Whitepaper

Grounded by complexity

How digital twins reveal the challenges of aircraft lifecycle digitalization

eraneos

"We're moving to model-based engineering, digitizing our entire engineering and development system up front including down into our supply chain and connecting that with the production system and how we service and support to create value for our customers. That digital life cycle, think of it as a digital twin of our airplanes, will unleash incredible value in the future."

Dennis Muilenburg, Former CEO of Boeing, 2018

Executive summary

The global aviation industry is set for accelerated expansion. According to Airbus's 2024 Global Market Forecast, the global number of commercial aircraft in operation is expected to nearly double by 2043, growing from 24,260 to 48,230 aircraft, driven by a sharp focus on operational efficiency, sustainability, and replacing older, less efficient aircraft.[1]

Simultaneously, the digital twin market is booming. Valued at $10.25 billion in 2022, it is expected to surge to $269.1 billion by 2032. In aerospace and defense alone, the market could expand from $1.8 billion to $48.2 billion by 2032.[2] Some forecasts from industry leaders predict an even faster rise. Regardless of the exact figures, one thing is certain: Digital twin adoption in aviation is accelerating at an extraordinary pace.

For over a century, aviation has driven technological innovation, evolving from the Wright brothers' first flight to today's highly sophisticated aircraft. However, with progress come major challenges. Rising complexity in design and manufacturing, strict safety regulations, and complex supply chains make production increasingly demanding. Once in operation, aircraft generate massive data streams that must be managed, analyzed, and integrated in real time, a demanding task for the industry.

1 Airbus GMF, 2024
2 Malone, 2024

The shift to a highly connected digital ecosystem also increases cybersecurity risks, while stringent international regulations add layers of complexity, requiring global coordination.

At the same time, a growing talent gap threatens innovation. With retirements outpacing new skilled workers, particularly in digital fields like AI, data analytics, and automation, aviation companies must compete with tech firms for top talents. Leading players like Airbus and Boeing are investing heavily in upskilling programs[3] [4], but without a large-scale workforce transformation, the industry faces rising costs, productivity losses, and even safety risks.

Against this backdrop, digital twins offer a groundbreaking solution. By creating virtual replicas of aircraft and processes, they enable real-time simulation, predictive maintenance, and data-driven decision-making. This technology allows for optimized quality and performance and reduced downtime, helping companies stay ahead in a highly competitive industry. However, successful adoption requires navigating the complexity of integration and understanding both their potential and obstacles, such as the need for robust data infrastructure and alignment across multiple stakeholders.

This whitepaper dives into the pressing challenges of aviation digitalization and highlights the clear potential of digital twins throughout the aircraft lifecycle. It examines the critical obstacles to their adoption while showcasing their business value and offering a comprehensive roadmap for successful implementation.

3 Shalamanov, 2022
4 Terlep, 2024

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Key challenges in aircraft lifecycle digitalization

The digitalization of the aircraft lifecycle spanning manufacturing, maintenance, and operations holds significant potential through technologies like digital twins, IoT, and AI. However, despite advancements, the aviation industry faces considerable barriers in fully integrating these technologies. Key challenges include achieving seamless data interoperability, adapting legacy systems to modern digital infrastructures, and mitigating cybersecurity risks. Additionally, automation in aviation is primarily driven by the need to ensure consistent, high-quality outcomes rather than merely saving time. Organizational resistance to change and compliance with stringent regulatory frameworks further complicate digital transformation efforts. This section explores these obstacles across four critical dimensions: data management, technological integration, organizational barriers, and regulatory compliance.

Manuel Held
Senior Consultant
Eraneos

manuel.held@eraneos.com

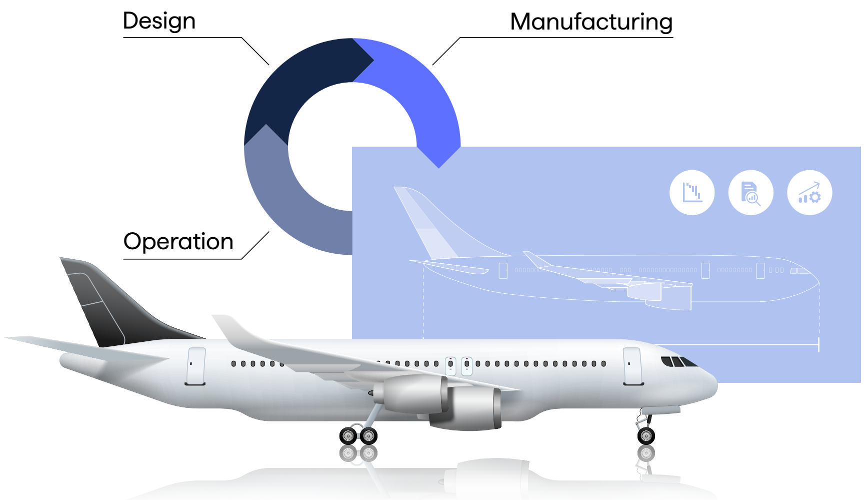


Figure 1: Digital twin of an aircraft along its lifecycle

01. Data management challenges

Data quality and integration: Aircraft lifecycle processes generate vast data from sensors and software along design, manufacturing, and operations. Ensuring accuracy, consistency, and interoperability is challenging, as fragmented systems, non-standard formats, and poor connectivity hinder integration and real-time decisions.

Data security: As digitalization increases, so does exposure to cybersecurity risks. Protecting sensitive aviation data including design specifications, flight operations, and maintenance reports from cyber threats is critical. However, balancing robust security measures with accessibility for various stakeholders remains a complex challenge for manufacturers and operators.

02. Technological integration challenges

Adoption of emerging technologies: The aviation industry must integrate advanced technologies such as IoT, AI, and cloud computing to support efficiency and decision-making. However, many existing infrastructures were not designed for these innovations, making large-scale adoption costly and complex. Retrofitting legacy systems and ensuring compatibility with new digital solutions require significant investment and expertise.

System interoperability and legacy constraints: One of the core challenges in technological integration lies in bridging the gap between new digital solutions and existing legacy systems. Aircraft programs often rely on long-established platforms for manufacturing, testing, and maintenance that were not designed for real-time data exchange or AI integration. These fragmented architectures lack standard APIs, making it difficult to interconnect modern technologies such as digital twins or cloud-based analytics. Achieving smooth interoperability demands costly system overhauls, rigorous validation, and alignment across OEMs, suppliers, and MRO providers.

03. Organizational barriers

Cultural and operational resistance: Digital transformation is not just a technological shift but also an organizational one. Resistance to change, lack of digital literacy among employees, and deeply ingrained traditional workflows can slow down adoption. Successful transformation requires a cultural shift, supported by strong leadership, training programs, and change management initiatives.

Collaboration and communication: Managing the aircraft lifecycle requires coordination across engineering, manufacturing, maintenance, and regulatory teams. However, siloed operations and fragmented communication hinder collaboration. Effective digitalization demands better data sharing and cross-functional alignment to support operational efficiency.

04. Regulatory compliance challenges

Evolving regulatory frameworks: Aviation operates under strict regulations. As digital technologies evolve, adapting frameworks results in delays, rising costs, and uncertainty. Ensuring compliance with emerging data governance, cybersecurity, and digital certification standards remains a continuous challenge for OEMs, manufacturers, and airlines.

Certification and validation: Every new digital technology, from automated assembly processes to AI-driven maintenance systems, requires rigorous validation and certification. Regulatory approval processes are lengthy, involving extensive testing and coordination with authorities. These requirements, while essential for safety, can slow down the adoption of innovative digital solutions.

The digital twin as a driver of digital transformation of aircraft lifecycles

A digital twin is a dynamic virtual model of a physical asset, process, or system, continuously updated through real-time data. It serves as a living representation that mirrors its real-world counterpart throughout its lifecycle. It acts as a bridge between the physical and digital worlds, enabling monitoring, simulation, and intelligent decision-making.

A Digital twin has three core components:

Physical model: A real-world system embedded with sensors, cyber-physical systems (CPS), and edge computing for continuous data capture.

Data pipeline: A seamless, automated connection ensuring real-time synchronization and bidirectional communication.

Digital twin: A virtual counterpart that processes, analyzes, and interacts with the physical system, allowing visualization, predictive modeling, and automated decision support.

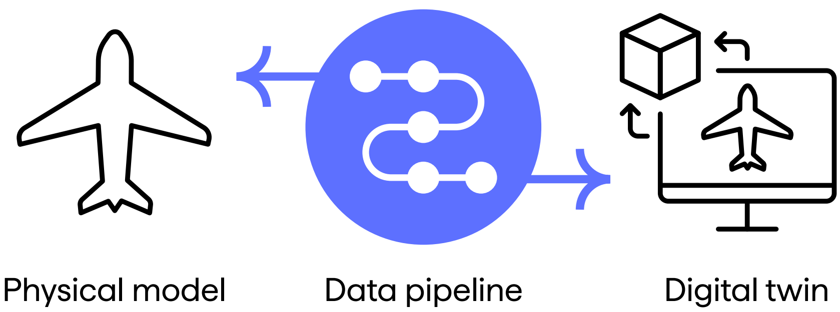


Figure 2: Core components of a digital twin

Digital twins vary along two fundamental dimensions: maturity and structural scope. The maturity spectrum ranges from Pre-Twins that are static simulations used in design phases to fully autonomous Innovation Twins that continuously learn and optimize. In parallel, digital twins differ by scope: from Component Twins that model individual parts, to Asset, System, and Process Twins that represent increasingly complex assemblies and workflows. Understanding both dimensions is essential to assessing where value can be created across the aircraft lifecycle. All types of digital twins play a relevant role in supporting every stage of the aircraft lifecycle from initial design to final decommissioning by enhancing efficiency, streamlining coordination, and improving decision-making at each phase.

To better understand their applications, the aircraft lifecycle can be categorized into three key phases: Concept to Distribution, Operational Service and Decommissioning, as illustrated in Figure 3. Below, we explore the primary applications of digital twins across these stages.

Concept to distribution: This phase encompasses the design, manufacturing, and delivery of a new aircraft. Pre-Twins facilitate simulations of workflows, enhancing efficiency. For example, design optimization via simulations of various configurations allows engineers to refine designs before physical production. Similarly, production process simulation models´ assembly lines to identify bottlenecks and optimize workflows, while supplier integration enables better coordination by sharing specifications tailored to specific aircraft variants, reducing lead times and ensuring meeting customer requirements more accurately.

Operational service: In this phase, where aircraft are integrated into fleets and undergo maintenance, the previously Pre-Twins develop into full-fledge digital twins as connected to the aircraft via sensors and enable proactive approaches using real-time data. Predictive maintenance uses operational data to forecast potential failures, while assisted quality assurance improves inspection accuracy. In manufacturing-related activities such as retrofits or component replacement, digital twins of assets such as robotic positions or tooling setups are already in use, although real-time monitoring of entire MRO facilities remains limited. Furthermore, digital twins streamline retrofits by simulating modifications to increase operational efficiency and documenting the history of each component for effective lifecycle tracking.

Decommissioning: This stage focuses on decommissioning aircraft, where digital twins aid in resource management. They facilitate efficient disassembly planning to recover valuable parts and materials, and their role in data-driven recycling ensures that high-value components are refurbished while minimizing waste. In retrofitting processes, they support efficient planning and cost-effective modifications, ultimately supporting sustainability.

The integration of digital twins within the aviation industry is increasingly harmonized with trending technologies like IoT and AI, driving enhanced operational performance. By optimizing resources and maximizing efficiencies, digital twins play a pivotal role in advancing sustainability efforts. As the industry evolves, leveraging these virtual models is crucial for adapting to market demands, reducing carbon emissions, and fostering an innovative, sustainable future for aviation.

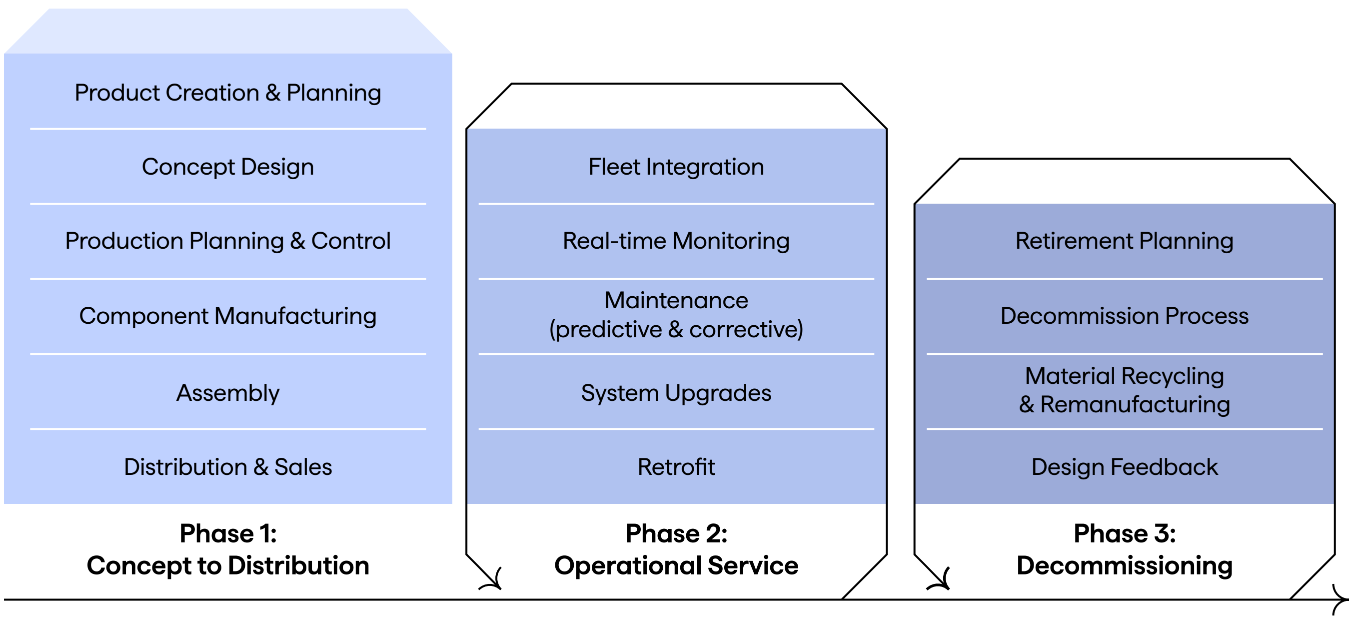


Figure 3: Aircraft Lifecycle Phases

Challenges of implementing digital twins in aircraft lifecycle

Mourad Siala
Analyst
Eraneos

mourad.siala@eraneos.com

Digital twin implementation presents significant challenges that must be addressed to maximize its value. These challenges span regulatory, organizational, technical, and economic domains. Getting to know those challenges and where they apply is crucial for understanding how to effectively implement the digital twin technology in the aircraft lifecycle. By identifying these challenges early on, stakeholders can develop targeted strategies to overcome barriers, ensure smooth integration, and capitalize on the advantages of real-time monitoring and digitalization in aircraft lifecycle management.

01.
Regulatory & compliance challenges

011. Certification & safety regulations

The aviation industry is heavily regulated by authorities like the FAA (USA), EASA (Europe), and CAAC (China). Any modification based on the insights of a digital twin requires certification, which may require years. To support approval, decisions derived from a digital twin must be explainable, ideally by replaying the situation and demonstrating the impact of each decision. For instance, if a digital twin suggests structural design changes to improve fuel efficiency in the Airbus A321XLR, regulatory bodies must first validate the changes, delaying deployment. Similarly, a digital twin predicting structural fatigue in Boeing 737 wings may recommend preventive reinforcement. However, such modifications would require FAA approval, which involves extensive testing and documentation, delaying time-to-market.

012. Cybersecurity & data privacy risks

Digital twins collect highly sensitive aircraft design, operational, and performance data, making them ideal targets for cyberattacks. For example, Rolls-Royce's IntelligentEngine program, based on advanced Engine Health Monitoring (EHM), continuously gathers real-time sensor data from Rolls-Royce engines to predict failures and optimize maintenance. If hackers gained access to this digital twin data in the cloud storage, they could manipulate engine health predictions, potentially leading to delayed maintenance, operational disruptions, or safety risks.[5 6] Moreover, the collaborative nature of EHM data-sharing between Rolls-Royce and multiple airlines further increases cybersecurity exposure, as vulnerabilities in one partner's system could compromise the entire network. In a broader context, if a real-time digital twin system were integrated into the operations of an airline, a cyberattack could alter critical performance data, increasing the risks of incorrect pilot responses.

> "Digital twins are a cornerstone of our digital transformation, enabling Airbus to deliver more innovative, sustainable, and high-performing solutions at an unprecedented pace. From the initial design concept to the final flight, we're effectively building each aircraft twice: first in the digital world, and then in the real one. This is the power of digital twin technology, and it's shaping the future of aerospace."

Airbus Newsroom, 2025

5 Rolls Royce, IntelligentEngine: Our vision for the future of aircraft power, 2025

6 Rolls-Royce, Intelligent Engine Health Monitoring, 2025

02. Organizational & workforce challenges

021. Skill gap & resistance to change

The successful deployment of digital twins requires cross-functional expertise in AI, aerospace engineering, and data science. However, many professionals in aviation lack training in data analytics. For example, an airline´s engineering team may distrust AI-driven predictive maintenance insights, preferring traditional diagnostic methods. Overcoming skepticism in that case requires significant change management efforts. However, this challenge is not unique to airlines. Airbus' Skywise platform for fleet optimization and Lufthansa Technik's AVIATAR platform for predictive maintenance both incorporate digital twin technologies.[77] However, early users often struggled to interpret AI-driven insights, necessitating extensive training and targeted data literacy initiatives.

022. Lack of cross-department collaboration

Digital twin adoption requires close coordination between engineering, IT, production, and operations. However, aerospace organizations often operate in silos, hindering seamless data integration. For example, during aircraft production, development and production planning teams often rely on separate data systems, which disrupts alignment. If production is not involved early in digital twin-supported design processes, inefficiencies like rework and ramp-up delays can occur. In flexible cabin assembly projects, the lack of collaboration between design engineers and production planners may lead to inconsistencies between the digital model and the physical reality on the shop floor. Without an integrated digital twin approach across departments, costly adjustments during the installation phase become necessary.

7 Baessler et al., 2020

03.
Technical challenges

031. Data silos and integration with legacy systems

Many aerospace companies rely on decades-old IT infrastructures built for isolated, project-specific use and not for real-time data sharing. As a result, legacy systems often use proprietary formats and incompatible architectures, complicating integration with modern digital twin platforms. For instance, suppliers like Safran and Rolls-Royce must interfere with entirely separate digital environments when working with different aircraft manufacturers, each maintaining their own engineering databases and design tools. Because there is no standardized framework, synchronizing data streams across programs is complex and costly, and often requires middleware and custom integration solutions. This interoperability challenge extends to maintenance providers as well. Major MROs that are responsible for maintaining aircraft from various manufacturers often struggle to integrate real-time operational data from newer wide-body and regional aircraft due to differing data formats and IT systems. As a result, predictive maintenance efforts are slowed, reducing overall operational efficiency.

032. Real-Time data synchronization & sensor limitations

An aircraft digital twin relies on IoT sensors to provide real-time operational data. However, not all sensors deliver continuous or reliable data, and missing or inconsistent measurements complicate the development of robust models. Sensor degradation, network latency, and data inconsistencies further challenge the maintenance of accurate models. For example, during transatlantic flights, aircraft such as the Boeing 777 generate vast amounts of performance data , but satellite connectivity limitations can cause transmission lags, preventing real-time synchronization between the aircraft and its digital twin.[8] Data reliability issues are not limited to aircraft systems but extend to engine performance monitoring as well. Major engine manufacturers operate health monitoring systems that continuously collect performance data from their engines while installed on in-service aircraft. If sensors misreport engine vibration levels due to calibration errors, false maintenance alerts could be triggered, leading to unnecessary grounding of aircraft and increased operational costs.

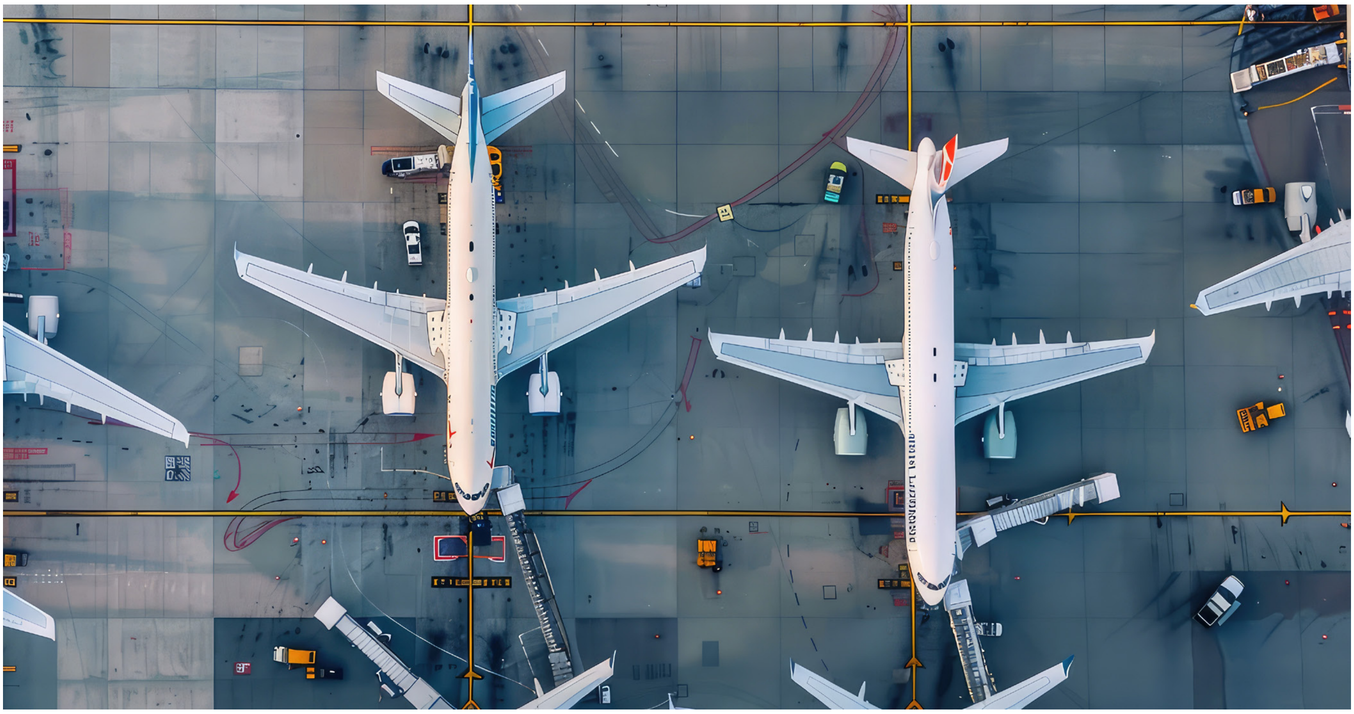
033. Computational scalability

High-fidelity digital twins require enormous computing resources, whether deployed on-premise or in the cloud. On-premise solutions offer more control and lower latency but are limited by local hardware capacity. Cloud platforms address scalability but introduce cybersecurity risks and potential latency issues. For example, GE Aviation uses digital twins to simulate wear and tear on jet engines, but running full simulations on thousands of engines simultaneously demands massive cloud computing power. Without efficient resource allocation, computational bottlenecks slow down performance analytics. A digital twin modeling the entire structure of a Boeing 787 [9] must process stress, vibration, and thermal data simultaneously across multiple flights. Ensuring this level of accuracy at fleet scale remains a computational challenge, requiring hybrid cloud-edge solutions.

Ralph Tritsch
Senior Manager
Eraneos

ralph.tritsch@eraneos.com

8 Li et al., 2022
9 Design and Inquiry, 2017



04.
Economic & financial challenges

041. Strategic investment & ROI uncertainty

Adopting digital twin technology in aviation requires substantial capital investment (for sensor systems, data infrastructure, computing platforms, and specialized software) alongside employee training and change management. While the long-term potential of predictive maintenance is promising, the extended payback period and uncertain ROI complicate investment decisions, especially under short-term financial constraints. Building a digital twin for just one engine or aircraft type offers limited return. Scalability, configurability, and the ability to calibrate for future products are essential to justify investments. Airlines have started implementing predictive maintenance systems that incorporate digital twin principles, such as real-time monitoring and system modeling. However, full digital twin adoption remains limited, as integration costs and infrastructure upgrades continue to pose significant challenges. This often leads to phased rollouts rather than enterprise-wide deployment.

An Aircraft could use a digital twin to monitor composite material fatigue, potentially extending component life and lowering maintenance costs over time. However, the high initial investment and delayed benefits require clear communication to leadership, emphasizing long-term strategic value over short-term budget constraints. To support investment planning, structured cost-benefit analyses and scenario modeling incorporating discount rates and projected cash flows can help align technology decisions with broader business objectives and risk tolerance.

042. Data ownership & monetization issues

The effectiveness of digital twin systems hinges on access to high-quality, integrated data. Yet in aviation, data is fragmented across manufacturers, airlines, and maintenance providers, each with competing interests. Lack of standardized frameworks for data sharing creates legal and operational barriers, limiting collaborative potential. For example, OEMs depend on operational data for design improvements, but airlines often resist sharing detailed maintenance data due to competitive and privacy concerns. This hinders the full realization of end-to-end digital twin benefits across the lifecycle. At an airport, a digital twin to optimize aircraft turnaround would require coordinated data sharing among an airline, the airport authority, and ground services. In reality, unclear ownership and limited interoperability often limit such integration. Establishing industry-wide agreements and governance models is essential to fully realize the economic value of digital twin applications.

Business value of a digital twin along aircraft lifecycle

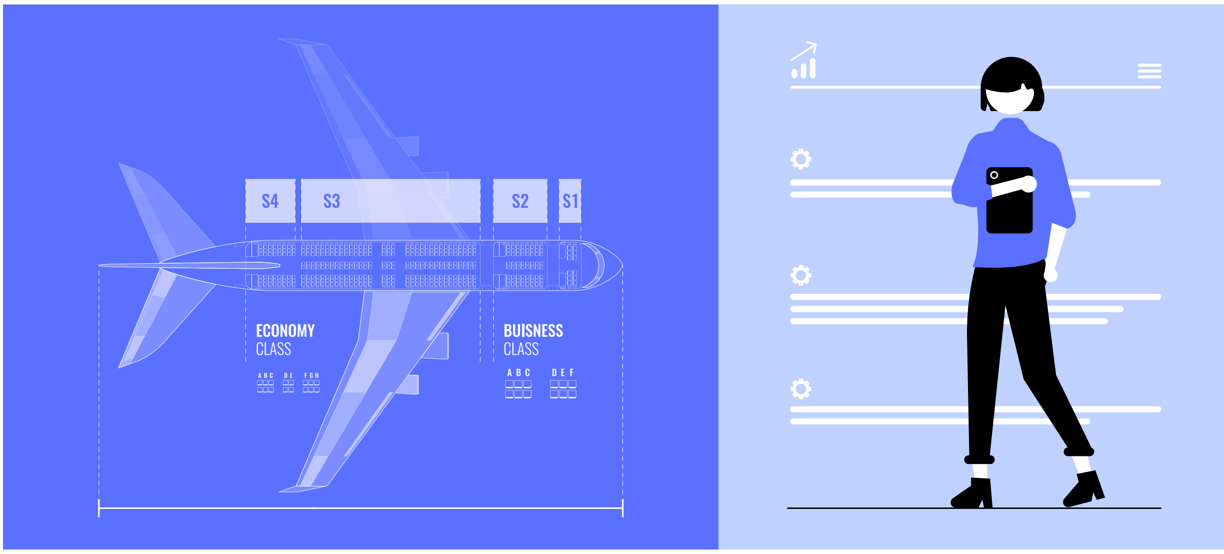
Faster time-to-market through virtual design and validation

Digital twin technology speeds up product development by enabling design teams to simulate, test, and refine concepts in a virtual environment far before any physical building process begins. This approach reduces the need for physical prototypes, helps detect design flaws early, and removes delays linked to hardware, materials, and labor. For instance, researchers found that applying digital twins to aircraft pilot seat development shortened the design cycle from 24–32 months to just 6 months, while cutting costs from 3.5 million to under 1 million.[10] Similarly, Airbus Defence and Space implemented a full digital twin for its A330 MRTT aircraft, minimizing physical prototyping and enhancing functional validation from initial design through in-service support.[11]

Operational and ESG efficiency through real-time optimization

Digital twins support operational efficiency while supporting the aviation industry's sustainability goals. By simulating engine behavior, flight paths, and load configurations, DTs enable data-driven decisions that reduce fuel consumption and emissions. For example, Rolls-Royce has used digital twins and machine learning to **extend time between engine maintenance by up to 50%, contributing to a reduction of 22 million tons of CO_2** across its fleet operations to date[12]. Another initiative within Rolls-Royce helped an airline save 85 million kilograms of fuel and over **200 million kilograms of CO_2**, by analyzing flight operations and pilot behavior using digital twin[13]. Additionally, GE Aviation employs digital twins to monitor engine performance in real time, allowing operators to optimize fuel burn and reduce in-flight inefficiencies.

10 McDonald, 2022
11 Gurdal & Testik, 2024
12 McDonald, 2022
13 Olavsrud, 2021



Higher product and process quality through real-time data and feedback

Digital twins enable manufacturers to improve product and process quality by providing a continuous feedback loop between virtual models and real-world production data. By simulating production conditions and monitoring key variables like temperature, pressure, or material stress, digital twins help identify and correct deviations before they affect product integrity. For instance, Boeing has reported up to a **40% improvement in first-time quality** through the use of digital twins in their production and assembly processes.[14] In aircraft manufacturing, digital twins allow for real-time defect detection and dynamic adjustment of production parameters, reducing rework and ensuring compliance with stringent aviation quality standards. Aerospace OEMs like Airbus are implementing DTs not only to improve assembly planning but also to support quality control across life stages from part-level tolerancing to final aircraft configuration verification. These insights drive measurable improvements in both product consistency and production efficiency.

Improved safety and system reliability

Digital Twins significantly enhance aircraft safety by enabling early detection of component degradation, structural stress, or system faults before they pose operational risks. Through continuous data streams from embedded sensors, digital twins allow for real-time monitoring and predictive diagnostics that align with safety-critical maintenance protocols. For instance, structural health monitoring systems integrated with digital twins detect stress, fatigue, and micro-cracks in fuselage components, allowing for timely interventions that reduce failure risk and extend aircraft lifespan. Similarly, in engine systems, digital twins have been used to identify early signs of sensor failure, improving diagnostic accuracy and system reliability in mission-critical subsystems like braking and electrical power supply. These predictive insights reduce reliance on reactive fault handling, enabling safer, more reliable aircraft operations at scale.

14 Singh, 2021

Conclusion

Digital twin technology is reshaping the aviation industry, enabling a new standard for lifecycle efficiency, cost optimization, and sustainability. By integrating real-time simulation, predictive analytics, and connected data ecosystems, digital twins bridge physical assets with their digital counterparts, providing aerospace stakeholders with the capabilities to manage data complexity and improve reliability and data-driven decision-making.

Engine OEMs like Rolls-Royce (Via its EHM) and MTU Aero Engines (with its “Virtual Engine”) believe in digital twins to forecast component durability, reduce inspection times, and automate maintenance planning based on real-world operational data. Major aircraft manufacturers like Airbus and Boeing employ digital twins across development programs to reduce physical prototyping, improve functional validation, and compress development cycles for new platforms. Airbus’s Skywise and Lufthansa Technik’s Aviatar enable airlines like easyJet, Delta, Lufthansa, and United to implement predictive maintenance by providing the data and analytics foundation for digital twin applications across their fleets. Moreover, digital twins are directly contributing to sustainability goals. By enabling more efficient fuel planning, condition-based operations, and optimized design iterations, operators have achieved fuel savings. These benefits translate into measurable progress toward emissions reduction, an imperative as environmental regulations tighten and ESG expectations rise globally.

As regulatory and commercial pressures converge, digital twins are emerging as a strategic differentiator. At Eraneos, we see this as a pivotal opportunity and firmly believe that those who industrialize digital twin capabilities early will lead the future of aviation.

Our Expertise

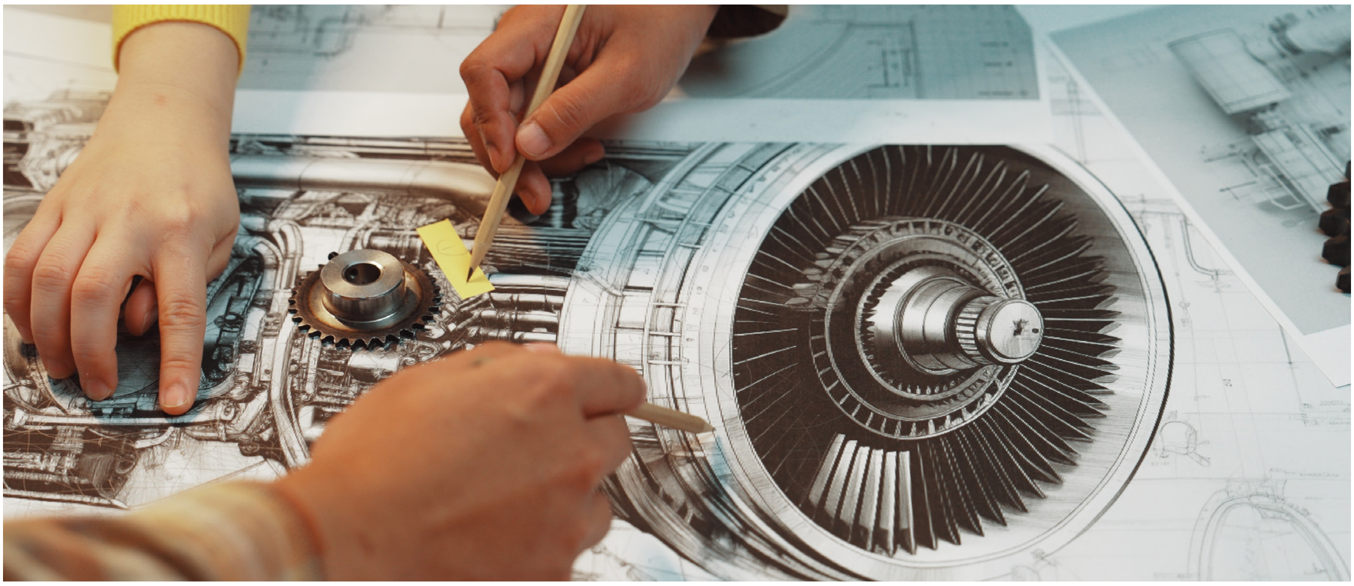
At Eraneos, we guide clients across the full lifecycle of digital twin initiatives strategically, through IT consulting, and operationally during implementation. Our support includes **strategy**, **architecture design**, **analytics**, **prototyping**, **cybersecurity**, and **testing**. From concept to deployment, we help transform digital twin potential into measurable outcomes.

Examples of our work include:

- Developed a digital twin for a European railway operator using reinforcement learning and real-time simulation, enabling dispatchers to prevent disruptions and **reducing delays by 58,000 minutes annually.**
- Implemented a digital twin for a pharmaceutical packaging provider. Simulations improved pill-to-machine allocation, **increasing automation by 14%** and **saving €500,000 per year**. A Planner Module further optimized scheduling.
- Built a service-ready digital twin for wind turbines by integrating structural and operational data to **enable predictive maintenance and reduce downtime**.
- Enhanced an aircraft oxygen system twin with adaptive Kalman filters, **improving trend detection** and **alert reliability** in safety-critical contexts.
- Created a **scalable digital twin framework** for an industrial fleet, turning **400+ hypotheses** into a **strategic roadmap** with reusable templates for implementation and scaling.
- Supporting the evolution of a **major airline MRO platform** by advancing predictive maintenance through analytics and consulting.

Eraneos combines expertise in consulting, IT architecture, data analytics, and cybersecurity to support aviation clients in developing future-ready digital twin solutions that are technically robust, strategically grounded, and operationally impactful.

Phase	Strategy & Use Case Definition	Requirements & Architecture Design	Development & Simulation	Deployment & Scaling	Optimization & Reuse
Definition	• Establish vision • Secure stakeholder buy-in • Identify high-impact use cases by aligning digital twin initiatives with operational goals such as reducing AOG (Aircraft-on-Ground), improving time-on-wing, or optimizing cabin systems	• Translate strategic goals into system and data architecture by defining input/output streams, selecting integration targets (e.g., PLM, ERP, Airbus Skywise) • ensuring compliance with aviation cybersecurity and data regulations.	• Develop validated models and simulations using operational data • Calibrate against real-world events • Create initial digital twin prototypes for systems like aircraft engines, hydraulics, or fuselage assembly line	• Integrate with airline or OEM systems and automate real-time data flow • Use high-fidelity sensors to ensure accurate, reliable twin data • Deploy across platforms or fleets for scalable impact	• Maximize long-term value by reusing validated models across new aircraft types, developing monetization approaches • Continuously optimizing predictive performance
How we can support	• Facilitate workshops to define vision and priorities • Identify high-impact use cases with ROI analysis • Map stakeholders and align across teams	• Design system architecture and data flows • Ensure regulatory compliance and cybersecurity • Integrate with legacy and modern systems	• Build and refine digital twin models • Select tools and calibrate with real-world data • Run iterative test cycles with engineering teams	• Integrate with operational and IT systems • Enable real-time data flow for scalability • Train teams and establish monitoring frameworks	• Build business cases for platform reuse with ROI analysis • Develop KPI dashboards to track value creation • Track benefits via savings, uptime, and emissions impact



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Authors

Ralph Tritsch
Senior Manager
Eraneos

ralph.tritsch@eraneos.com

Manuel Held
Senior Consultant
Eraneos

manuel.held@eraneos.com

Mourad Siala
Analyst
Eraneos

mourad.siala@eraneos.com

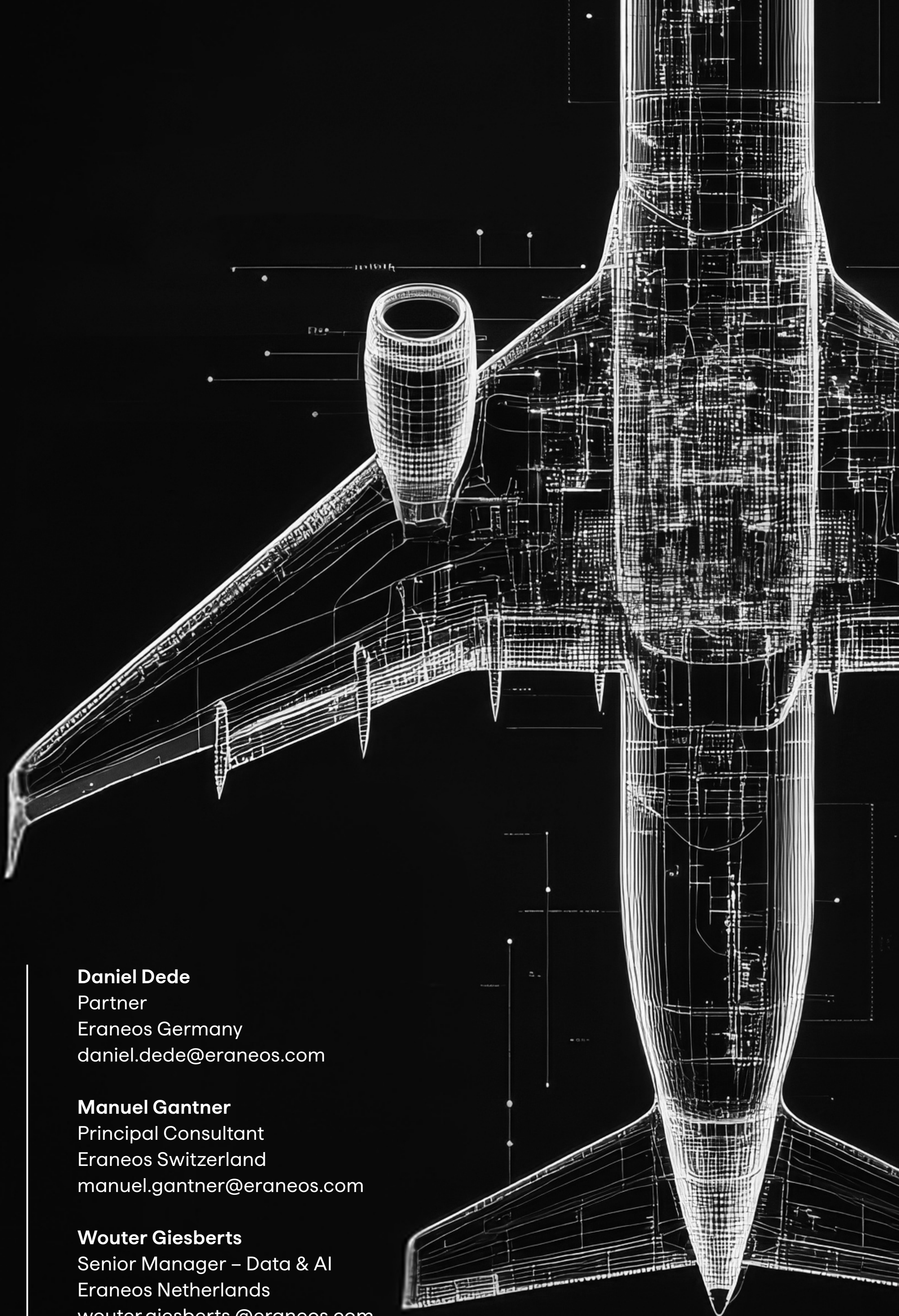
Contributors

Emilio Oldenziel
AI Lead
Eraneos

emilio.oldenziel@eraneos.com

Sean Whiteley
Subject Matter Expert
Eraneos

sean.whiteley@eraneos.com



Get in touch

Daniel Dede
Partner
Eraneos Germany
daniel.dede@eraneos.com

Manuel Gantner
Principal Consultant
Eraneos Switzerland
manuel.gantner@eraneos.com

Wouter Giesberts
Senior Manager – Data & AI
Eraneos Netherlands
wouter.giesberts.@eraneos.com