Digital Twin-based IVHM for Predictive Maintenance

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ABSTRACT

This paper proposes a Digital Twin-based Integrated Vehicle Health Management (IVHM) approach to enable predictive maintenance in aviation and aerospace industry. Predictive maintenance enables the identification of potential failure before they occur, improving operational efficiency, safety, and cost management by reducing downtown and optimizing maintenance scheduling. However, conventional approaches face three key challenges: lack of reliable run-to-failure data, uncertainties in system behavior and predictions, and fragmented processes between design and maintenance activities. This article introduces the concept of *Authoritative Hybrid as-operated Digital Twin* to overcome the current limitations. The proposed solution brings three main technical advancements: the integration of physics-informed Artificial Intelligence (AI) architecture reusing design artifacts into an IVHM system; the implementation of a comprehensive Validation, Verification, and Accreditation (VVA) process to support certification; and the enhancement of Model-Based Systems Engineering (MBSE) methods to ensure digital continuity across the different processes. This supports the development of advanced predictive maintenance capabilities, aligned with the vision of Type III IVHM systems, ultimately enabling more resilient, informed, and cost-effective operations in aerospace domain.

1. INTRODUCTION

Robust diagnostic and prognostic health management services offer a substantial value to aviation and aerospace businesses, enhancing operational efficiency, safety, and cost management. Predictive maintenance identifies when potential failures occur, enabling a proactive approach to maintenance scheduling compared to traditional scheduled maintenance, thereby reducing downtimes and future flight legs based on the actual aircraft conditions. Today, the Integrated Vehicle Health Management (IVHM) (*SAE ARP6803*) system services, i.e. diagnostic & prognostic, indicated as Type I/II, are mainly based on data analytics and developed and provided by Original Equipment Manufacturing (OEM) or services-oriented companies (*SAE ARP6887*). The industry is moving towards Smart Products to enable predictive maintenance (PdM) and inform operations (e.g. pilots/airlines), requiring more competitive solutions with advanced predictive capabilities, i.e. Type III IVHM (*SAE ARP6887*).

Three main challenges currently exist in conventional approaches:

1. The lack of reliable run-to-failure data, the growing product complexity, and the limited availability of on-board sensors make it difficult to correlate operational data with degradation phenomena; (*Sikorska, Hodkiewicz & Ma. (2011)*)
2. The inherent uncertainties of the physical system, the uncertain nature of predictions and the lack of appropriate assurance criteria for certification hinder the deployment of IVHM systems as Alternative Means of Compliance (AMoC) to scheduled maintenance for Safety-critical systems; (*IMRBPR IP 180 (2018)*)
3. The hand-off of critical information from the design and safety assessment processes to the maintenance process is still heavily document-based with manual traceability across artifacts, leading to significant risks of overlooking assumptions or missing critical changes.

The as-operated Digital Twin (*Michael, Pfeiffer, Rumpe, & Wortmann, (2022)), (Hartwell, Montana, Jacobs, Kadirkamanathan, Ameri & Mills, (2024))* is a virtual representation of a specific real-world system, with synchronized interactions using real-time and historical data. It allows advanced diagnostic and prognostic analysis, providing accurate forecasting of future conditions (*Shahin, K. I., & Lazarova-Molnar, (2024)*) that can be used to enable a Type III IVHM. Importantly, as *Ferrari, A., & Willcox, K. (2024)* emphasize, a Digital Twin does not need to be a perfect virtual replica, but rather one that is *fit for purpose*, based on capability requirements

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and cost–benefit considerations. This research addresses the above-mentioned challenges by introducing the concept of Authoritative Hybrid Digital Twin, that differentiates from current approaches proposed in the literature by building on three key technical advancements: 1) the combination of data-driven and model-based engineering (MBE) into a hybrid physics-informed AI architecture embedded in an IVHM system; 2) the assessment of existing guidelines on Validation, Verification and Accreditation (VVA) in conjunction with ongoing effort on AI trustworthiness and VV guidelines for IVHM systems; 3) the application of advancements in Model-Based Systems Engineering (MBSE) to enable digital continuity. This study proposes a methodology to enable the usage of Digital Twins in IVHM systems. The application and validation of the proposed approach in an industrial setting are left for future research.

2. INTRODUCTION TO IVHM

The IVHM is defined as a system of systems, capable of assessing current and future health status (*SAE ARP6803*). The implementation of an IVHM system on an aircraft is driven by different business needs e.g. to enhance safety and reliability, to reduce maintenance and operational costs. A set of standards governing IVHM system development process has been delivered by SAE International and shown in Figure 2.

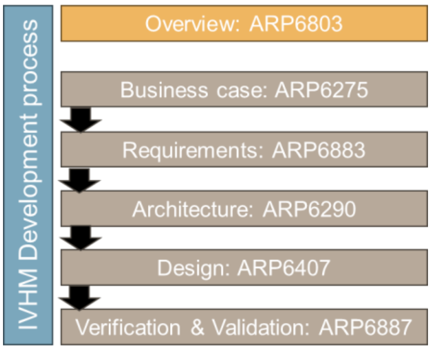

Figure 2. Map of standards guiding the IVHM system development process.

A feasibility assessment, including cost/benefit analysis, is first performed, involving different parties as customers, OEM and IVHM providers. At this stage, the identification of enabled services is crucial, e.g. enable predictive maintenance before a NOGO condition or inform the pilot to extend product lifetime. A list of potential benefits for each in-service (*continuing airworthiness*) and design (*continued airworthiness*) consumer is provided in Figure 1 with related need for certification of the IVHM system. As general practice, if the IVHM recommendations are used to improve scheduled maintenance, the certification authorities need to be involved. This is not the case when the recommendations are used to improve operations (airline or logistics) or improve a new product design. However, each service should be analyzed separately, involving OEM, certification authorities and IVHM provider.

The guidance for IVHM systems development, provided by the other standards listed in Figure 2, will support the definition of the Digital Twin-based IVHM architecture proposed in this contribution.

2.1. The different types of IVHM

An IVHM system provides diagnostic and prognostic capabilities. Within this context, three main types of IVHM systems have been defined by *Adhikari, Rao & Buderath, (2018)* and referenced in *SAE ARP 6887*:

- Type I, known as Reliability Data-based, focuses on estimating the expected lifetime of a component operating under historically average conditions.
- Type II, or Stress-based, estimates the average components lifetime under a specific operational environment.
- Type III is Condition-based and aims to assess the lifetime of a specific component in its specific environmental conditions.

	Consumer	Services	Certification
In-Service	Maintenance (Airline/MRO)	Enable preventative maintenance before a NOGO condition (pre-failure)	Y
		Prevent the operator from risk of departure delay or flight cancelation due to time-consuming inspections (pre-failure)	
		Provide improved diagnosis for better fault isolation in repair process to support shorter gate turnaround (post-failure)	
		Avoid unnecessary maintenance actions and flight delay due to unreliable indications	
		Support the throubleshooting analysis	
	Airline operator	Provide awareness about hard conditions that potentially happened during operation to perform inspection after flight	N
		Provide prediction of potential NOGO conditions	
		Minimize operations cost	
		Minimize lifetime fuel i.e., lifetime operating cost.	
		Inform pilot to safety recommendation (fault prediction)	
		Inform pilot to extend product lifetime	
		Predict and assess the Minimum Equipment List (MEL) with operating conditions	
	Logistics	Detect failure with advanced warning to start parts requisition process while the system will continue in operation to allow agile logistics	N
Design	Product owner or supplier	Support/inform design accounting for actual operating conditions (1)	NA
		Optimized margin of safety	
		Inform/extend traditional FMEA/FMECA	

Figure 1 List of enabled services (not exhaustive) for each consumer, with related need of IVHM certification.

2.2. Value Proposition of Type 3

Today, the IVHM services of diagnostics and prognostics are mainly based on data analytics and consider average component lifetime and/or average operating conditions (Type I and II). The industry is moving towards Smart IVHM Products to inform maintenance and operations (Pilots/Airlines) requiring more competitive solutions, as Type III, with predictive capabilities. The accurate prediction of Remaining Useful Life (RUL) of aircraft components offers a substantial value to aviation and aerospace businesses, enhancing operational efficiency and cost management. Predictive maintenance identifies when potential failures occur, enabling a proactive approach to maintenance scheduling thereby reducing downtimes and future flight legs based on the actual aircraft conditions rather than on a fixed schedule. Moreover, predictive maintenance has a positive impact on sustainability of the aerospace industry as efficiently maintained aircrafts consume less fuel and produce fewer discarded parts by optimizing the time in operation. In 2022, the regulators approved the IVHM as an Alternative Means of Compliance (AMOC) to scheduled maintenance for non-safety critical systems. The airlines are working with the OEMs to modify their current maintenance programs to use IVHM on as many systems as possible, including tasks mandated by an airworthiness directive (AD). The industry is working with the regulators to extend this AMOC to include safety-critical systems by 2030.

3. IVHM TYPE 3: OPEN CHALLENGES AND EXISTING APPROACHES

3.1. Lack of run-to-failure data and physics complexity

Traditionally, predictive modelling can be identified into two main categories, namely physics-based and data-driven approaches. Physics-based modelling allows to keep the physical interpretation of the results, but its applicability is challenging when there is partial or poor knowledge of physics or when dealing with complex physical phenomena that are difficult to be modelled numerically. Conversely, data-driven approaches are based on ML algorithms, and they are employed to mitigate drawbacks of physics-based modelling as they don't require prior knowledge of physical system and can model complex physical phenomena based only on data. Despite these advantages, the field of ML modelling can also be challenging as it requires a huge amount of data and can lack model generalization. Hybrid or physics-informed ML solutions have been developed to integrate advantages of both approaches. By constraining the hybrid model with partial physical knowledge, it enables better understanding and trust in the model predictions (model interpretability) and can achieve more robustness and reliable predictions in a wide range of scenarios (generalization) compared with data-driven models. Moreover, hybrid modelling requires less knowledge of physics as it can fill-in details that might not be captured by the available physics models (dependency on physical knowledge) and can perform well also with limited data (data requirement). Hybrid methods provide robust RUL prediction against model assumptions of physics-based methods or data selection policies of data-driven approaches, thus combining advantages of different prognostic methods (*Li, Zhang, Li, & Si (2024)*). A detailed comparison between the three main existing methods applied to a case study can be found in *Liao & Köttig (2014)*. Despite the advantages of hybrid modelling, these techniques are recently emerging and there is still some work to enable rapid deployment in industrial applications. Some technical challenges are identified in literature (*Li, Zhang, Li, & Si (2024)*): i) trade-off between physical knowledge and data-driven modelling, ii) model coupling and integration, iii) uncertainty quantification and robustness, iv) model scalability and management. Moreover, harmonizing the validation and calibration processes in hybrid models is essential to ensure accuracy and reliability.

3.2. IVHM as AMOC for fixed-wing aircraft

ATA MSG-3 Vol. 1 Revision 2022.1 (*ATA MSG-3 2022*) introduces the integration of IVHM capability for fixed-wing aircraft into the MSG-3 process. A key update is the recognition of IVHM as an AMOC to scheduled maintenance, where the use of IVHM requires certification of associated on-aircraft components by the type certification staff of the Regulatory Authority. Importantly, IVHM use is limited to non-safety tasks, provided these tasks do not involve Certification Maintenance Requirements (CMRs), as outlined in *IMRBPR IP 197*, which incorporates feedback from Airbus and Boeing. Additionally, the ATA MSG-3 2022 revision introduces the concept of IVHM Level 3 Analysis. This analysis is applied when a system offers IVHM capability and involves assessing whether AHM can address failure causes related to lubrication and servicing, degradation detection, and hidden failure detection. The outcome of this Level 3 analysis may result in one of three determinations: No IVHM (the classical task, named Level 2, remains necessary), IVHM Alternative (IVHM fully replaces the classical task), or Hybrid IVHM, where both IVHM and classical tasks are required because IVHM alone does not sufficiently cover all failure causes. OEM is responsible for IVHM system configuration and respective functionality within the IVHM analysis, while the operator has the possibility to switch between Level 2 and Level 3 outcome. Today, the industry is working with the regulators to extend IVHM as AMOC in MSG-3 to include safety-critical systems by 2030.

3.3. Document-based hand-offs between design and maintenance processes

One of the main challenges in engineering processes lies in the document-based hand-offs between system design, safety assessment, and maintenance activities. These hand-offs are prone to errors because information extraction is labor-intensive, and assessing the impact of changes and tracking them is prone to omissions.

A recent contribution in addressing this challenge is the simulation-driven approach proposed by *Rhein, Bimbi,* *Miraglia & Holzapfel (2024)*. This approach introduces a digital link between system development and safety assessment processes by establishing traceability and consistency between artifacts produced by these processes. Thanks to the use of model-based architecture specifications, performance models and the automated injection of faults associated to failure modes in the FMEA tables, simulations are used to automatically evaluate the adherence of failure effects and the data reported in FMEA tables, enabling early detection of inconsistencies between the different artifacts. However, despite these advantages, the approach focuses primarily on the design phase and does not extend these digital links to the maintenance phase.

The proposed methodology addresses this limitation by defining a model-based approach to integrate design artifacts for maintenance management and leverage digital links to assess impact and track changes. This allows less effort in monitoring changes in different data, increasing the consistency among them.

4. METHODOLOGY

The proposed methodology is structured around two interconnected activities: **Digital Continuity** and **Digital Twin** (Figure 3). These two activities are designed to interact and reinforce each other through continuous exchange of information.

The **Digital Continuity** activity focuses on establishing digital links between design artifacts and maintenance data. This includes integrating system architectures, performance model, failure propagation model and safety artifacts (e.g. FMEA table) with maintenance and operational information. Through these links, the methodology enables continuous evaluation of the consistency between design assumptions and real-world system behavior. Adequacy of maintenance policies can be continuously evaluated by comparing maintenance reports and operational data against design assumptions and safety assessments, thus supporting early identification of deviations and potential design gaps.

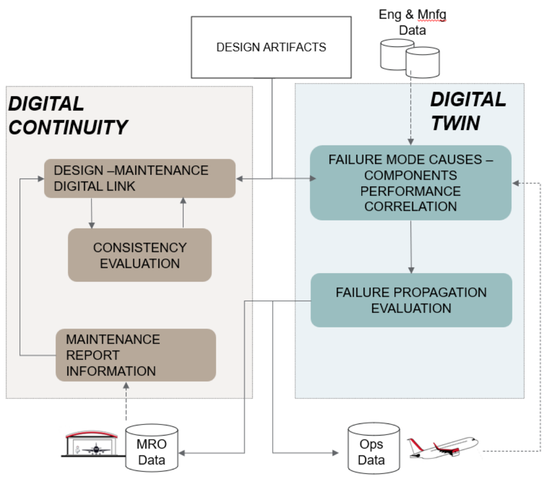

Figure 3. As-operated hybrid Digital Twin for IVHM workflow.

The as-operated **Digital Twin** is associated to one or more failure causes and can correlate these failures, e.g. wear, oxidation, with operational data, evaluating their impact at component or subsystem level. Another capability of the as-operated Digital Twin is to evaluate the fault propagation, with potential cascading effects, at system-level. The definition of the as-operated Digital Twin architecture requires the selection of a modelling technique, e.g. MBE, data-driven or hybrid, which is driven by the number and type of data sources and type of prior physical knowledge of the system. To enable the concept of **Authoritative Digital Twin**, a model accreditation process to build a trustworthiness framework for usage in new and more effective after-market services, e.g., predictive maintenance, is crucial.

The next sections discuss the proposed methodology, addressing the challenges related to the Digital Continuity and the Digital Twin predictive modelling.

4.1. Methodology Workflow for predictive modelling

The field of predictive modelling offers numerous methods in literature, each suitable for a specific type of physical model. The selection of a particular method depends on different factors:

1. Amount and type of available data, e.g. engineering/test and operational data;

2. Type of physical prior, which refers to the numerical formulation that describes the physical behavior of a real system, which can range from first-principle laws (i.e. *intuitive physics* in Figure 4) to high-fidelity complex models;

3. Level of fidelity of the physical prior, which drives the selection of the most suitable hybrid approach.

Based on these 3 key factors and starting from the availability of a physical model and a set of data, this section provides a methodology framework (Figure 4) to identify the most suitable category of predictive modelling methods among physics-based, data-driven or hybrid approaches, for a given case-study. Four main categories of hybrid modelling are identified in literature *(Thelen, A., Zhang, X., Fink, O., Lu, Y., Ghosh, S., Youn, B. D., Todd, M. D., Mahadevan, S., Hu, C. & Hu, Z. (2022); Li H., Zhang, Li T. and Si, (2024)):*

1. Data augmentation: e.g. *Zhuang, Qi, Duan, Xi, Zhu, Zhu, Xiong & He (2020)* provides method to increase the number of available data with high-fidelity simulation results.
2. Physics-informed AI, where the physical prior is embedded in the model or in the loss function *(Raissi, Perdikaris & Karniadakis, (2019))*. Residual formulations are also proposed to compensate for the unknown physics with a black-box model (*Ansys*).
3. Physics-informed architecture design: method to improve the interpretability of the ML models by

constraining some parameters of the architecture with physical information *(Nascimento & Viana, (2019))*.

4. Physical model and data fusion: these methods integrate physical models of degradation mechanisms with real-time monitoring data to update model parameters and enhance real-time predictions. Examples are Bayesian filters, Kalman filters (*Simon, 2001*) and particle filters.

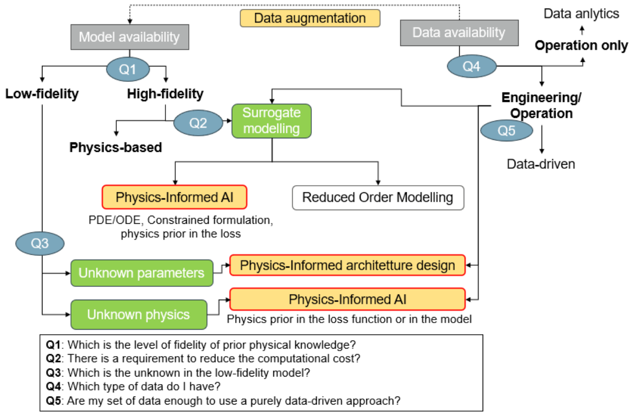

Figure 4. Methodology workflow for the selection of predictive modelling techniques.

4.2. VVA approach

To provide certification evidence that an aircraft complies with the applicable airworthiness requirements, and it is in a condition for safe operation, by using a hybrid Digital Twin-based IVHM system, there is a need to define a Validation, Verification, and Accreditation (VVA) process for the Digital Twin to support existing guidelines for IVHM V&V (SAE ARP6887, ARP6883). In this paper, the term VVA is adapted from the VVA used in Initial Airworthiness (EASA CM-S-014 Issue 01(2020), MIL-STD-3022 (2021)). It establishes a framework for simulation credibility, allowing a safety regulator to accept the simulation results to show compliance of an aeronautical product with a certification requirement (Certification by Analysis – MoC 2). The VVA process is essential, in conjunction with ARP6887, ARP6883, ARP5783 and other applicable standards, to build a trustworthiness framework to enable the usage of Digital Twin in new and more effective after-market services. It allows product design and manufacturing optimization and validates system requirements. The main challenge is how to demonstrate that the hybrid model and associated analysis/simulation are fit for purpose with respect to specific objectives. Today, several VVA guidelines are provided in the literature (EASA CM-S-014 Issue 01(2020), MIL-STD-3022 (2021)) for initial airworthiness and applied mainly in structural applications (EASA CM-S-014 Issue 01(2020)). This process is still not sufficiently explored in other application domains and limited to physics-based modelling The implications of health monitoring specific metrics (SAE ARP5783) on the VVA process must be assessed. Certification guidance exists for vibration health monitoring (AMC 29.1465) and Rotorcrafts health usage monitoring system (AC 29-2C MG 15). Information from such guidelines, especially as regards diagnostics and prognostics performance, may be applicable to other health monitoring applications and transport categories and be used to adapt and instantiate a VVA process to support credit validation when the Digital Twin is used as part of the health monitoring algorithm.

According to ARP6887, the design, verification, and validation process of a Hybrid Digital Twin-based IVHM System must be carried out in accordance with the technical standards required for onboard aerospace applications, such as ARP4754A (for development process), ARP4761 (for safety assessment process), RTCA DO-178 (for software), RTCA DO-254 (for hardware), and FAA guidance provided by AC 25.1309-1A. In addition, when AI technologies are used within the IVHM System, they introduce development and implementation approaches that are not fully aligned with existing design and development assurance methods. For this reason, the aerospace industry is making efforts to provide additional guidelines that complement existing development assurance methods (SAE ARP6983). These guidelines support the continued development of aeronautical safety-related products implementing ML, ensuring they meet the safety intent of applicable regulations. Therefore, the development of an as-operated hybrid Digital Twin needs to consider this future regulation once it will be available.

4.3. Digital Continuity

One of the main challenges, as highlighted in Section 3.3, lies in the document-based hand-offs between the different processes. These hand-offs often lead to the risk of omission or misinterpretation of critical information, which complicates the tracking of changes and increases the risk of inconsistencies, especially when moving toward maintenance process.

To address this challenge, the proposed methodology introduces a **model-based approach** to support **digital continuity** across the different key artifacts from the different processes. The core idea is to convert key outputs from the System Development process - such as system performance model and architectural models - and from Safety Assurance process – such as FHA and FMEA tables – into interoperable models that can be formally integrated by digital links. These digital links enable comprehensive traceability for the artifacts originating from the different processes, ensuring their consistency.

These digital links proposed in our methodology span across multiple dimensions. It starts with the creation of digital links between system's functional and physical architectures and the corresponding performance representations, allowing to trace how each component contributes to the realization of system functions and to assess whether performances expectation is met. At the same time, failure conditions identified during safety assessments, such as those in the FHA, are linked to behavioral models to monitor system performances, thus enabling the identification of operational deviations from nominal conditions. Furthermore, failure modes and their associated effects, as described in the FMEA table, are linked to simulation models that represent how specific faults influence the performance of the components or subsystems, supporting validation of the alignment of the modeled fault propagation with the assumptions of the safety analysis.

The creation of these links ensures a coherent digital thread that enables a systematic assessment of completeness: by tracing simulation and test cases back to the FMEA, it becomes possible to ensure that all failure scenarios and their effects are properly analyzed and effectively captured in the FMEA.

While our current instantiation of the methodology does not yet digitally link to maintenance artifacts, it provides a framework to trace simulation and test cases to the information needed for maintenance policies management, such as maintenance intervals. The same framework allows analyzing how the system responds to degradation in real conditions and continuously reassesses the adequacy of the maintenance policy. This is particularly relevant in the context of the SAE JA1012 standard (Reliability-Centered Maintenance), where maintenance strategies are expected to evolve over time. So, according to the standard, maintenance policies are not static; they must adapt to operational feedback that may reveal unanticipated system behavior, failures that may progress faster than originally predicted, or new failure scenario that may emerge during operation.

The digital continuity established by our methodology enables the early detection of such deviations, providing evidence to support adjustments in maintenance scheduling or policies. In this sense, our methodology aligns with the vision of "A Living Program" outlined in the RCM standard by helping the identification of new failure modes, cascading failure effect or unexpected failure behavior.

5. CONCLUSION AND FUTURE WORK

This contribution proposes a hybrid Digital Twin-based approach for IVHM, aiming to enhance predictive maintenance capabilities in the aerospace domain. The proposed methodology was designed to address key limitations of conventional processes, including the lack of run-to-failure data, trustworthiness framework, and the disconnection between design and maintenance processes.

To overcome these challenges, we introduced the concept of the *Authoritative Hybrid Digital Twin,* which integrates physics-informed AI models, a structured VVA process to support certification, and the use of MBSE techniques to ensure digital continuity across the different processes. This approach enabled a more coherent and traceable integration of safety, design, and operational artifacts, ultimately supporting advanced predictive capabilities aligned with the vision of Type III IVHM systems.

Future research on the topic will focus on extending the digital continuity framework to include maintenance data, enabling the creation of digital links that connect safety and system development artifacts with in-service maintenance records. This integration will support a more unified and consistent data ecosystem, enhancing reliability of maintenance decisions and enabling proactive updates to inspection policies.

Furthermore, the Digital Twin architecture will be upgraded to support the continued and continuing airworthiness and additionally cover multiple failure causes. A key enhancement in this direction will be the ability to dynamically update the failure probability, enabling a shift from static assumption to dynamic assessments that reflect actual usage and degradation conditions.

While this paper does not include a case study validation, the proposed methodology is designed to be applicable to real-world scenarios and will be evaluated in future work.

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NOMENCLATURE

AD	Airworthiness Directive
AHM	Aircraft Health Management
AI	Artificial Intelligence
AMoC	Alternative Means of Compliance
CMRs	Certification Maintenance Requirements
FHA	Functional Hazard Assessment
FMEA	Failure Modes and Effects Analysis
IVHM	Integrated Vehicle Health Management
ML	Machine Learning
MBE	Model Based Engineering
MBSE	Model Based System Engineering
OEM	Original Equipment Manufacturing
PdM	Predictive Maintenance
RCM	Reliability-Centered Maintenance
RUL	Remaining Useful Life
VV	Validation and Verification
VVA	Validation, Verification and Accreditation

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