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AVATAR

Business Case for DT Roadmap for Urban Air

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Jan Papuga[1], Zahra Sharif Khodaei[2]

[1]Evektor, spol. s r.o.

[2]Imperial College London

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Author (s)	Jan Papuga, Zahra Sharif Khodaei

TABLE OF CONTENTS

1 Executive Summary 5
2 Digital Twins in Urban Air Mobility 6
2.1 Policy and Market Context for Urban Air Mobility 6
2.2 Digital Twins across the lifecycle of urban air vehicles 7
2.3 Digital Twins deployment in the Avatar Framework 8
2.4 DT as an enabling technology for urban air ecosystems 8
3 AVATAR Digital Twin Ecosystem 9
3.1 Sensing and data acquisition layer 9
3.2 Edge–cloud data infrastructure 9
3.3 Modelling, analytics, and prognostics 10
3.4 Demonstrator platforms 10
3.5 Digital Twin dashboards and decision support 10
3.6 Towards integrated lifecycle Digital Twins 10
4. Digital Twin Deployment Roadmap 11
4.1 Stage 1 — Component-level DT (structural monitoring) 11
4.2 Stage 2 — Aircraft-level DT (predictive maintenance) 11
4.3 Stage 3 — Fleet-level DT (operational optimization) 12
4.4 Stage 4 — Urban air DT ecosystem 12
5. Stakeholders and Value Chain Analysis 13
5.1 Aircraft manufacturers and system integrators 13
5.2 Operators and fleet managers 14
5.3 Maintenance, Repair, and Overhaul (MRO) organizations 14
5.4 Regulators and certification authorities 14
5.5 Digital infrastructure and data-platform providers 15
6. Business Case Analysis 15
6.1 Value creation through predictive maintenance 15
6.2 Operational benefits for urban air systems 16
6.3 Economic Value Logic and Cost Categories 16
6.4 Adoption drivers 17

6.5 Adoption challenges and barriers 18
6.6 Exploitation and Sustainability perspective 18
6.7 Societal and Strategic Impact 19
6.7 Business-case outlook 19
6.9 Digital Twin Value Proposition for Urban Air Mobility 20
7. Conclusions 21

1 EXECUTIVE SUMMARY

Urban Air Mobility (UAM) is expected to introduce a new operational paradigm in aviation characterized by high mission frequency, distributed fleet operations, and strong requirements for safety, availability, and lifecycle cost efficiency. Emerging air vehicle concepts—including electric vertical take-off and landing (eVTOL) aircraft, unmanned aerial vehicles (UAVs), and lightweight urban aircraft—will operate under operational conditions that differ significantly from conventional aviation.

Under these conditions, **Digital Twin (DT) technologies represent a key enabling infrastructure** for lifecycle-aware monitoring, predictive maintenance, and operational optimization.

This deliverable presents the **business case and deployment roadmap for Digital Twin technologies in urban air mobility**, building on the sensing, modelling, and predictive maintenance capabilities demonstrated in the AVATAR project.

The AVATAR Digital Twin ecosystem integrates:

- IoT-based sensing technologies,
- edge–cloud data infrastructure,
- structural health monitoring methods,
- probabilistic diagnostics,
- Remaining Useful Life (RUL) estimation,
- dashboard-based decision-support tools.

Together, these components form an integrated framework for **data-driven lifecycle management of air vehicles**.

The business case presented in this document demonstrates that Digital Twins can generate value across multiple dimensions:

- improved aircraft availability,
- optimized maintenance planning,
- reduced lifecycle costs,
- enhanced safety through early anomaly detection,
- improved fleet-level operational efficiency.

The document also proposes a **Digital Twin roadmap** describing the evolution of these capabilities from component-level structural monitoring toward aircraft-level predictive maintenance systems, fleet-level lifecycle optimization, and integration into future urban air mobility ecosystems.

2 DIGITAL TWINS IN URBAN AIR MOBILITY

Urban Air Mobility (UAM) is emerging as part of a broader transformation of aviation toward more sustainable, digitalized, and highly automated mobility systems. Within Europe, this development is aligned with strategic objectives related to sustainable transport, smart cities, and the digital transformation of industry. Future urban air services—including logistics, inspection, surveillance, and passenger mobility—are expected to operate within complex urban environments where safety, environmental impact, and operational efficiency must be carefully balanced.

2.1 POLICY AND MARKET CONTEXT FOR URBAN AIR MOBILITY

From both a policy and market perspective, these developments create demand for technologies capable of supporting safe, scalable, and economically viable operations. Urban air vehicles are expected to operate with higher mission frequency, shorter turnaround times, and more distributed operational fleets than conventional aircraft. These characteristics require robust approaches to monitoring vehicle health, managing lifecycle performance, and supporting operational decision-making in real time.

Plans for expansion of Urban Air Mobility therefore introduce a new operational paradigm in aviation characterized by high-frequency missions, distributed fleets, lightweight structures, and strong requirements on safety, availability, and lifecycle cost efficiency. Unlike conventional aviation, many UAM vehicles will operate with short mission cycles, frequent take-off and landing operations, and mission-dependent load spectra. These characteristics increase the importance of continuous structural monitoring, lifecycle-aware maintenance strategies, and data-driven decision support.

In this context, **Digital Twin (DT)** technologies are increasingly recognized as a key enabling framework. A Digital Twin can be understood as a dynamic virtual representation of a physical asset that evolves throughout its lifecycle using operational, inspection, and environmental data combined with physics-based and data-driven models. By integrating sensing technologies, digital infrastructure, and predictive analytics, Digital Twins allow operational data to be continuously connected with engineering models and maintenance processes.

Within aviation, this paradigm supports a gradual transition from conservative design-based maintenance toward condition-based and predictive maintenance strategies. Such an approach enables maintenance decisions to be informed by the actual structural usage and health state of the aircraft rather than relying solely on fixed inspection intervals and conservative assumptions.

In the context of urban air systems, Digital Twins are particularly relevant because they support several key operational capabilities:

- monitoring of structural usage and operational loads,
- early detection of damage or abnormal structural behaviour,
- estimation of remaining useful life (RUL),
- mission-aware lifecycle management,
- fleet-level availability optimization.

These capabilities are particularly important for urban air mobility systems, where high fleet utilization, operational reliability, and efficient lifecycle management will be essential for economic viability. By improving understanding of structural degradation processes and enabling more targeted maintenance actions, Digital Twins can contribute to reducing unnecessary inspections, minimizing unplanned downtime, and improving fleet availability.

For this reason, Digital Twin technologies are increasingly considered a foundational element of future digital aviation ecosystems. Their integration with sensing systems, data infrastructure, and predictive analytics platforms supports a more connected and lifecycle-aware approach to aircraft management, which is particularly relevant for the emerging operational environment of urban air mobility.

2.2 DIGITAL TWINS ACROSS THE LIFECYCLE OF URBAN AIR VEHICLES

Digital Twin technologies can support multiple lifecycle phases of UAM systems.

The concept of a Digital Twin extends beyond simple monitoring of operational parameters and instead encompasses the entire lifecycle of a physical asset. In aviation systems, this lifecycle typically includes design, manufacturing, operation, maintenance, and end-of-life phases. Each of these stages generates valuable information that can contribute to a continuously evolving representation of the asset's structural state and operational performance.

During the **design and development phase**, Digital Twin models can support validation of structural assumptions, evaluation of load scenarios, and assessment of potential degradation mechanisms. Physics-based simulations and digital prototypes enable engineers to explore different operational conditions and identify potential structural vulnerabilities before aircraft enter service.

In the **manufacturing phase**, information related to material properties, production variability, and structural assembly can be incorporated into the initial Digital Twin model. This information provides a baseline description of the aircraft structure that can later be updated as operational data becomes available.

During the **operational phase**, the Digital Twin becomes progressively enriched through real-world data collected from sensors, inspection results, and maintenance records. Structural loads, environmental conditions, and mission profiles contribute to the understanding of how the aircraft is used and how its structural state evolves over time. This operational feedback enables more accurate estimation of degradation processes and remaining structural life.

Maintenance and inspection activities also play an important role in updating the Digital Twin. Inspection results, anomaly reports, and repair actions provide additional information that can refine the digital representation of the aircraft and improve the accuracy of diagnostic and prognostic models.

By continuously integrating information from these lifecycle stages, the Digital Twin evolves into a dynamic system capable of supporting predictive maintenance, lifecycle optimization, and informed decision-making. In the context of urban air mobility, where vehicles may experience frequent operational cycles and diverse mission profiles, such **lifecycle**

awareness becomes particularly important for maintaining safety while ensuring efficient fleet operation.

2.3 DIGITAL TWINS DEPLOYMENT IN THE AVATAR FRAMEWORK

Within the AVATAR project, the Digital Twin concept is implemented through an integrated framework that combines sensing technologies, data infrastructure, modelling tools, and decision-support methods. The objective is to demonstrate how these elements can be connected to support structural health monitoring and predictive maintenance for future urban air systems.

A central component of this framework is the integration of distributed sensing technologies capable of capturing structural responses and operational loads. These sensing systems provide continuous information about the behaviour of aircraft structures under real operating conditions. The collected data is transmitted through an edge–cloud architecture that enables scalable data storage, processing, and analysis.

Within this architecture, physics-based models and data-driven algorithms are used to interpret the collected measurements. These analytical components support several key functions, including anomaly detection, diagnosis of structural degradation mechanisms, and estimation of Remaining Useful Life (RUL). The resulting insights are then made available through visualization and decision-support tools that assist operators, maintenance personnel, and engineers in assessing the health state of the aircraft.

By combining sensing, modelling, and analytics within a coherent framework, the AVATAR Digital Twin architecture demonstrates how real-world operational data can be transformed into actionable knowledge for lifecycle management. The modular design of the system also allows individual components—such as sensing technologies, data-processing pipelines, or prognostic models—to be deployed independently or integrated into broader Digital Twin ecosystems.

2.4 DT AS AN ENABLING TECHNOLOGY FOR URBAN AIR ECOSYSTEMS

While Digital Twins are often introduced at the level of individual assets, their full value emerges when they are integrated into broader operational ecosystems. In the context of urban air mobility, such ecosystems include aircraft manufacturers, fleet operators, maintenance organizations, regulators, and digital service providers.

Digital Twins enable these stakeholders to share consistent and traceable information about the structural condition and operational history of aircraft. This capability supports improved coordination between design, operations, and maintenance activities. For example, operational feedback collected through Digital Twins can inform design improvements in future aircraft generations, while maintenance organizations can benefit from better predictions of inspection needs and resource allocation.

At the fleet level, Digital Twins enable aggregation and analysis of data across multiple aircraft operating under different mission profiles and environmental conditions. Such fleet-level insights can support optimization of maintenance scheduling, identification of common degradation patterns, and improved planning of spare parts and maintenance resources.

From a broader perspective, Digital Twins can also contribute to the development of digital aviation ecosystems where data-driven services support safer and more efficient air operations. Integration with air traffic management systems, urban infrastructure platforms, and smart-city data environments may further enhance the operational capabilities of urban air mobility systems.

In this sense, Digital Twins should be viewed not only as monitoring tools for individual aircraft but as enabling technologies supporting the digital transformation of future aviation systems. The AVATAR framework contributes to this vision by demonstrating how sensing, modelling, and predictive analytics can be integrated into a scalable Digital Twin architecture suitable for emerging urban air mobility applications.

3 AVATAR DIGITAL TWIN ECOSYSTEM

AVATAR demonstrates a reference architecture for Digital Twin deployment in urban air systems. The developed DT combines sensing technologies, data infrastructure, modelling tools, and decision-support interfaces into a coherent framework capable of supporting lifecycle-aware structural integrity management.

Rather than focusing on a single technology component, AVATAR demonstrates how Digital Twin capabilities emerge from the integration of physical sensing, digital modelling, data analytics, and user-oriented visualization tools.

The AVATAR DT architecture consists of several interconnected layers.

3.1 SENSING AND DATA ACQUISITION LAYER

The physical entry point of the AVATAR DT ecosystem is the IoT sensing skin, which enables continuous monitoring of structural response and operational loads. The sensing skin integrates lightweight strain gauges, accelerometers, temperature sensors, and piezoelectric elements into a distributed embedded monitoring system.

The sensing infrastructure is designed to be scalable, lightweight, and compatible with both metallic aircraft and composite UAV structures. Real-time data acquisition is supported by onboard microcontroller-based sensing nodes capable of preprocessing, anomaly detection, and wireless communication.

3.2 EDGE–CLOUD DATA INFRASTRUCTURE

AVATAR implements an end-to-end data pipeline connecting onboard sensing systems with Digital Twin analytics. Sensor data are collected through embedded acquisition nodes and transferred via edge-computing devices that provide buffering, preprocessing, and synchronization. From there, the data are transmitted to a cloud-based infrastructure supporting long-term storage, visualization, and analytics.

This edge–cloud Digital Twin architecture ensures reliable data availability while minimizing onboard computational requirements. It also enables scalability toward fleet-level Digital Twin deployment, which is particularly relevant for future urban air mobility operations.

3.3 MODELLING, ANALYTICS, AND PROGNOSTICS

The digital core of the AVATAR ecosystem combines physics-based modelling, structural-health-monitoring analytics, and probabilistic prognostics.

High-fidelity numerical models and surrogate modelling approaches are used to simulate structural behaviour and support load reconstruction and damage detection. Structural-health-monitoring methods process sensor data to detect anomalies, identify damage, and characterize structural response under operational conditions.

Building on these capabilities, AVATAR integrates probabilistic diagnosis and Remaining Useful Life (RUL) estimation methods that account for operational variability, uncertainty, and mission-dependent load spectra. Explainable machine-learning techniques further enhance model transparency and support sensor prioritization and decision-making.

Together, these modelling and analytics components enable the Digital Twin to evolve continuously as new operational data become available.

3.4 DEMONSTRATOR PLATFORMS

The AVATAR Digital Twin ecosystem is validated through multiple demonstrators representing different classes of air vehicles:

- a metallic aircraft of LSA category (SportStar RTC),
- an all-metal aircraft platform (Cobra),
- a composite UAV platform (ASTERO).

These demonstrators allow validation of sensing technologies, load reconstruction methods, structural-health-monitoring techniques, and predictive-maintenance analytics under realistic operational conditions. The use of both manned aircraft and UAV platforms demonstrates the cross-platform applicability of Digital Twin technologies in future urban air systems.

3.5 DIGITAL TWIN DASHBOARDS AND DECISION SUPPORT

The AVATAR DT ecosystem includes user-oriented dashboards that transform sensor data and model outputs into actionable information. These dashboards support different user roles, including pilots, analysts, and operators, and provide visualization of structural usage, anomalies, fatigue-life consumption, crack growth, and remaining useful life.

By integrating real-time visualization with predictive analytics, the dashboard environment demonstrates how Digital Twin technologies can support operational decision-making and maintenance planning.

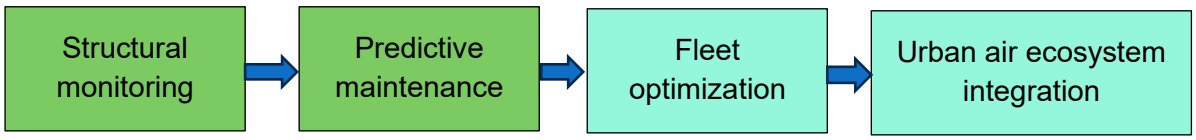
3.6 TOWARDS INTEGRATED LIFECYCLE DIGITAL TWINS

The AVATAR ecosystem illustrates how Digital Twin capabilities can be progressively deployed, starting from component-level monitoring and evolving toward aircraft-level predictive maintenance systems. The integration of sensing, modelling, analytics, and visualization provides a foundation for future Digital Twin deployment in urban air mobility environments, where lifecycle awareness and fleet availability will be critical.

4. DIGITAL TWIN DEPLOYMENT ROADMAP

The deployment of Digital Twin technologies in urban air mobility is expected to follow a progressive evolution from component-level monitoring toward fleet-level lifecycle management systems. The AVATAR project demonstrates several foundational building blocks of this evolution, including sensing technologies, data infrastructure, structural-health-monitoring analytics, probabilistic diagnostics, and predictive-maintenance dashboards.

Based on these capabilities, a Digital Twin roadmap for urban air mobility can be understood as a transition between four maturity stages.



Due to its limited scope and low final TRL level, AVATAR project contributed primarily to the **first two stages of this roadmap**, while establishing the technological and architectural foundations required for future deployment at fleet and ecosystem levels.

4.1 STAGE 1 — COMPONENT-LEVEL DT (STRUCTURAL MONITORING)

The first stage focuses on instrumented components and structures, where sensing technologies and structural models are combined to monitor loads, detect anomalies, and characterize structural behaviour.

Typical capabilities at this stage include:

- distributed sensing using embedded sensor networks,
- load reconstruction from strain or vibration data,
- detection of abnormal structural response,
- validation of sensing reliability and data acquisition pipelines.

The AVATAR IoT sensing skin and component-level monitoring activities represent this stage of DT deployment. At this level, DTs primarily serve as structural-health-monitoring tools that provide visibility into structural usage and enable early detection of damage.

This stage is essential for urban air mobility because many UAM platforms rely on lightweight structures and operate under mission-dependent load conditions that differ from traditional aviation usage assumptions.

4.2 STAGE 2 — AIRCRAFT-LEVEL DT (PREDICTIVE MAINTENANCE)

The second stage extends DT capabilities from individual components to the aircraft, enabling predictive maintenance and lifecycle management based on operational data.

Capabilities at this stage include:

- integration of sensing data with structural models,
- probabilistic diagnosis of structural condition,
- Remaining Useful Life (RUL) estimation,

- mission-aware fatigue-life tracking,
- condition-based maintenance planning.

The AVATAR Digital Twin demonstrators for the SportStar RTC aircraft and the ASTERO UAV illustrate this stage. In the safe-life aircraft paradigm, the Digital Twin enables recalculation of fatigue usage based on real load spectra. In damage-tolerant structures, the Digital Twin supports detection, localization, and monitoring of structural damage.

Aircraft-level DTs can significantly reduce maintenance uncertainty and improve aircraft availability, which is particularly important for urban air operations with high utilization rates.

4.3 STAGE 3 — FLEET-LEVEL DT (OPERATIONAL OPTIMIZATION)

The next stage involves extending DT capabilities to fleet-level, where data from multiple vehicles are aggregated to improve operational efficiency and maintenance planning.

Potential capabilities include:

- fleet-level usage monitoring,
- predictive maintenance scheduling across vehicles,
- reliability statistics derived from operational data,
- mission-profile optimization,
- shared degradation models across similar aircraft.

For urban air mobility operators managing multiple vehicles, fleet-level Digital Twins can improve resource utilization, reduce downtime, and support maintenance logistics.

The AVATAR edge–cloud architecture and scalable analytics framework provide the technological foundation for this stage, even though full fleet-level deployment is beyond the scope of the project.

4.4 STAGE 4 — URBAN AIR DT ECOSYSTEM

At the highest maturity level, Digital Twins become part of a broader urban air ecosystem, interacting with operational, regulatory, and infrastructure systems.

Potential capabilities include:

- integration with traffic-management systems,
- digital records supporting certification and airworthiness,
- infrastructure Digital Twins (vertiports, ground systems),
- city-scale lifecycle monitoring of urban air fleets,
- integration with autonomous flight operations.

At this stage, Digital Twins evolve from aircraft-specific tools into system-level lifecycle-management platforms supporting safe and efficient urban air transportation.

While AVATAR focuses on aircraft-level Digital Twins, the technologies demonstrated in the project — including sensing systems, predictive maintenance analytics, probabilistic diagnostics, and Digital Twin dashboards — represent essential building blocks for this future ecosystem. The TRL evolution of this ecosystem is presented in this table:

Stage	Description	TRL
Component DT	Structural monitoring	4–5
Aircraft DT	Predictive maintenance	5–6
Fleet DT	Fleet analytics	6–7
Ecosystem DT	Urban air integration	7–8

5. STAKEHOLDERS AND VALUE CHAIN ANALYSIS

The deployment of Digital Twin (DT) technologies in urban air mobility (UAM) depends on the coordinated interaction of multiple stakeholders across the aviation value chain. Unlike traditional aircraft lifecycle management, UAM systems are expected to operate within highly digitalized operational environments where sensing, analytics, and maintenance decision-making are closely integrated. Digital Twins therefore act as enabling infrastructure connecting aircraft, operators, maintenance organizations, and regulatory bodies.

The AVATAR project demonstrates DT capabilities across several layers of this ecosystem, providing insight into how Digital Twins may be adopted in future urban air operations. It represents an early step toward this broader integration, demonstrating how structural-health monitoring, predictive maintenance, and data-driven lifecycle management can be combined into a unified framework.

Stakeholder	Role in DT ecosystem	Value generated
Aircraft manufacturers	Integration of sensors and DT models	improved design validation
Operators	Fleet management	reduced downtime
MRO	predictive maintenance services	improved planning
Regulators	certification support	improved traceability

5.1 AIRCRAFT MANUFACTURERS AND SYSTEM INTEGRATORS

Aircraft manufacturers and system integrators are among the primary stakeholders in Digital Twin deployment. For these actors, Digital Twins provide opportunities to:

- validate structural behaviour using operational data,
- improve structural design assumptions through real load spectra,
- support certification-by-analysis approaches,
- enable lifecycle-aware product development.

In the context of urban air mobility, manufacturers of eVTOL aircraft, UAV platforms, and light aircraft are expected to increasingly integrate sensing technologies and Digital Twin

capabilities directly into aircraft architectures. The AVATAR demonstrators illustrate how Digital Twins can support both metallic and composite airframe structures.

5.2 OPERATORS AND FLEET MANAGERS

Urban air mobility operations are expected to rely on fleet-based operational models, making operators and fleet managers key stakeholders in Digital Twin adoption.

Digital Twins can support operators by:

- monitoring structural usage across vehicles,
- enabling predictive maintenance planning,
- improving aircraft availability,
- reducing operational uncertainty.

For high-frequency UAM missions, predictive-maintenance capabilities enabled by Digital Twins may become essential for maintaining operational efficiency and economic viability.

The AVATAR dashboard environment demonstrates how Digital Twin outputs can be translated into operator-oriented decision-support tools.

5.3 MAINTENANCE, REPAIR, AND OVERHAUL (MRO) ORGANIZATIONS

Maintenance organizations will play an important role in the Digital Twin ecosystem as maintenance strategies evolve from scheduled inspections toward condition-based maintenance.

Digital Twin technologies can support MRO activities through:

- improved diagnostics and fault localization,
- remaining-life estimation for components,
- mission-aware maintenance planning,
- integration of inspection data into lifecycle models.

This transition will require new workflows in which sensor data, inspection results, and predictive models are combined to support maintenance decisions.

5.4 REGULATORS AND CERTIFICATION AUTHORITIES

Regulatory bodies and certification authorities are critical in the adoption of DT technologies in aviation. The use of predictive-maintenance analytics and data-driven structural-health monitoring requires validation, traceability, and confidence in model reliability.

Digital Twins may support:

- evidence-based airworthiness assessment,
- lifecycle monitoring of structural integrity,
- certification-by-simulation approaches,
- documentation of operational load spectra.

As urban air mobility evolves, regulatory frameworks are expected to gradually incorporate Digital Twin concepts into maintenance and certification processes.

5.5 DIGITAL INFRASTRUCTURE AND DATA-PLATFORM PROVIDERS

Digital Twin deployment in urban air mobility relies on robust data infrastructure, including:

- edge-computing platforms,
- cloud analytics services,
- communication frameworks,
- data visualization tools.

These elements form the backbone of scalable Digital Twin ecosystems. The AVATAR project demonstrates how sensing systems, edge computing, and cloud-based analytics can be integrated into a coherent Digital Twin platform.

6. BUSINESS CASE ANALYSIS

Digital Twin technologies have the potential to become a key enabler for the safe, reliable, and economically viable operation of urban air mobility (UAM) systems. Unlike traditional aviation segments with relatively predictable operational profiles, urban air operations are expected to involve high flight frequency, mission variability, distributed fleets, and strong pressure on operational availability. Under these conditions, lifecycle-aware monitoring and predictive maintenance become essential capabilities.

The AVATAR project demonstrates how Digital Twin technologies can support these needs by integrating sensing, modelling, analytics, and visualization into a unified predictive-maintenance framework. The business case for Digital Twins in urban air mobility is therefore closely linked to value creation through improved structural integrity management, maintenance optimization, and operational availability.

6.1 VALUE CREATION THROUGH PREDICTIVE MAINTENANCE

A key economic benefit of DT deployment in urban air systems is the transition from conservative maintenance strategies toward condition-based and predictive maintenance.

Traditional maintenance approaches rely on:

- predefined inspection intervals,
- conservative load assumptions,
- design flight spectra,
- safety margins that may not reflect real usage.

Digital Twins enable maintenance decisions based on actual operational load exposure and structural condition, allowing:

- more accurate estimation of remaining useful life,
- reduction of unnecessary inspections,
- early detection of structural anomalies,
- improved maintenance planning,
- potential service-life extension of components and structures.

For high-utilization urban air fleets, these capabilities can significantly improve aircraft availability while maintaining safety.

The AVATAR demonstrators illustrate this value through:

- recalculation of fatigue usage for metallic aircraft structures,
- damage detection and localization in composite UAV structures,
- mission-aware load monitoring,
- probabilistic Remaining Useful Life estimation.

6.2 OPERATIONAL BENEFITS FOR URBAN AIR SYSTEMS

Digital Twin technologies support several operational objectives relevant to urban air mobility:

Improved aircraft availability: Predictive maintenance reduces unplanned downtime and allows maintenance scheduling to be aligned with operational needs.

Lifecycle cost reduction: Monitoring structural usage in real operation enables more efficient utilization of structural margins and reduces unnecessary maintenance actions.

Safety enhancement: Continuous monitoring and probabilistic diagnostics support early detection of anomalies and improve situational awareness for operators.

Fleet management support: Digital Twins enable operators to compare usage patterns across vehicles and optimize maintenance strategies at fleet level.

These benefits become increasingly important as urban air mobility evolves toward fleet-based operations with high mission frequency.

6.3 ECONOMIC VALUE LOGIC AND COST CATEGORIES

The business case for Digital Twin deployment in urban air mobility is based on the balance between implementation cost and lifecycle value creation. In practice, DT adoption is justified when the combined benefits of improved maintenance planning, reduced downtime, better asset utilization, and enhanced safety exceed the additional cost of sensing, data infrastructure, analytics, and organizational integration.

For UAM operators and fleet managers, the most important value drivers are expected to be aircraft availability and maintenance efficiency. In high-frequency operations, even modest reductions in unplanned downtime can have a significant economic effect because they improve mission continuity and asset utilization. Similarly, improved knowledge of structural usage and degradation can reduce unnecessary inspections and enable maintenance actions to be scheduled in a more targeted manner.

For manufacturers and system integrators, Digital Twins create value through improved understanding of operational load spectra, more realistic validation of structural assumptions, and support for lifecycle-aware design. Over time, such feedback may improve product development, reduce uncertainty in structural margins, and support future certification and service strategies.

For MRO organizations, Digital Twins provide a basis for moving from reactive and interval-based approaches toward condition-based maintenance supported by diagnostics and

prognostics. This may improve planning of inspections, spare parts, and maintenance resources, especially in distributed fleet operations.

The cost structure of Digital Twin deployment can be grouped into four principal categories:

Sensing and onboard integration costs.
These include embedded sensors, acquisition electronics, integration into aircraft structures, calibration, and validation of reliability under operational conditions.

Data and computing infrastructure costs.
These include edge devices, communication systems, cloud storage, processing capacity, cybersecurity provisions, and data-management services.

Modelling and analytics costs.
These include development and validation of structural models, anomaly-detection methods, diagnostics, Remaining Useful Life estimation, and dashboard functionalities.

Organizational and operational integration costs.
These include workflow adaptation, user training, maintenance-process updates, and integration with existing operator or MRO information systems.

Digital Twin deployment becomes economically attractive when it supports one or more of the following outcomes:

- reduction of unnecessary inspection actions,
- earlier identification of structural anomalies,
- lower incidence of unplanned maintenance events,
- improved planning of maintenance resources,
- increased aircraft or fleet availability,
- extension of useful service life under controlled conditions.

The AVATAR project demonstrates that the core technological elements required to realise these benefits can already be integrated into a coherent framework. Although full-scale economic validation in operational fleets remains beyond the scope of the project, the results indicate a credible pathway toward lifecycle-cost reduction and improved operational efficiency in future urban air systems.

6.4 ADOPTION DRIVERS

Several technological and operational trends support the adoption of Digital Twin technologies in urban air mobility:

- increasing availability of lightweight embedded sensing technologies,
- advances in edge and cloud computing,
- maturation of AI-assisted diagnostics and prognostics,
- growing importance of predictive maintenance in high-utilization fleets,
- increasing acceptance of data-driven lifecycle management in aviation.

Urban air systems, including UAV logistics platforms and eVTOL aircraft, are particularly well suited for Digital Twin deployment because they rely on repetitive missions and digitally integrated operations.

The AVATAR project demonstrates that Digital Twin deployment is feasible using currently available sensing, modelling, and data-infrastructure technologies.

6.5 ADOPTION CHALLENGES AND BARRIERS

Despite strong potential benefits, several challenges remain for large-scale deployment of Digital Twins in urban air mobility.

Certification and regulatory acceptance: The integration of Digital Twin analytics into airworthiness and maintenance decision-making requires validation and regulatory acceptance of data-driven methods.

Sensor integration and cost: While sensing technologies are becoming more affordable, integration into aircraft structures must remain lightweight, reliable, and maintainable.

Data governance and interoperability: Fleet-level Digital Twins require standardized data formats, secure communication, and reliable long-term data management.

Model validation and trustworthiness: Predictive-maintenance models must demonstrate reliability and interpretability to gain operator and regulator confidence.

The AVATAR project addresses several of these challenges by demonstrating explainable AI methods, probabilistic modelling, and integrated sensing architectures.

6.6 EXPLOITATION AND SUSTAINABILITY PERSPECTIVE

The Digital Twin ecosystem developed in AVATAR opens several exploitation pathways that are relevant beyond the project itself. These pathways include both technology-oriented exploitation and service-oriented exploitation, and they can be pursued incrementally as Digital Twin maturity increases from component monitoring to aircraft-level and fleet-level lifecycle management.

A first exploitation route concerns **sensing and monitoring technologies**. The embedded sensing concepts, IoT sensing skin approaches, and associated acquisition architectures demonstrated in AVATAR can form the basis for deployable structural-monitoring solutions for metallic aircraft, composite UAVs, and future urban air vehicles. These solutions may be exploited as standalone monitoring subsystems or as integrated modules within broader aircraft health-management architectures.

A second exploitation route concerns **analytics and prognostics software**. Methods for anomaly detection, structural-health monitoring, probabilistic diagnosis, and Remaining Useful Life estimation can be further developed into software components supporting predictive maintenance workflows. Such components may be integrated into maintenance-support tools, Digital Twin platforms, or operator dashboards.

A third route concerns **Digital Twin platform integration**. The AVATAR architecture shows how sensing, edge-cloud infrastructure, modelling, analytics, and visualization can be combined into a modular ecosystem. This architecture is relevant for future Digital Twin platforms serving aircraft manufacturers, fleet operators, MRO organizations, and infrastructure providers. The modularity of the approach supports progressive deployment,

allowing stakeholders to adopt selected capabilities before transitioning toward broader lifecycle-management solutions.

A fourth route concerns **data-driven services**. The project results support the future development of services such as structural usage assessment, mission-aware maintenance planning, remaining-life assessment, fleet monitoring, and lifecycle decision support. These services may be particularly valuable in high-utilization fleet environments where operational efficiency and availability are critical.

From a sustainability perspective, the exploitation potential of AVATAR is strengthened by the fact that the demonstrated building blocks are not limited to one aircraft type or one use-case. The results are relevant to general aviation, UAV operations, and future UAM platforms. This cross-platform applicability increases the likelihood that project outcomes can be transferred into follow-up research, industrial development, and pre-commercial implementation activities.

The long-term sustainability of exploitation will depend on several factors, including certification acceptance, interoperability with existing aviation workflows, reliability of sensing systems, and confidence in data-driven prognostic methods. However, the AVATAR project reduces these barriers by demonstrating an integrated and modular approach, rather than an isolated proof of concept. In this sense, AVATAR provides not only technological results, but also a reference architecture and exploitation logic for future deployment of Digital Twin technologies in urban air mobility.

6.7 SOCIETAL AND STRATEGIC IMPACT

Digital Twin deployment in urban air mobility has relevance beyond direct operational efficiency. By improving structural integrity management, maintenance planning, and lifecycle awareness, Digital Twins can contribute to safer and more reliable air operations. This is particularly important in the urban context, where public acceptance of new air mobility concepts will depend strongly on confidence in safety, robustness, and transparency of operations.

In addition, Digital Twin technologies support a broader digital transformation of aviation by enabling data-driven decision-making across the lifecycle of air vehicles. This can strengthen European industrial capability in sensing, prognostics, and digital aviation systems, while also supporting future integration of urban air services into wider mobility and infrastructure ecosystems.

Although the AVATAR project is focused on structural monitoring and predictive maintenance, the demonstrated approach contributes to the long-term vision of connected, lifecycle-aware, and operationally efficient urban air systems. For this reason, the business case for Digital Twins should be understood not only in terms of direct maintenance savings, but also in terms of strategic value for future aviation ecosystems.

6.7 BUSINESS-CASE OUTLOOK

The long-term business case for Digital Twin deployment in urban air mobility will depend on the balance between implementation costs and the operational value created through improved lifecycle management. While the AVATAR project focuses primarily on

technological feasibility and integration of key Digital Twin components, the results indicate a credible pathway toward measurable operational and economic benefits.

In urban air mobility operations, aircraft are expected to operate with high mission frequency and short turnaround times. Under such operational conditions, fleet availability and maintenance efficiency become key drivers of economic viability. Digital Twin technologies contribute to these objectives by enabling continuous monitoring of structural usage, early detection of degradation processes, and improved estimation of remaining structural life.

Based on experience from predictive maintenance applications in aerospace and other high-value industrial systems, Digital Twin–enabled maintenance strategies have the potential to deliver several operational benefits. These may include reductions in maintenance-related costs in the order of approximately 10–25%, primarily through more targeted inspection activities and improved planning of maintenance actions. In addition, early detection of structural anomalies may reduce unplanned maintenance events, potentially lowering operational downtime by approximately 15–30%.

Improved knowledge of structural usage and degradation may also support more efficient maintenance scheduling and better allocation of maintenance resources across distributed fleets. For operators of urban air systems, this may translate into increased fleet availability and improved asset utilization, both of which are critical for achieving economically viable high-frequency operations.

It should be noted that these indicative benefit ranges depend strongly on operational context, fleet size, sensor reliability, and integration of Digital Twin analytics within existing maintenance workflows. For this reason, full economic validation requires long-term operational deployment and large-scale fleet data, which remain beyond the scope of the AVATAR project.

Nevertheless, the project demonstrates that the technological building blocks required to support such benefits—including structural sensing, data infrastructure, diagnostic and prognostic models, and decision-support tools—can be integrated into a coherent Digital Twin ecosystem. This integration represents an important step toward future operational deployment of Digital Twins in urban air mobility systems.

6.9 DIGITAL TWIN VALUE PROPOSITION FOR URBAN AIR MOBILITY

The business case for Digital Twin deployment in urban air mobility is based on the capacity of DT technologies to create value across multiple stakeholders in the aviation ecosystem. The AVATAR project demonstrates how sensing technologies, data infrastructures, and predictive analytics can support this value creation by enabling lifecycle-aware aircraft management and data-driven maintenance strategies.

The following table summarizes the principal stakeholders involved in the Digital Twin ecosystem and the corresponding value generated through DT-enabled capabilities.

Stakeholder	Role in UAM Ecosystem	Value Generated by Digital Twins
Aircraft manufacturers	Design and production of urban air vehicles	Improved understanding of operational loads, feedback for design improvements, validation of structural assumptions
Fleet operators	Operation of aircraft fleets	Increased aircraft availability, improved maintenance planning, reduced downtime
Maintenance, Repair and Overhaul (MRO) organizations	Inspection and maintenance services	Transition from reactive maintenance toward predictive maintenance workflows
Digital service providers	Data analytics and digital platform services	Development of DT platforms, predictive analytics tools, and operational dashboards
Regulators and certification bodies	Oversight of safety and compliance	Improved traceability of structural usage and operational history
Urban mobility ecosystem stakeholders	Integration of air mobility within urban systems	Improved operational reliability and safer integration of UAM services

From an operational perspective, Digital Twins enable several measurable benefits that contribute directly to the economic viability of urban air systems. These benefits may include reductions in unnecessary inspections, earlier detection of structural anomalies, improved maintenance scheduling, and increased fleet availability.

Indicative benefits reported in predictive maintenance and Digital Twin applications across aviation and other high-value industrial sectors suggest that such technologies may contribute to maintenance cost reductions on the order of **approximately** 10–25%, reductions in unplanned downtime of approximately 15–30%, and improved asset utilization in the range of 10–20%. Although the precise magnitude of these benefits depends on operational conditions and system maturity, these ranges illustrate the potential economic impact of Digital Twin adoption.

By enabling more efficient lifecycle management, Digital Twins therefore contribute not only to operational efficiency but also to the broader scalability of urban air mobility services.

7. CONCLUSIONS

Urban Air Mobility introduces a new operational paradigm in aviation characterized by high mission frequency, distributed fleets, lightweight structures, and strong requirements for

safety, reliability, and cost efficiency. In such an operational environment, traditional maintenance strategies based on conservative design assumptions and fixed inspection intervals may become increasingly inefficient. Digital Twin technologies offer a promising pathway toward addressing these challenges by enabling continuous monitoring of structural usage, improved diagnostics of degradation processes, and predictive estimation of remaining useful life.

This deliverable has presented the business case for Digital Twin deployment in urban air mobility within the framework of the AVATAR project. The analysis demonstrates that Digital Twins can provide significant value across multiple stages of the aircraft lifecycle, including structural monitoring, maintenance planning, fleet management, and operational decision support. By integrating sensing technologies, digital infrastructure, and advanced analytics, Digital Twins enable a more connected and lifecycle-aware approach to aircraft management.

The AVATAR project contributes to this vision by demonstrating key building blocks of a Digital Twin ecosystem, including embedded sensing technologies, data acquisition architectures, anomaly detection methods, probabilistic diagnostics, and Remaining Useful Life estimation. The integration of these elements illustrates how operational data can be transformed into actionable insights supporting predictive maintenance and improved lifecycle management of urban air vehicles.

From a business perspective, the adoption of Digital Twin technologies is driven by their capacity to improve operational efficiency and reduce lifecycle costs. Predictive maintenance strategies supported by Digital Twins have the potential to reduce unnecessary inspection activities, minimize unplanned downtime, and improve fleet availability. Although the precise economic impact depends on operational conditions and fleet characteristics, indicative benefits reported in related industries suggest potential maintenance cost reductions in the range of 10–25% and reductions in unplanned downtime of approximately 15–30%.

Beyond direct operational benefits, Digital Twins also contribute to the broader digital transformation of aviation. By enabling continuous integration of operational data, engineering models, and decision-support tools, Digital Twins support more transparent, traceable, and data-driven management of aircraft assets. Such capabilities are particularly relevant for the emerging ecosystem of urban air mobility, where public acceptance, regulatory confidence, and operational reliability will be essential for long-term deployment.

In this context, the AVATAR Digital Twin framework represents an important step toward future Digital Twin ecosystems for urban air systems. The modular architecture demonstrated in the project shows how sensing technologies, analytics platforms, and lifecycle management tools can be combined into scalable solutions supporting aircraft operators, manufacturers, and maintenance organizations.

While full-scale operational deployment of Digital Twins in urban air mobility will require further technological maturation, certification acceptance, and large-scale fleet validation, the results of the AVATAR project demonstrate that the fundamental technological components are already available. Continued research, industrial development, and ecosystem collaboration will therefore play a key role in translating these technological capabilities into operational and economic benefits for future urban air mobility systems.