maintenance Scheduling of an Aircraft Fleet Under Partial Observability: A Deep Reinforcement Learning Approach. *Reliab. Eng. Syst. Saf.* **2023** (accepted for publication).
10. Tseremoglou, I.; van Kessel, P.J.; Santos, B.F. A Comparative Study of Optimization Models for Condition-Based Maintenance Scheduling of an Aircraft Fleet. *Aerospace* **2023**, *10*, 120. <https://doi.org/10.3390/aerospace10020120>.
11. Atamuradov, V.; Medjaher, K.; Dersin, P.; Lamoureux, B.; Zerhouni, N. Prognostics and Health Management for Maintenance Practitioners—Review, Implementation and Tools Evaluation. *Int. J. Progn. Health Manag.* **2017**, *8*, 1–31. <https://doi.org/10.36001/ijphm.2017.v8i3.2667>.
12. Ingemarsdotter, E.; Kambanou, M.L.; Jamsin, E.; Sakao, T.; Balkenende, R. Challenges and solutions in condition-based maintenance implementation—A multiple case study. *J. Clean. Prod.* **2021**, *296*, 126420. <https://doi.org/10.1016/j.jclepro.2021.126420>.
13. van de Kerkhof, R.M.; Akkermans, H.A.; Noorderhaven, N.G. Knowledge Lost in Data: Organizational Impediments to Condition-Based Maintenance in the Process Industry. In: Zijm, H., Klumpp, M., Clausen, U., Hompel, M. (Eds.) *Logistics and Supply Chain Innovation. Lecture Notes in Logistics*; Springer: Cham, Switzerland, 2016; pp. 223–237. https://doi.org/10.1007/978-3-319-22288-2_13.
14. Esperon-Miguez, M.; John, P.; Jennions, I.K. Uncertainty of performance requirements for IVHM tools according to business targets. *PHM Soc. Eur. Conf.* **2012**, *1*. <https://doi.org/10.36001/phme.2012.v1i1.1413>
15. Altay, A.; Ozkan, O.; Kayakutlu, G. Prediction of Aircraft Failure Times Using Artificial Neural Networks and Genetic Algorithms. *J. Aircr.* **2014**, *51*, 47–53. <https://doi.org/10.2514/1.c031793>.
16. Che, C.; Wang, H.; Fu, Q.; Ni, X. Combining multiple deep learning algorithms for prognostic and health management of aircraft. *Aerosp. Sci. Technol.* **2019**, *94*, 105423. <https://doi.org/10.1016/j.ast.2019.105423>.
17. Loutas, T.; Eleftheroglou, N.; Zarouchas, D. A data-driven probabilistic framework towards the in-situ prognostics of fatigue life of composites based on acoustic emission data. *Compos. Struct.* **2017**, *161*, 522–529. <https://doi.org/10.1016/j.compstruct.2016.10.109>.
18. Verhagen, W.J.C.; De Boer, L.W.M. Predictive maintenance for aircraft components using proportional hazard models. *J. Ind. Inf. Integr.* **2018**, *12*, 23–30. <https://doi.org/10.1016/j.jii.2018.04.004>.
19. Broer, A.; Galanopoulos, G.; Benedictus, R.; Loutas, T.; Zarouchas, D. Fusion-based damage diagnostics for stiffened composite panels. *Struct. Health Monit.* **2022**, *21*, 613–639. <https://doi.org/10.1177/14759217211007127>.
20. Vianna, W.O.L.; Yoneyama, T. Predictive Maintenance Optimization for Aircraft Redundant Systems Subjected to Multiple Wear Profiles. *IEEE Syst. J.* **2018**, *12*, 1170–1181. <https://doi.org/10.1109/jsyst.2017.2667232>.
21. Papakostas, N.; Papachatzakis, P.; Xanthakis, V.; Mourtzis, D.; Chryssolouris, G. An approach to operational aircraft maintenance planning. *Decis. Support Syst.* **2010**, *48*, 604–612. <https://doi.org/10.1016/j.dss.2009.11.010>.
22. Hölzel, N.B.; Gollnick, V. Cost-benefit Analysis of Prognostics and Condition-based Maintenance Concepts for Commercial Aircraft Considering Prognostic Errors. *Annu. Conf. PHM Soc.* **2015**, *7*. <https://doi.org/10.36001/phmconf.2015.v7i1.2716>
23. Yang, D.; Wang, H.; Feng, Q.; Ren, Y.; Sun, B.; Wang, Z. Fleet-level selective maintenance problem under a phased mission scheme with short breaks: A heuristic sequential game approach. *Comput. Ind. Eng.* **2018**, *119*, 404–415. <https://doi.org/10.1016/j.cie.2018.04.005>.
24. Feldman, K.; Jazouli, T.; Sandborn, P.A. A Methodology for Determining the Return on Investment Associated with Prognostics and Health Management. *IEEE Trans. Reliab.* **2009**, *58*, 305–316. <https://doi.org/10.1109/tr.2009.2020133>.
25. Gerdes, M.; Scholz, D.; Galar, D. Effects of condition-based maintenance on costs caused by unscheduled maintenance of aircraft. *J. Qual. Maint. Eng.* **2016**, *22*, 394–417. <https://doi.org/10.1108/jqme-12-2015-0062>.
26. Kählert, A.; Giljohann, S.; Klingauf, U. Cost-benefit analysis and specification of component-level PHM systems in aircraft. *Univers. J. Mech. Eng.* **2016**, *4*, 88–98.
27. de Pater, I.; Mitici, M. Predictive maintenance for multi-component systems of repairables with Remaining-Useful-Life prognostics and a limited stock of spare components. *Reliab. Eng. Syst. Saf.* **2021**, *214*, 107761. <https://doi.org/10.1016/j.res.2021.107761>.
28. MIMOSA, OSA-CBM: Open System Architecture for Condition-Based Maintenance. Available online: <https://www.mimosa.org/mimosa-osa-cbm/> (accessed on 14 August 2021).
29. Leigh, D. SWOT Analysis. In *Handbook of Improving Performance in the Workplace*; Silber, K.H., Foshay, W.R., Watkins, R., Leigh, D., Moseley, J.L., Dessinger, J.C., Eds.; 2010, Volumes 1–3, Pfeiffer (An Imprint of Wiley), San Francisco, CA, USA. <https://doi.org/10.1002/9780470592663.ch24>.
30. Ho, J.K.K. Formulation of a systemic PEST analysis for strategic analysis. *Eur. Acad. Res.* **2014**, *2*, 6478–6492.

31. Porter, M.E. Competitive Strategy. *Meas. Bus. Excel.* **1997**, *1*, 12–17. <https://doi.org/10.1108/eb025476>.
32. Porter, M.E.; Heppelmann, J.E. How smart, connected products are transforming competition. *Harv. Bus. Rev.* **2014**, *3*. Available online: <https://hbr.org/2014/11/how-smart-connected-products-are-transforming-competition> (accessed on 12 July 2023).
33. Alter, S.; Work system theory: Overview of core concepts, extensions, and challenges for the future. *J. Assoc. Inf. Syst. Online* **2013**, *14*, 72–121. <https://doi.org/10.17705/1jais.00323>.
34. Alavi, M.; Leidner, D. Review: Knowledge Management and Knowledge Management Systems: Conceptual Foundations and Research Issues. *MIS Q.* **2001**, *25*, 107–136. <https://doi.org/10.2307/3250961>.
35. Thijssens, O.; Verhagen, W.J. Application of Extended Cox Regression Model to Time-On-Wing Data of Aircraft Repairables. *Reliab. Eng. Syst. Saf.* **2020**, *204*, 107136. <https://doi.org/10.1016/j.ress.2020.107136>
36. Linardatos, P.; Papastefanopoulos, V.; Kotsiantis, S. Explainable AI: A Review of Machine Learning Interpretability Methods. *Entropy* **2021**, *23*, 18. <https://doi.org/10.3390/e23010018>.
37. European Commission—Cordis, Horizon 2020 Real-Time Condition-Based Maintenance for Adaptive Aircraft Maintenance Planning. Available online: <https://cordis.europa.eu/project/id/769288/> (accessed on 16 August 2023)
38. Airlines for America, 2018. MSG-3: Operator/Manufacturer Scheduled Maintenance Development, VOLUME 1—FIXED WING AIRCRAFT. Available online: https://infostore.saiglobal.com/en-us/standards/ata-msg-3-vol-1-2018-1-162842_saig_ata_ata_2765605/ (accessed on 12 July 2023)
39. International Maintenance Review Board Policy Board (IMRBPB), 2018. Issue Paper (IP) 180, Aircraft Health Monitoring (AHM) integration in MSG-3. Available online: <https://www.easa.europa.eu/download/imrbpb/IP%20180%20-%20AHM%20integration%20in%20MSG-3.pdf> (accessed on 27 February 2023)
40. International Maintenance Review Board Policy Board (IMRBPB), 2018. Issue Paper (IP) 197, Amendment to IP180 to Clarify System Features to Be Certified by Type Certification Staff. Available online: https://www.easa.europa.eu/sites/default/files/dfu/ip_197_-_amendment_to_ip180.pdf (accessed on 27 February 2023).
41. Li, L.; Fan, Y.; Tse, M.; Lin, K.-Y. A review of applications in federated learning. *Comput. Ind. Eng.* **2020**, *149*, 106854. <https://doi.org/10.1016/j.cie.2020.106854>.
42. Che, C.; Wang, H.; Xiong, M.; Luo, S. Few-shot fatigue damage evaluation of aircraft structure using neural augmentation and deep transfer learning. *Eng. Fail. Anal.* **2023**, *148*, 107185. <https://doi.org/10.1016/j.engfailanal.2023.107185>.
43. Dabetwar, S.; Ekwaro-Osire, S.; Dias, J.P. Fatigue Damage Diagnostics of Composites Using Data Fusion and Data Augmentation With Deep Neural Networks. *ASME J Nondestruct. Eval.* **2022**, *5*, 021004. <https://doi.org/10.1115/1.4051947>.
44. Kim, S.; Kim, N.H.; Choi, J.-H. Prediction of remaining useful life by data augmentation technique based on dynamic time warping. *Mech. Syst. Signal Process.* **2020**, *136*, 106486. <https://doi.org/10.1016/j.ymsp.2019.106486>.
45. DeQun, Z.; JiaYu, Z. Remaining life prediction of turbofan engine based on multi-path feature fusion.. In Proceedings of the 4th International Conference on Information Science, Electrical, and Automation Engineering (ISEAE 2022), 122573O, Hangzhou, China, 1 August 2022. <https://doi.org/10.1117/12.2640207>.
46. Arrieta, A.B.; Díaz-Rodríguez, N.; Del Ser, J.; Bennetot, A.; Tabik, S.; Barbado, A.; Garcia, S.; Gil-Lopez, S.; Molina, D.; Benjamins, R.; et al. Explainable Artificial Intelligence (XAI): Concepts, taxonomies, opportunities and challenges toward responsible AI. *Inf. Fusion* **2020**, *58*, 82–115. <https://doi.org/10.1016/j.inffus.2019.12.012>.

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