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Guidelines for maintenance and certification for transformative digital air vehicle

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EXECUTIVE SUMMARY

The increasing integration of sensing technologies, structural-health-monitoring (SHM) methods, and Digital Twin (DT) platforms is enabling new approaches to maintenance and lifecycle management of air vehicles. These developments are particularly relevant for digitally monitored aircraft and emerging urban air mobility systems, where high utilization rates and mission variability create demand for maintenance strategies supported by operational data.

This deliverable presents guidelines for maintenance and certification considerations for transformative digital air vehicles, based on the development and validation activities performed within the AVATAR project. The project demonstrates an integrated Digital Twin ecosystem combining IoT sensing skin technologies, edge–cloud data infrastructure, SHM analytics, probabilistic diagnostics, Remaining Useful Life (RUL) estimation, and dashboard-based decision-support tools.

The document first reviews the relationship between traditional structural-integrity concepts and emerging data-driven maintenance approaches. It then provides practical guidelines for integrating sensing technologies, SHM analytics, and Digital Twin platforms into maintenance workflows. Certification considerations related to monitoring-based lifecycle assessment are discussed, together with lessons learned from demonstrator platforms including metallic aircraft structures and a composite UAV system.

The AVATAR results show that Digital Twin–supported maintenance can complement established safe-life and damage-tolerant maintenance philosophies while enabling improved lifecycle awareness through monitoring of real operational loads and structural behaviour. The guidelines presented in this deliverable aim to support gradual adoption of SHM-enabled maintenance concepts in future digital air vehicles and urban air mobility systems.

1. INTRODUCTION

Aviation is undergoing a gradual transition toward digitally enabled aircraft systems in which sensing technologies, data connectivity, and advanced analytics support the operation and maintenance of air vehicles. Structural-health monitoring (SHM) and Digital Twin (DT) technologies are becoming increasingly important tools for understanding how aircraft structures behave in real operational environments.

For decades, structural integrity in aviation has been ensured through conservative design assumptions, predefined load spectra, and well-established maintenance philosophies such as safe-life and damage-tolerant approaches. These concepts have proven reliable across a wide range of aircraft categories. At the same time, advances in sensing technologies and data processing now make it possible to complement these traditional approaches with monitoring-based lifecycle assessment and predictive-maintenance support.

The AVATAR project explores this transition by integrating sensing skin technologies, Digital Twin platforms, structural-health-monitoring methods, and probabilistic prognostic tools into a unified framework for digitally monitored air vehicles. The project validates these concepts through demonstrator platforms including metallic aircraft structures and a composite unmanned aerial vehicle.

This deliverable provides guidelines for maintenance and certification considerations related to such digitally monitored air vehicles. Drawing on the AVATAR project experience, it discusses the relationship between traditional maintenance philosophies and monitoring-based lifecycle assessment, summarizes practical guidance for integrating SHM-enabled maintenance concepts, and highlights certification-related considerations for future digital air vehicles and urban air mobility systems.

2. MAINTENANCE CONCEPTS FOR DIGITALLY MONITORED AIRCRAFT

The introduction of sensing technologies, structural-health-monitoring (SHM) methods, and Digital Twin (DT) platforms enables a gradual transition from traditional maintenance approaches toward data-driven lifecycle management of air vehicles. This transition is particularly relevant for digitally monitored aircraft and unmanned systems expected to operate in future urban air mobility environments.

This section outlines how conventional maintenance concepts relate to emerging condition-based and predictive maintenance strategies supported by Digital Twin technologies.

2.1 TRADITIONAL MAINTENANCE APPROACHES

Design and maintenance strategies in aviation have historically been based on well-established structural-integrity concepts, including safe-life, fail-safe, and damage-tolerant design philosophies. Currently, all these approaches rely on conservative assumptions about operational loads, inspection intervals, and structural degradation mechanisms.

In the **safe-life approach**, components are designed to withstand all expected operational loads for a predefined lifetime without the occurrence of fatigue cracks. Maintenance actions are typically scheduled based on accumulated flight hours or cycles, using design load spectra and safety factors.

The **fail-safe approach** assumes that damage may develop in structural elements during service, but the structures must remain capable of carrying loads safely until detection through inspection. Redundancy of load paths and load redistribution play important roles in this concept.

The **damage-tolerant approach** explicitly accounts for crack initiation and growth from the very start of in-service operations. It thus requires periodic inspections and analysis of crack propagation to ensure structural integrity over time.

These traditional approaches have proven highly effective in conventional aviation. However, they typically rely on conservative assumptions about operational usage, which may not reflect the actual mission profiles of individual aircraft, particularly in high-frequency operational environments, which is expected to be typical for the upcoming transition to urban air mobility.

2.2 DIGITAL MAINTENANCE CONCEPTS

The concept of digitally monitored aircraft introduces new possibilities for maintenance planning using embedded sensing systems, continuous data acquisition, and predictive analytics. These technologies enable maintenance strategies that are increasingly based on actual structural usage and health state rather than predefined inspection schedules.

Condition-based maintenance (CBM) uses monitoring data to determine whether maintenance actions are necessary based on the observed state of the structure or system.

Predictive maintenance (PdM) extends this concept by using models and analytics to estimate degradation progression and predict future maintenance needs, often through Remaining Useful Life (RUL) estimation.

Usage-based maintenance relies on monitoring operational load spectra and fatigue usage to update lifecycle assessments dynamically.

For digitally monitored aircraft, these approaches can coexist with traditional maintenance philosophies, complementing safe-life or damage-tolerant design concepts rather than replacing them.

The AVATAR project demonstrates how such digital maintenance concepts can be implemented using sensing skin technologies, Digital Twin platforms, and probabilistic SHM analytics.

2.3 ROLE OF SENSING AND DIGITAL TWINS IN MAINTENANCE

Digital Twins provide a framework for integrating sensing data, structural models, and predictive analytics into maintenance decision-making processes.

Embedded sensing systems enable:

- monitoring of structural loads and response,
- detection of anomalies or damage,
- reconstruction of operational load spectra.

Structural-health-monitoring (SHM) methods process these data to identify potential structural issues and characterize structural behaviour under operational conditions.

Digital Twin analytics then combine monitoring data with physics-based models and probabilistic methods to:

- estimate structural degradation,
- track fatigue-life consumption,
- predict **Remaining Useful Life (RUL)**,
- support maintenance planning.

The Digital Twin dashboards developed during the AVATAR project illustrate how these capabilities can be translated into operator-oriented decision-support tools, enabling maintenance decisions to be informed by real operational data.

2.4 INTEGRATION WITH EXISTING MAINTENANCE PHILOSOPHIES

Digital maintenance concepts do not replace established certification philosophies but rather augment them with operational data and predictive analytics.

For aircraft designed according to the **safe-life concept**, Digital Twins can support:

- recalculation of fatigue usage,
- monitoring of accumulated damage,
- potential service-life extension based on real load spectra.

For **damage-tolerant structures**, Digital Twins can support:

- early damage detection,
- crack monitoring,
- load reconstruction,
- prognosis of structural degradation.

The AVATAR demonstrators illustrate both paradigms through metallic aircraft structures and composite UAV systems, showing how Digital Twin technologies can be integrated into different maintenance philosophies. By combining sensing technologies, structural-health-monitoring methods, and predictive analytics, digitally monitored aircraft can progressively transition toward lifecycle management strategies based on operational data while preserving established safety principles.

2.5 CONSERVATISM AND MONITORING-BASED LIFECYCLE ASSESSMENT

Traditional structural-integrity management in aviation relies on predefined load spectra, conservative assumptions, and safety factors. Although fatigue-life estimation methods are inherently approximate, these conservative design and maintenance philosophies have proven effective over decades of aircraft operation. The accumulated operational experience with safe-life and damage-tolerant concepts provides confidence in their robustness, even when uncertainties exist in modelling and operational variability.

Digital Twin–supported maintenance introduces the possibility of updating lifecycle assessment using measured operational loads and structural response. Monitoring-based fatigue-life tracking and Remaining Useful Life estimation allow structural usage to be evaluated for individual aircraft rather than relying solely on design load spectra. This creates the potential to use structural capability more efficiently and align maintenance decisions with actual operational conditions.

At the same time, reducing conservatism requires careful consideration. Fatigue-life prediction remains subject to uncertainty arising from modelling assumptions, material variability, sensing accuracy, and load-reconstruction methods. Approaching structural-life limits based on monitoring-supported estimates therefore requires validated monitoring systems, robust prognostic methods, and conservative interpretation of results.

The long-term reliability of Digital Twin–supported maintenance will depend on the accumulation of operational evidence linking monitored load data, fatigue-life estimation, inspection results, and maintenance decisions. As monitoring technologies become more widely deployed, this feedback loop will progressively improve predictive models and increase confidence in monitoring-based lifecycle assessment.

For this reason, Digital Twin–enabled maintenance should be viewed as a gradual evolution of existing structural-integrity practices, complementing established safe-life and damage-tolerant concepts while preserving safety margins during early adoption.

3. DIGITAL AIR VEHICLE CONCEPT IN AVATAR

To demonstrate the transition toward digitally monitored aircraft described in the previous section, the AVATAR project develops and validates an integrated Digital Twin ecosystem for monitoring, maintenance support, and lifecycle assessment of digitally monitored air vehicles. The concept of a “digital air vehicle” in AVATAR refers to an aircraft or unmanned aerial system equipped with embedded sensing technologies, connected data infrastructure, and Digital Twin analytics capable of supporting structural-health monitoring and predictive maintenance.

The AVATAR Digital Twin architecture combines several complementary technological layers. At the physical level, distributed sensing is enabled through an IoT sensing skin, integrating lightweight printed strain sensors, accelerometers, temperature sensors, and piezoelectric elements. These sensors allow monitoring of structural response, operational loads, and anomalous events at selected locations of the airframe.

Sensor data are collected through onboard acquisition nodes and processed using an edge–cloud data infrastructure. Edge devices perform local preprocessing, synchronization, and anomaly detection, while cloud-based Digital Twin platforms enable long-term storage, visualization, and predictive analytics. This architecture supports scalable monitoring across different aircraft platforms.

In the digital domain, the AVATAR concept integrates physics-based structural models, structural-health-monitoring methods, and probabilistic prognostic tools. High-fidelity numerical simulations and surrogate modelling approaches support load reconstruction and structural-response prediction. SHM analytics enable anomaly detection, damage

characterization, and monitoring of structural behaviour under operational conditions. These capabilities are combined with probabilistic diagnosis and Remaining Useful Life (RUL) estimation methods that account for operational variability and uncertainty.

A key element of the AVATAR Digital Twin ecosystem is the dashboard-based decision-support environment, which provides visualization of monitoring data, fatigue-life usage, anomaly detection results, and RUL estimates. These dashboards translate Digital Twin outputs into actionable maintenance-support information for different user roles.

The AVATAR concept is validated through multiple demonstrators representing different structural-integrity paradigms. Metallic aircraft structures designed according to the safe-life concept are monitored using fatigue-usage tracking and load reconstruction methods. A composite UAV platform demonstrates damage-detection and SHM-based monitoring consistent with damage-tolerant structural philosophy. Together, these demonstrators illustrate how Digital Twin technologies can support maintenance and lifecycle monitoring across different categories of air vehicles.

By integrating sensing technologies, monitoring analytics, predictive modelling, and visualization tools, AVATAR establishes a practical reference architecture for digitally monitored air vehicles. This concept forms the technological foundation for the maintenance guidelines and certification considerations presented in the following sections.

4. GUIDELINES FOR SHM-ENABLED MAINTENANCE

The AVATAR project demonstrates how sensing technologies, structural-health-monitoring (SHM) methods, and Digital Twin platforms can support maintenance decision-making for digitally monitored air vehicles. Based on the development and validation activities performed in the project, this section summarizes practical guidelines for integrating SHM-enabled maintenance concepts into small aircraft and UAV systems.

The guidelines presented here are not intended to replace established maintenance procedures or certification requirements, but rather to provide recommendations for implementing monitoring-based maintenance support in future digital air vehicles.

4.1 INTEGRATION OF SENSING TECHNOLOGIES

Reliable sensing is the foundation of SHM-enabled maintenance. The AVATAR project demonstrates that distributed sensing systems can be integrated into aircraft structures using lightweight and scalable approaches such as printed sensing skins and embedded sensor nodes.

Key recommendations include:

1. Sensor positioning should be guided by structural-analysis results and expected load paths.
2. Monitoring should focus on critical structural locations where fatigue damage or impact events are most likely to occur.
3. Environmental effects, particularly temperature influence on strain measurements, should be compensated in the sensing design.

4. Sensor systems should be lightweight, robust, and compatible with aircraft manufacturing and maintenance processes.
5. Scalability and manufacturability of sensing technologies should be considered from early design stages.
6. The maturity of sensing technologies should be carefully evaluated. For example, printed strain gauges currently remain at a development stage and may not yet provide sufficiently stable output over longer time periods. Their use in operational environments should therefore be validated before deployment in maintenance-relevant applications.
7. At the same time, printed-electronics technologies can be effectively used for non-sensing functions, such as replacing conventional wiring with printed conductive tracks. This approach has shown positive results in improving integration of wiring paths and connections within the structure.
8. The selection between different sensing modalities should consider long-term operational aspects. Accelerometers offer advantages in terms of robustness and ease of recalibration, whereas strain gauges may require more complex installation and can be more sensitive to environmental degradation. The suitability of each sensing approach should therefore be evaluated for the specific application and operating conditions.

These considerations support reliable long-term monitoring while minimizing impact on aircraft weight, complexity, and maintenance procedures.

4.2 DATA ACQUISITION AND INFRASTRUCTURE

SHM-enabled maintenance requires reliable acquisition, synchronization, and storage of structural monitoring data. AVATAR demonstrates an edge–cloud data architecture in which onboard sensing nodes perform local data acquisition and preprocessing, while long-term analytics are performed in cloud-based environments.

Recommended practices include:

1. Use event-triggered or adaptive data-acquisition strategies to balance data resolution, its volume and power consumption.
2. Ensure synchronization of sensor data across acquisition channels.
3. Implement preprocessing at the edge level to detect anomalies and to reduce data-transfer requirements.
4. Maintain secure and reliable communication between onboard systems and cloud infrastructure.
5. Preserve traceability of monitoring data for lifecycle analysis.
6. The selection of sampling frequency should reflect the physical phenomena of interest. Load spectra used for fatigue assessment are typically constructed to capture the effects of flight manoeuvres and gust loads, while filtering out higher-frequency excitations such as those induced by engine operation. However, the relative importance of these excitation sources may vary across different aircraft structures. Sampling strategies should therefore be defined with respect to the specific structural component and its dominant loading mechanisms.
7. The choice of data-transfer architecture should consider trade-offs between system simplicity, weight, and integration complexity. While wireless communication solutions offer flexibility, they may introduce additional hardware, power requirements, and system complexity. In small aircraft, where distances between monitored components are limited, wired connections or integrated conductive tracks may provide a more efficient and robust solution.

4.3 SHM ANALYTICS AND DIAGNOSTICS

Structural-health-monitoring methods transform sensing data into actionable maintenance information. AVATAR demonstrates a multi-level SHM workflow including anomaly detection, load reconstruction, damage identification, and probabilistic diagnosis.

Guidelines derived from these activities include:

1. Combine physics-based modelling with data-driven analytics for robust monitoring performance.
2. Use probabilistic methods to account for uncertainty in sensing, modelling, and operational conditions.
3. Validate SHM algorithms using controlled experiments and demonstrator platforms.
4. Integrate explainable-AI approaches where machine-learning models are used.
5. Design SHM workflows that allow both real-time monitoring and offline diagnostic analysis.
6. Particular attention should be paid to the interpretation of frequency content in monitoring data. Structural response is typically influenced by a combination of low-frequency loads (e.g., manoeuvres and gusts) and high-frequency excitations (e.g., engine operation and propeller-induced vibrations). The relative contribution of these effects may vary significantly across different structural locations. Understanding this mixture is essential for reliable load reconstruction and fatigue assessment.
7. The separation and appropriate weighting of different frequency components remain an important challenge for SHM-based fatigue analysis. Further research and validation are required to ensure that monitoring-based approaches correctly represent the fatigue-relevant loading of structures, particularly when transitioning from predefined load spectra toward Digital Twin–supported lifecycle assessment.

These practices support reliable interpretation of monitoring data and improve confidence in maintenance decisions.

4.4 MAINTENANCE DECISION SUPPORT AND DIGITAL TWIN INTEGRATION

Digital Twins provide the framework for integrating sensing, modelling, and SHM analytics into maintenance decision-support systems. The AVATAR DT dashboards demonstrate how monitoring results can be translated into operationally meaningful indicators such as fatigue-usage tracking, anomaly alerts, and Remaining Useful Life estimation.

Recommendations for DT-supported maintenance include:

1. Integrate monitoring outputs into maintenance-planning workflows through intuitive visualization tools.
2. Provide different information levels for different user roles (e.g., pilots, operators, analysts, maintenance engineers).
3. Support maintenance decisions using RUL estimation and probabilistic diagnostics.
4. Maintain compatibility between DT outputs and existing maintenance documentation processes.
5. Ensure that monitoring-based recommendations remain traceable and interpretable.

Such integration allows Digital Twins to complement traditional maintenance procedures while improving gradually lifecycle awareness.

4.5 GRADUAL DEPLOYMENT OF SHM-ENABLED MAINTENANCE

The AVATAR project shows that SHM-enabled maintenance can be introduced progressively, starting from monitoring of critical components and evolving toward aircraft-level predictive-maintenance systems.

A gradual deployment strategy may include:

1. initial monitoring of selected structural components,
2. validation of sensing reliability and SHM analytics,
3. integration with Digital Twin visualization tools,
4. extension toward predictive-maintenance planning.

This incremental approach reduces implementation risk while enabling adoption of Digital Twin technologies in operational environments. It allows stakeholders to progressively build up the experience with them before transiting to the next deployment level.

5. CERTIFICATION CONSIDERATIONS FOR DIGITAL AIR VEHICLES

The integration of sensing technologies, SHM systems, and DT platforms into air vehicles introduces new opportunities for maintenance support and lifecycle monitoring. At the same time, these technologies raise important questions regarding validation, reliability, and integration with existing certification and airworthiness frameworks.

The AVATAR project does not aim to define certification requirements. Instead, this section summarizes considerations and lessons learned related to the use of SHM and Digital Twin technologies in digitally monitored aircraft and unmanned systems.

5.1 VALIDATION OF SHM SYSTEMS

Certification-relevant deployment of SHM systems requires demonstration of reliability, repeatability, and robustness of sensing technologies and monitoring algorithms.

Key considerations include:

- validation of sensing performance under operational conditions even within long-term use,
- robustness of sensor measurements to environmental influences,
- reliability of anomaly-detection methods,
- verification of load-reconstruction approaches,
- traceability between sensing data and structural models.

The AVATAR demonstrators show that sensing-skin technologies and SHM analytics can be validated through laboratory experiments, wind-tunnel testing, and aircraft-level demonstrations. Such multi-level validation approaches are important for building confidence in monitoring-based maintenance support.

5.2 DIGITAL TWIN AND AIRWORTHINESS SUPPORT

Digital Twins can support airworthiness management by providing additional evidence on structural usage and health state during operation. Monitoring-based information may complement traditional inspection records and maintenance documentation.

Potential contributions of Digital Twins to airworthiness processes include:

- tracking of operational load spectra,
- monitoring of fatigue-life consumption,
- documentation of structural usage history,
- support for maintenance planning decisions.

For aircraft designed according to the safe-life concept, Digital Twins may enable recalculation of fatigue usage based on real operational data. For damage-tolerant structures, SHM methods can support detection and monitoring of structural damage.

These capabilities may contribute to future evolution of maintenance and certification practices, provided that monitoring systems and predictive models are validated and traceable.

5.3 DATA TRACEABILITY AND RELIABILITY

Certification-relevant use of monitoring data requires reliable data handling throughout the Digital Twin pipeline, from sensing to analytics and visualization.

Important aspects include:

- synchronization and integrity of monitoring data,
- secure data storage and communication,
- reproducibility of analytics results,
- transparency of predictive models,
- documentation of Digital Twin outputs.

The edge–cloud architecture demonstrated in AVATAR illustrates how monitoring data can be acquired, stored, and processed in a traceable manner suitable for lifecycle analysis.

5.4 INTEGRATION WITH EXISTING CERTIFICATION PHILOSOPHIES

Digital Twin technologies are expected to complement, rather than replace, established structural-integrity and certification philosophies.

For **safe-life structures**, Digital Twins may support:

- usage-based fatigue assessment,
- improved estimation of remaining service life,
- monitoring of operational load spectra.

For **damage-tolerant structures**, Digital Twins may support:

- early detection of structural damage,
- crack monitoring,
- probabilistic prognosis of degradation.

The AVATAR project demonstrates both paths through metallic aircraft and composite UAV demonstrators, illustrating how Digital Twin technologies can be integrated into different structural-integrity frameworks.

5.5 OUTLOOK ON CERTIFICATION EVOLUTION

As digital air vehicles and urban air mobility systems evolve, monitoring technologies and Digital Twin platforms may play an increasing role in maintenance and airworthiness processes. Continued collaboration between aircraft manufacturers, operators, researchers, and certification authorities will be necessary to define validation methods and acceptable use of monitoring-based maintenance support.

The AVATAR project contributes to this process by demonstrating integrated sensing, SHM analytics, probabilistic diagnostics, and Digital Twin decision-support tools in realistic aircraft and UAV applications. These results provide practical insight into how Digital Twin technologies may support future certification and maintenance frameworks for digital air vehicles.

6. DEMONSTRATOR LESSONS LEARNED

The AVATAR project validated DT concepts, sensing technologies, SHM methods, and predictive-maintenance workflows through multiple demonstrator platforms. These demonstrators provided practical insight into the integration of monitoring technologies with aircraft structures and Digital Twin analytics in realistic operational environments.

The lessons summarized below focus on maintenance- and certification-relevant experience gained during the project.

6.1 METALLIC AIRCRAFT DEMONSTRATOR (SPORTSTAR RTC)

The metallic aircraft demonstrators enabled validation of monitoring-based fatigue-usage tracking and Digital Twin–supported lifecycle assessment in structures designed according to the safe-life concept.

One of the key findings is that load-monitoring data can be successfully integrated with fatigue-analysis workflows to track structural usage over time. The sensing systems demonstrated stable strain and acceleration measurements under operational conditions, and load-reconstruction methods provided consistent estimation of structural loading.

At the same time, the experiments highlighted the importance of careful selection of sensing technologies. While conventional sensors provided reliable results, some emerging solutions, such as printed strain gauges, showed limitations in long-term signal stability under operational conditions. This indicates that further maturation and validation are required before such technologies can be used in maintenance-relevant applications.

Another important observation concerns the choice of sensing modality. Accelerometer-based measurements proved advantageous in terms of robustness and recalibration capability, while strain-gauge-based measurements require more careful installation and may be more sensitive to environmental effects. The suitability of each sensing approach depends on the monitored structural location and intended use.

The demonstrators also confirmed that integrating sensing systems into metallic aircraft structures is feasible with limited impact on aircraft operation when lightweight and well-integrated solutions are used, including the use of printed conductive tracks for wiring.

From a maintenance perspective, the experiments show that monitoring-based fatigue-usage tracking can complement traditional safe-life maintenance strategies by providing aircraft-specific lifecycle information.

6.2 COMPOSITE UAV DEMONSTRATOR (ASTERO)

The ASTERO UAV demonstrator provided validation of SHM-based monitoring and Digital Twin analytics in a damage-tolerant structural context.

The experiments demonstrated that vibration-based monitoring, guided-wave sensing, and load-reconstruction methods can detect anomalous events and support structural-health assessment of composite structures. The integration of sensing nodes, SHM analytics, and Digital Twin visualization enabled detection and characterization of structural events such as impact-like disturbances and load anomalies.

A key lesson from the UAV demonstrator is that multi-level SHM workflows are necessary, combining real-time anomaly detection with offline diagnostics and prognosis. This layered approach improves reliability of monitoring-based maintenance support.

The UAV platform also demonstrated the importance of edge-level preprocessing and event-triggered data acquisition, which help balance monitoring performance with power consumption and data-transfer requirements.

6.3 INTEGRATION OF SENSING, DIGITAL TWINS, AND MAINTENANCE WORKFLOWS

Across all demonstrators, one of the most important outcomes is the confirmation that DT–supported maintenance requires integration across multiple system layers, including sensing hardware, data-acquisition infrastructure, analytics methods, and visualization tools.

The project shows that:

- sensing technologies must be designed together with monitoring objectives,
- SHM analytics must be validated with experimental data,
- Digital Twin platforms must provide interpretable outputs,
- maintenance-relevant indicators such as fatigue-usage tracking and RUL estimation must be clearly defined.

The demonstrators also highlight the importance of robust data pipelines, from sensor acquisition through edge computing to cloud-based Digital Twin analytics.

Another key observation is that accurate fatigue-relevant load representation remains a challenge. The mixture of low-frequency and high-frequency excitation must be properly understood and reflected in monitoring-based load reconstruction and fatigue assessment. This is particularly important when transitioning toward Digital Twin–supported lifecycle management with reduced reliance on conservative assumptions.

6.4 LESSONS FOR FUTURE DIGITAL AIR VEHICLES

The AVATAR demonstrators illustrate that Digital Twin–supported maintenance can be introduced progressively, starting from monitoring of critical components and evolving toward aircraft-level lifecycle assessment.

Key lessons include:

- monitoring technologies must be reliable and lightweight to enable long-term deployment,
- integration of sensing and modelling should be considered early in aircraft design,
- selection of sensing modality should reflect long-term operational robustness and maintainability,
- sampling strategies must reflect the dominant loading mechanisms of the monitored structure,
- probabilistic diagnostics improve confidence in monitoring-based maintenance support,
- visualization tools are essential for translating monitoring data into maintenance decisions,
- gradual deployment helps build confidence in monitoring-based lifecycle assessment.

These lessons provide practical guidance for future digital air vehicles and urban air mobility systems that aim to integrate sensing technologies and Digital Twin platforms into maintenance and certification workflows.

7. OUTLOOK

The results of the AVATAR project demonstrate that the core technological building blocks required for Digital Twin–supported maintenance of air vehicles are already available. Sensing technologies, structural-health-monitoring methods, probabilistic diagnostics, Digital Twin platforms, and dashboard-based decision-support tools have been successfully integrated and validated across multiple demonstrator platforms.

Looking forward, the adoption of these technologies is expected to progress gradually, following the evolution of digital air vehicles and urban air mobility systems. Early deployment will likely focus on monitoring of critical structural components and usage-based fatigue assessment, where sensing technologies and Digital Twin analytics can complement established maintenance practices without requiring major changes to certification frameworks.

As operational experience with monitoring-based maintenance grows, Digital Twin capabilities may expand toward aircraft-level predictive maintenance systems, enabling more accurate lifecycle assessment and improved maintenance planning. In fleet-based urban air mobility operations, aggregation of monitoring data across multiple vehicles may support fleet-level lifecycle management and reliability analysis.

Further development is expected in areas such as:

- lightweight and energy-efficient sensing technologies,
- integration of Digital Twin platforms with aircraft avionics and maintenance systems,
- explainable AI methods for predictive maintenance,

- standardization of monitoring data formats and interfaces,
- validation approaches for SHM-enabled maintenance support.

Collaboration between aircraft manufacturers, operators, researchers, and certification authorities will be essential for defining acceptable validation procedures and operational use of Digital Twin technologies in aviation maintenance.

In the longer term, Digital Twins may become an integral part of digital aviation ecosystems, interacting with maintenance management systems, fleet-operation platforms, and emerging urban air traffic-management infrastructure. Such integration could enable lifecycle-aware operation of air vehicles, supporting safe, reliable, and economically sustainable urban air mobility.

The AVATAR project provides an important step toward this future by demonstrating how sensing, modelling, monitoring, and Digital Twin technologies can be combined into a coherent maintenance-support framework for digital air vehicles.

8. CONCLUSIONS

The AVATAR project demonstrates that the integration of sensing technologies, structural-health-monitoring (SHM) methods, and Digital Twin (DT) platforms enables new approaches to maintenance and lifecycle management of air vehicles. The results show that monitoring-based assessment of structural usage and condition can complement established maintenance philosophies and provide improved insight into the actual operational behaviour of aircraft structures.

At the same time, the transition from predefined load spectra and conservative assumptions toward monitoring-supported lifecycle assessment requires careful consideration. Fatigue-life estimation remains subject to uncertainty, and the reduction of conservatism must be supported by validated sensing systems, robust data-processing methods, and reliable interpretation of monitoring results. In particular, accurate representation of fatigue-relevant loading — including the balance between low-frequency operational loads and high-frequency excitation — remains a key challenge.

The AVATAR demonstrators confirm that Digital Twin–supported maintenance is technically feasible across different structural-integrity paradigms, including both safe-life metallic aircraft structures and damage-tolerant composite UAV systems. They also show that successful implementation requires consistent integration of sensing, data acquisition, analytics, and decision-support tools.

The guidelines presented in this deliverable highlight practical considerations for the deployment of SHM-enabled maintenance and outline certification-related aspects associated with monitoring-based lifecycle assessment. A gradual adoption strategy, in which monitoring technologies complement existing maintenance practices, is essential for building confidence and operational experience.

Looking forward, the wider deployment of digitally monitored air vehicles will depend on continued validation of monitoring technologies, accumulation of operational evidence, and collaboration between industry, research, and certification authorities. The AVATAR project

provides a foundation for this transition and contributes to the development of reliable and data-driven maintenance approaches for future digital air vehicles and urban air mobility systems.