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Digital Twin in Aerospace Industry

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ABSTRACT

In an era defined by rapid technological advancement, the aerospace and defense sectors face increasing pressure to accelerate innovation, reduce costs, and enhance the safety and sustainability of complex systems. To meet these demands, the industry has increasingly adopted digital twin technology. A digital twin is regarded as an integrated, data-driven virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity. Digital twins are revolutionizing the aerospace industry, providing unprecedented efficiency, accuracy, and insight into aerospace assets. By bridging the physical and digital worlds, digital twins are accelerating innovation, optimizing manufacturing, and revolutionizing predictive maintenance. As the aerospace sector continues its digital transformation, the digital twin will undoubtedly remain a cornerstone technology, mirroring the skies to ensure a safer, more efficient, and sustainable future for aviation and space exploration. This paper explores the transformative applications of digital twin in the aerospace industry.

KEYWORDS: *digitalization, digital twin, data twin, aerospace, aerospace industry, aviation.*

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INTRODUCTION

The aerospace industry is currently undergoing a profound digital transformation, driven by the need for enhanced safety, efficiency, and sustainability. At the forefront of this revolution is the concept of the “digital twin.” A digital twin is regarded as a precise, dynamic virtual replica of a physical system that continuously updates itself using real-time data collected from sensors on its real-world counterpart. Digital twin (DT) is not merely a 3D model; it is a dynamic entity that continuously learns and updates itself using real-time data from sensors monitoring the physical product's environment and operating conditions. The aerospace industry has been an early adopter of this technology. Figure 1 shows a typical digital twin [1]. It is regarded as the next generation of digitalization for decision making support. The current development of digital technologies has dramatically increased the adoption of digital twin (DT) systems into the aerospace sector. Figure 2 shows the conceptual model of a digital twin [2].

In the aerospace sector, digital twins are revolutionizing the product lifecycle, from initial design to final assembly. Whether it be product development, design optimization, performance improvement, or predictive maintenance, digital twins are changing the ways work is undertaken in various industries with multifarious business applications. Aerospace industry, including its manufacturing base, is one such keen adopter of digital twins with an unprecedented interest in their bespoke design, development, and implementation across wider operations and critical functions. Aerospace companies use digital twins to enhance the engineering of new parts by replicating their accomplishments in different conditions. Companies like Airbus and Boeing are leveraging this technology to create a “digital-first” strategy, aiming to accelerate product development and enhance environmental performance [3]. At Boeing digital twins are used to design aircraft.

CONCEPT OF DIGITAL TWIN

The concept of the digital twin was introduced in 2002 by Michael Grieves of Florida Institute of Technology. He applied the concept in manufacturing and proposed the digital twin as the conceptual model underlying product lifecycle management (PLM). The concept was being practiced since the 1960s by NASA. The concept of digital twin consists of three distinct parts: the physical product, the digital/virtual product, and connections between the two products [4]. Figure 3 shows the historical evolution of DT technology [5].

A digital twin is much as it sounds: creating a digital duplicate of the physical entity.

It has two sides, one pertaining to a physical device and the other to a digital rendition of this device. DT is a real time digital replica of a physical device using 3D modeling and sensors. The DT is an emerging paradigm focusing on an enterprise asset such as a system, product or process. Its core goal is to virtually represent this asset as close to reality as possible. A digital twin may exist before its physical counterpart is made. Technologies enabling DT include AI, IoT, 5G, virtual reality, augmented reality, wearables, and cloud computing. Realizing the full potential of DTs requires a convergence of these technologies. Digital twins integrate AI, IoT, machine learning, and software analytics with spatial network graph to create living digital simulation models that change as their physical counterparts change.

The three main pillars of the digital twin technology are visualization, emulation, and simulation. The foundation of DT is the physical world, which may consist of devices/products, physical systems, process, or an organization. Service is an essential component of DT in view of the paradigm of everything-as-a-service. DT-related services include application service, resource service, knowledge service, and platform service. The process of implementing DT can be divided into four steps: digital representation, synchronous mapping, simulation and prediction, and virtual and physical fusion. Figure 4 depicts the digital twin conceptual architecture [6], while Figure 5 shows DT enabling technology [7].

There are numerous requirements to describe “digital twin.” To be considered a digital twin, the model must have some specific characteristics such as [8]:

1. Data is the carrier of information and the key driver of DT. Real-time data is important for knowing the status of the product. Data-driven digital twin can perceive, respond, and adapt to the changing environment.

   Integration of the different nodes is essential for creating valuable data. Sensors communicate the data to the digital world through integration technology between the physical world and the digital world, and vice versa.
2. Scalability (ability to analyze different scales of information);
3. Interoperability (ability to convert, match and establish equivalence between representation models);
4. Expansibility (ability to integrate models);
5. Fidelity (ability to conform to the physical model); the core of any DT is a high-fidelity virtual model.
6. Connectivity that indicates the level of communication with its physical counterpart; connectivity by design through IoT which is a paradigm for ubiquitous connectivity. Connect the products/services to a central location with streaming, big data, in-memory, and analytic capabilities to capture sensor data and enrich it with business and contextual data.

These are the most frequent requirements of digital twins.

DIGITAL TWIN IN AEROSPACE

The aviation industry is regarded as technology-intensive by virtue of the gradual digital transformation that has taken place over several decades within the entire aerospace industry. The aerospace industry, characterized by complex systems, stringent safety requirements, and high operational costs, is undergoing a profound transformation driven by digital innovation. At the forefront of this revolution is digital twin technology-a paradigm that creates dynamic, living virtual replicas of physical assets, processes, and systems. A digital twin is an actual virtual copying of a physical asset, system, or process, the nature of which mirrors the real-world behavior in real-time. By integrating real-time data from the Internet of things (IoT), advanced analytics, and artificial intelligence (AI), digital twins bridge the physical and virtual worlds [3].

In the ever-evolving landscape of aerospace engineering, DT has emerged as a groundbreaking technology, revolutionizing how aircraft are designed, tested, and maintained. The aerospace sector is uniquely poised to benefit from digital twins. For airlines, this has transformed maintenance models from reactive to preventative. Aircraft remain complex machines of millions of interrelated parts, operating in safety-critical environments where downtime is expensive. For example, Airbus has heavily invested in building digital twins of complete aircraft structures. Figure 6 shows a representation of DT in aerospace [9], while Figure 7 shows an aerospace engineer [10].

APPLICATIONS OF DIGITAL TWIN IN AEROSPACE

For aerospace engineers and aviation professionals today, digital twins are no longer mere futuristic ideas; the application spans aircraft manufacturing, predictive maintenance, air traffic systems, and even passenger experience optimization. Common applications of DT in aerospace include the following [3,11]:

- *Smart Manufacturing:* Digital twins are revolutionizing aerospace manufacturing floors and transforming production systems as well as aerospace manufacturing processes. By creating virtual representations of manufacturing lines, companies can simulate workflows, robotic operations, and supply chain logistics . This enables the optimization of factory layouts and the identification of bottlenecks before physical implementation. By creating virtual representations of manufacturing lines, tools, robots, and supply chains, aerospace manufacturers can predict how designs will perform and optimize industrial operations with precision. At Airbus, industrial digital twins utilize machine data to monitor logistics flows, track production progress in real-time against theoretical plans, and detect quality deviations at composite draping stations. This approach minimizes waste, reduces paperwork, and ensures "first-time quality" in manufacturing. Digital twins enable Airbus to deliver more innovative, sustainable, and high-performing solutions at an unprecedented pace. From the initial design concept to the final flight, they are effectively building each aircraft twice: first in the digital world, and then in the real one. This is the power of digital twin. Figure 8 shows aerospace manufacturing facility [12].
- *Maintenance:* Perhaps the most immediate and impactful application of digital twins in commercial aviation is in the realm of Maintenance, Repair, and Overhaul (MRO). Historically, aircraft maintenance has relied on scheduled intervals or reactive repairs following component failure. Digital twins facilitate a shift toward predictive maintenance, a proactive approach that leverages real-time data and advanced analytics. Modern aircraft are equipped with thousands of sensors that continuously monitor various parameters, such as temperature, pressure, and vibration.
- *Space Exploration:* The future of digital twins extends far beyond the earth's atmosphere. In space exploration, where physical intervention is often impossible, digital twins are vital for mission success. The harsh and inaccessible environment of space makes digital twins particularly valuable for spacecraft and satellite operations. NASA continues to pioneer this technology. The Joint Simulation Target and Application Framework (JSTAR) at NASA utilizes hardware emulation digital twins to condense entire flight systems into software solutions. This allows for the emulation of flight computer hardware and the simulation of sensors, enabling engineers to execute flight software binaries exactly as they would operate in space. For multi-spacecraft operations and satellite constellations, digital twins facilitate real-time monitoring and coordination, optimizing resource management in resource-constrained environments.
- *Defense:* In the defense sector, digital twins are critical for managing complex weapon systems and maintaining mission readiness. The F-35 Joint Program Office, in collaboration with the Air Force Research Laboratory, recently established a Micro-Electronics Digital Engineering Infrastructure facility to develop hardware-accurate digital twins of the F-35 Lightning II . This initiative aims to streamline development processes, validate hardware and software upgrades in a simulated environment, and mitigate schedule delays.
- *Asset Tracking*: Every modern commercial engine is delivered with its own digital thumbprint. This digital record tracks the engine from birth through retirement, monitoring flight cycles, part replacements, and service history. According to Boeing, digital twins allow for an understanding of the individual aircraft, system, and component, enabling predictive maintenance insights that are individualized rather than just fleet-wide averages. This level of precision reduces unplanned downtime, extends component life, and optimizes spare parts logistics.
- *Product Development*: In the early stages of product development, digital twins serve as a powerful tool for engineers to simulate and validate aircraft behavior under a multitude of real-world scenarios using physics-based models . This "Create Before You Aviate" approach significantly reduces the reliance on costly and time-consuming physical prototypes. For example, Airbus utilizes digital twins to simulate product flow and optimize manufacturing operations. By establishing a digital twin of an aircraft subsystem, such as the braking system or

the avionics architecture, engineers can conduct virtual software testing and hardware integration early in the lifecycle, thereby accelerating time-to-market.

- *Virtual Prototyping*: The traditional aerospace design process relies heavily on physical prototyping, which is both time-consuming and cost-intensive. Digital twins are fundamentally altering this paradigm by enabling "virtual prototyping," allowing engineers to simulate an aircraft's behavior under a multitude of real-world scenarios using physics-based models. This capability allows for rapid design iterations and the identification of potential issues long before physical construction begins. For example, Airbus utilizes 3D data and automation on the A320 family "heads of versions" to significantly reduce quality issues and shorten design lead times.
- *Simulation Software:* Simulation software enables engineers to predict how design changes would affect actual performance long before physical prototypes are put together. Simulation software is in the heart of every digital twin. In aerospace, the likes of Ansys, Siemens NX, and Dassault Systèmes' 3DEXPERIENCE are some of the simulation tools that mimic fluids, static materials, and airforces in real life. But traditional simulation software is run in airtight rooms. In a real digital twin, integration of simulation with real sensor data and AI analytics creates a continuously evolving model.
- *New Design:* Transitioning to alternative energy sources, such as hydrogen fuel cells or advanced electric batteries, requires massive redesigns of aircraft architecture. Digital twins provide the integrated design environment necessary to model, test, and analyze the impact of these new energy systems on aircraft configurations. This virtual testing allows engineers to overcome the complex design challenges of sustainable aviation-such as hydrogen storage or battery weight distribution-without the resource-intensive process of physical prototyping. Figure 9 shows a design of an aircraft [10].
- *Health Monitoring:* Digital twins enable comprehensive prognostic health monitoring of the entire aircraft. By analyzing stress on critical components over time, such as landing gear or avionics, the virtual model can anticipate long-term wear and tear. This ensures that maintenance interventions are targeted and performed at the optimal time, maximizing the operational lifespan of parts and reducing the labor and material costs associated with over-servicing. For example, astronaut digital twins-integrating genomic profiles and medical history-could provide real-time health monitoring and personalized medical interventions during deep space missions.
- *Fleet Management:* The benefits scale exponentially when applied to entire fleets. Platforms like Airbus's Skywise connect over 12,000 aircraft, feeding real-time data into their virtual twins. This massive data integration empowers airlines to optimize maintenance schedules across their operations, improving fleet-wide reliability, safety, and customer satisfaction.
- *Predictive Maintenance:* Perhaps the most significant and widely implemented application of digital twins in aerospace is predictive maintenance. Traditional maintenance strategies in aviation have historically relied on routine, scheduled inspections based on flight hours or cycles. While this ensures safety, it often leads to unnecessary downtime, over-maintenance, and the premature replacement of viable components. Once an aircraft enters service, its digital twin continues to evolve, providing invaluable insights for maintenance and fleet operations. This shift from reactive or scheduled maintenance to predictive, condition-based maintenance is one of the most significant impacts of digital twin technology.

BENEFITS

Digital twins represent a paradigm shift in the aerospace industry, offering the potential to revolutionize how aircraft are designed, manufactured, and maintained. The technology promises unprecedented benefits-including accelerated product development, enhanced predictive maintenance, and optimized manufacturing. The technology has the ability to bridge the physical and digital worlds, enabling engineers to predict failures, optimize performance, and make data-driven decisions across the entire lifecycle of aerospace assets. Other benefits of DT in aerospace include the following [3,9,11]:

- *Cost Savings:* General Electric (GE) employs DTs in the development and manufacturing of the LEAP aircraft engine, a collaboration with Safran Aircraft Engines. The usage of such has streamlined the testing and optimization processes, reducing the need for extensive physical testing. This has led to substantial cost savings in the development phase, making the LEAP engine more cost-effective and competitive in the market.

- *Enhanced Safety:* In the world of aviation, safety is paramount. Digital twin-enhanced safety simulates critical scenarios through continuous monitoring of real-time performance. It predicts potential faults before their actual occurrence so flights can be made safer, having fewer in-flight emergencies and hence greater acceptance by regulators, pilots, and passengers alike worldwide. Embraer utilizes Digital Twins in the design and safety testing of their E-Jets E2 series. By simulating various flight conditions and scenarios in the digital environment, Embraer can proactively identify and address potential safety concerns.
- *Sustainability:* The aviation industry is under immense pressure to reduce its environmental footprint and achieve carbon neutrality by 2050 under the Paris Agreement. Digital twins are emerging as a critical enabler of the industry's sustainable transformation. Achieving zero-emission flight will require a radical shift toward alternative energy sources, such as electric batteries or hydrogen fuel cells. These new energy paradigms necessitate entirely new aircraft configurations, such as blended wing bodies, to accommodate different storage requirements. Digital twins provide an integrated design environment where multi-disciplinary engineering teams can model, test, and analyze the impact of these alternative energy sources on new aircraft configurations from the component level to the entire integrated system.
- *Scalability:* The modular systems can scale from a twin of a single subsystem to an enterprise-wide fleet management system, ensuring that the growing needs of the aviation sector can be accommodated without throwing a wrench into the existing tech stack.
- *Collaborative Efforts:* Collaborative efforts within the aerospace industry will drive the development of standardized practices for digital twin implementation. Shared frameworks and guidelines will facilitate interoperability and the seamless exchange of digital twin data across different aerospace platforms. Future digital twins in aerospace will likely involve increased collaboration between humans and machine intelligence. Human expertise combined with AI-driven insights will lead to more informed decision-making and innovative solutions. The Digital Twin Consortium is an industry association working to establish best practices and drive the adoption of digital twins across various sectors, including aerospace. Collaborative initiatives like this promote standardization and ensure a cohesive approach to digital twin implementation
- *Fuel Efficiency:* By optimizing aircraft performance and enabling condition-based maintenance, digital twins directly contribute to reduced fuel consumption. An engine operating at peak efficiency burns less fuel, thereby lowering the carbon footprint of the aircraft.
- *Reduced Downtime:* Any sudden fault-induced grounding of an aircraft means millions in daily losses to an airline. With foresight built into a digital twin, the maintenance could be planned for windows for service, thus limiting any sudden malfunctions. This would in turn enhance the hours available for fleet utilization and optimize overall operational efficiency.
- *Lower Maintenance Costs:* Emergency repairs and grounding of an aircraft impose heavy cost burdens. Digital twin technology mitigates such risks by early failure prediction to allow cost-effective planning of interventions. This leads to the reduced maintenance expenditure incurred by airlines in the long run, along with cost of spare parts procurement, crew deployment, and optimizations of all sorts.
- *Extended Component Life:* Simulation-driven monitoring may show how, under certain conditions of high altitude or frequent take-offs, engines and components suffer more wear and tear. Properly adjusting operating patterns from the knowledge of such effects prolongs component life, delays replacement, and offsets other capital expenses considered under safety terms.

CHALLENGES

In spite of the profound benefits of DT in aerospace, the path to ubiquitous, widespread adoption is obstructed by significant challenges. Challenges regarding cybersecurity, data integration, standardization, interoperability, intellectual property protection, limited data availability, skill gap, and high cost persist. Other challenges of DT in aerospace include the following [3,9]:

- *High Implementation Costs*: Developing and maintaining high-fidelity digital twins requires significant investment in sensor technology, cloud infrastructure, and advanced computing power. While digital twins promise long-term ROI through reduced physical testing and optimized maintenance, the initial capital expenditure is substantial. Developing high-fidelity models, upgrading IT infrastructure, and maintaining cloud storage require significant upfront investment. For smaller suppliers within the aerospace ecosystem, these costs can be prohibitive, creating a barrier to industry-wide adoption.

- *Privacy Concerns*: Protecting the privacy of sensitive information, especially in a collaborative aerospace environment, is crucial. Stakeholders need to ensure that proprietary data and intellectual property are safeguarded.
- *Cybersecurity Risks:* The integration of digital twins fundamentally alters the cybersecurity landscape of aerospace operations. As digital twins require the continuous exchange of massive amounts of real-time data between physical assets and cloud-based virtual models, they present a substantial cybersecurity risk. Protecting sensitive design data, operational parameters, and proprietary algorithms from cyber threats is paramount, especially in the defense sector. The integration of artificial intelligence and machine learning is increasingly necessary to secure these digital twin systems and detect anomalies in network behavior. Zero-trust networking is becoming the standard for protecting these environments, ensuring that systems only grant the minimum privileges necessary for communication.
- *Standardization:* The aerospace supply chain is highly complex, involving numerous vendors and subcontractors. Currently, there is a lack of standardized data formats and interoperable platforms, making it difficult to integrate digital twins across different systems and organizations. Achieving full digitization requires a unified approach to digital architecture, leveraging secure and reliable platforms that can communicate seamlessly.
- *Skill Gap:* The successful deployment of digital twins requires a convergence of disciplines: aerospace engineering, data science, software development, and cybersecurity. There is currently a significant talent shortage in the aerospace sector for individuals possessing this cross-functional expertise. Bridging this skills gap requires sustained investment in workforce development and training. As noted by industry experts, having access to simulators is insufficient without the right modeling expertise to interpret the data and refine the virtual models.
- *Complexity:* The aerospace industry is inherently characterized by high stakes, immense complexity, and rigorous safety standards. It operates under extreme safety requirements, complex supply chains, and massive data volumes. The infrastructure required to support real-time data ingestion and analytics is costly and complex. As humanity prepares to return to the Moon and venture toward Mars, spacecraft systems are growing exponentially in complexity. Digital twins are essential for enabling real-time monitoring, predictive maintenance, and adaptive decision-making in environments where physical inspection is impossible. In the defense sector, digital twins manage the immense complexity of modern military assets, such as the Joint Strike Fighter, which contains over 25 million lines of software code. The ability to test software updates and system modifications on a digital twin before deployment ensures that mission-critical systems operate flawlessly under extreme conditions.
- *Interoperability:* Aerospace systems are inherently complex, often involving “systems of systems” developed by multiple vendors across a global supply chain. Achieving interoperability-the ability of different digital twins and modeling tools to communicate and exchange data seamlessly-is a major hurdle.
- *Intellectual Property:* Digital twins encapsulate the entirety of an asset's design, manufacturing processes, and operational parameters. Consequently, they represent a massive concentration of intellectual property. In the highly competitive aerospace and defense sectors, the theft of a digital twin could allow adversaries or competitors to reverse-engineer advanced technologies. Digital twins produce substantial volumes of data, designs, and algorithms that may be protected under various forms of intellectual property (IP) rights. Once data is aggregated into a digital twin, the risk of IP theft increases exponentially.
- *Airworthiness:* The aerospace industry is heavily regulated by authorities such as the Federal Aviation Administration (FAA) in the United States and the European Union Aviation Safety Agency (EASA). Before any new aircraft or critical component can enter service, it must undergo rigorous certification processes to prove its airworthiness. While regulatory bodies are increasingly accepting digital simulation as part of compliance demonstration, the process is complex. Regulators do not certify the software tools themselves; rather, they certify the data, processes, and methods used to generate the results.

FUTURE OF DIGITAL TWINS IN AEROSPACE

The future of digital twins in aerospace is intrinsically linked to advancements in enabling technologies such as artificial intelligence (AI), edge computing, and autonomous systems. The incorporation of advanced AI will allow digital twins to not only predict failures but also autonomously generate optimal solutions. As computational power increases and artificial intelligence algorithms become more sophisticated, the digital twin will undoubtedly remain a cornerstone of aerospace innovation, ensuring safer, more efficient, and more sustainable skies.

Future digital twins will evolve from being purely analytical tools to cognitive entities capable of autonomous decision-making and self-optimization, further reducing the need for human intervention in routine operational adjustments. Looking ahead, the digital twin paradigm is set to become even more critical in defense and space exploration. As the industry looks toward deep space exploration and sustainable aviation, the digital twin will serve as the critical virtual mirror guiding the physical reality of future flight [3].

CONCLUSION

The aerospace industry is undergoing a profound transformation driven by the need for enhanced safety, improved efficiency, and reduced environmental impact. In the industry, where precision, safety, and efficiency are paramount, digital twins are moving beyond theoretical concepts to become indispensable tools. The global market for digital twins in aerospace and defense is projected to experience exponential growth. The digital twin is not merely a technological trend; it is a fundamental paradigm shift that is reshaping the future of the aerospace industry. By creating dynamic, data-driven virtual replicas of physical assets, aerospace companies are unlocking unprecedented levels of efficiency, safety, and innovation. Digital twin is a highly transformative technology with profound implications. It has become the navigational instrument guiding the industry toward a more sustainable and technologically advanced future. More information about digital twin in the aerospace industry can be found in the books in [13,14].

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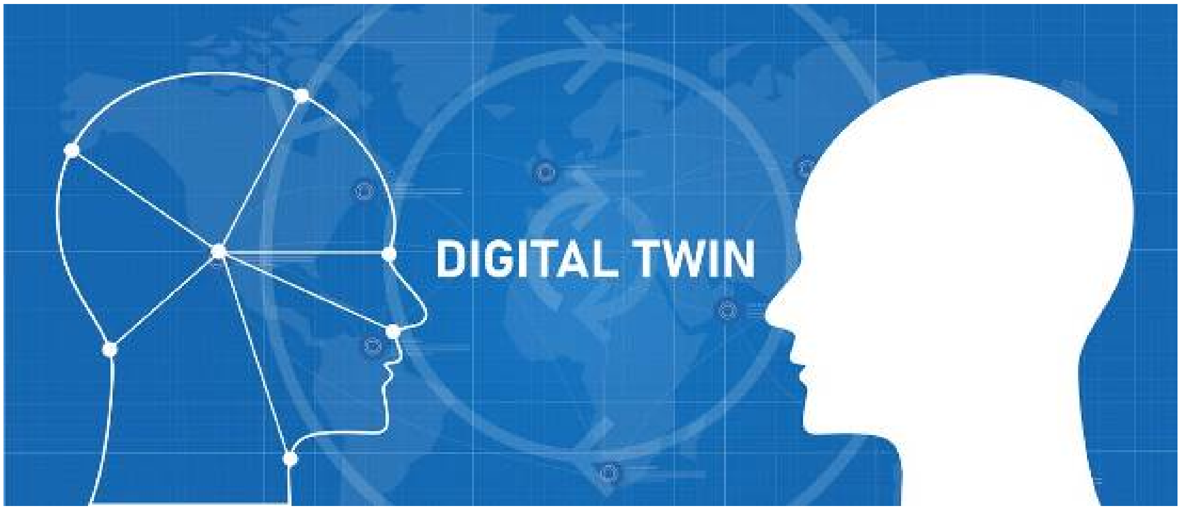


Figure 1 A typical digital twin [1].

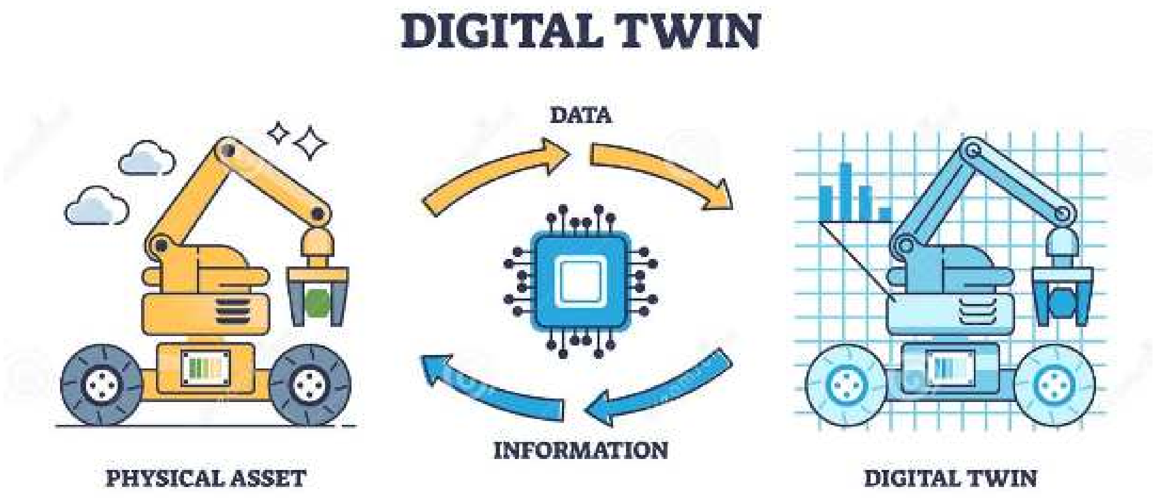
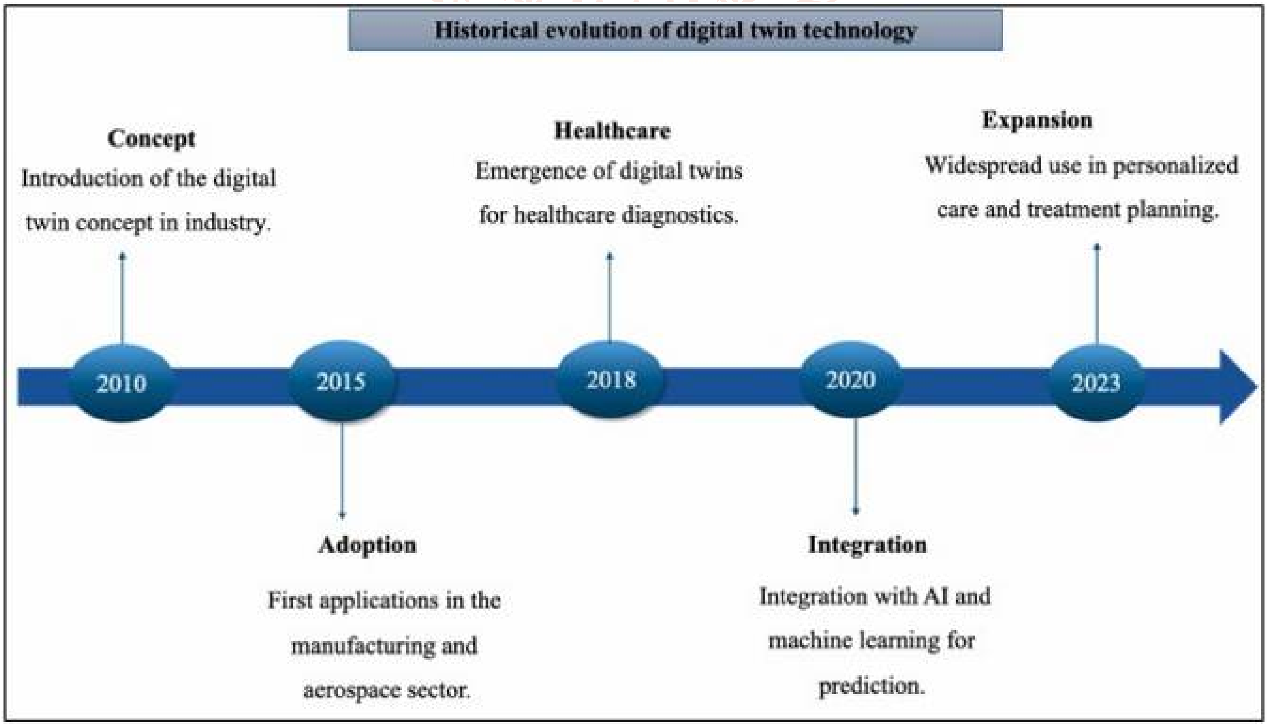


Figure 2 Conceptual model of a digital twin [2].



Concept
Introduction of the digital twin concept in industry.

Adoption
First applications in the manufacturing and aerospace sector.

Healthcare
Emergence of digital twins for healthcare diagnostics.

Integration
Integration with AI and machine learning for prediction.

Expansion
Widespread use in personalized care and treatment planning.

Figure 3 The historical evolution of DT technology [5].

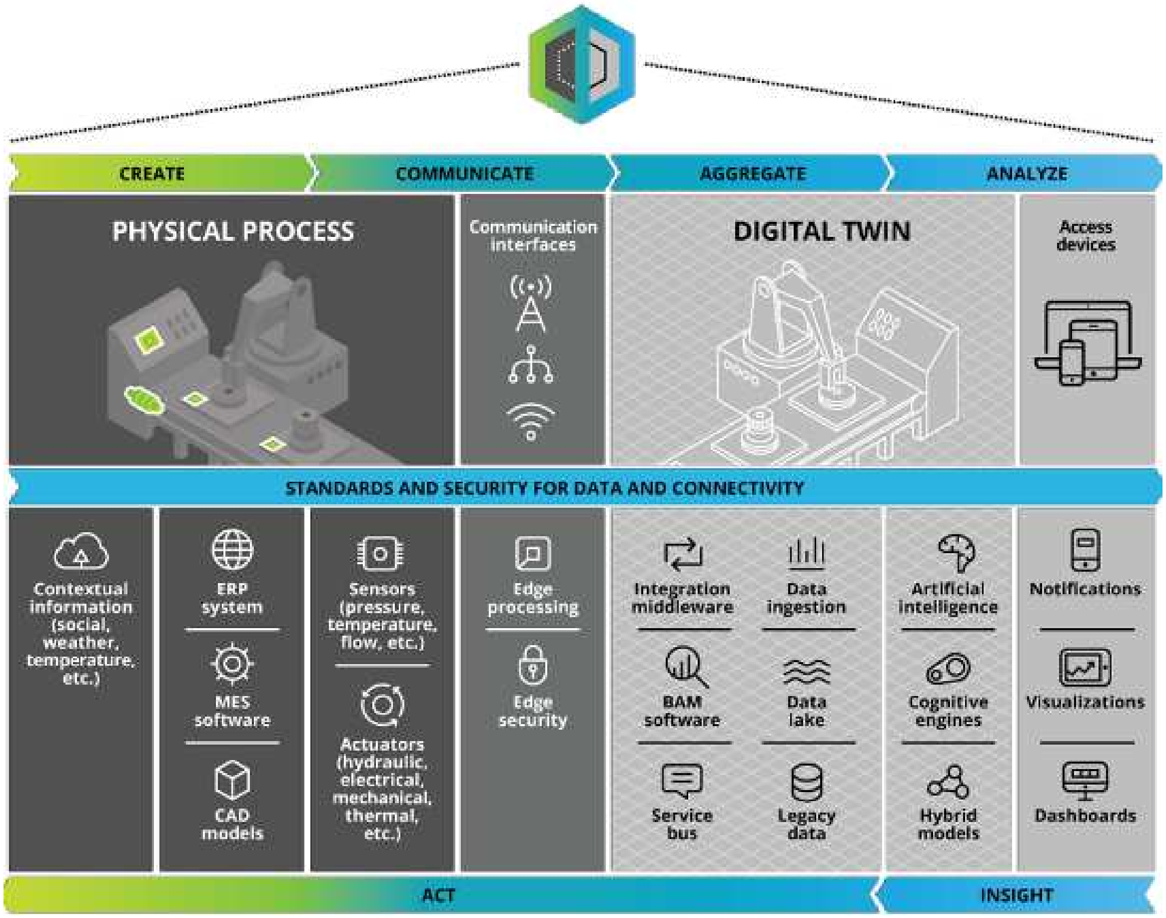


Figure 4 The digital twin conceptual architecture [6].

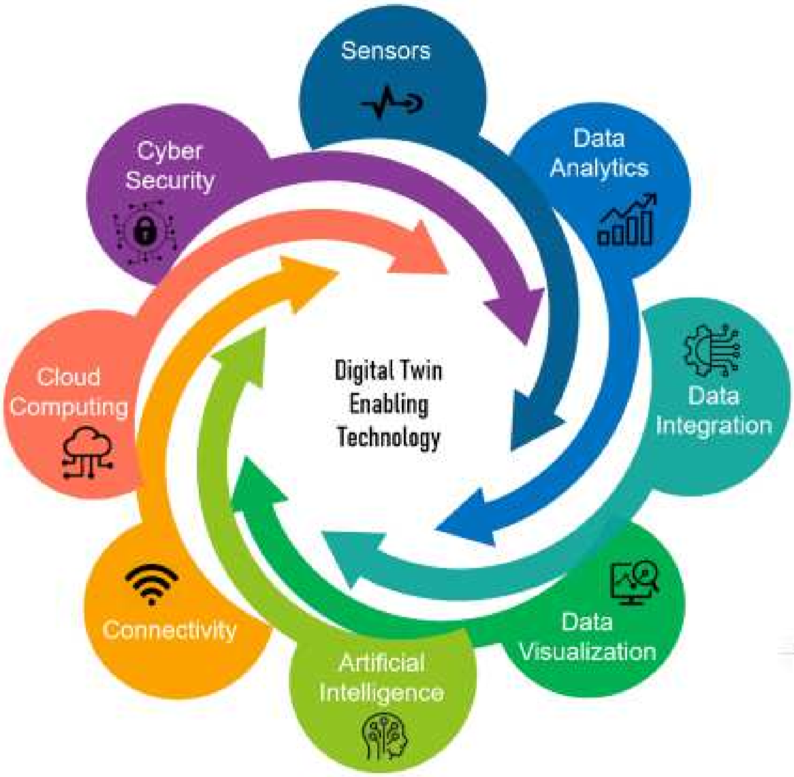


Figure 5 DT enabling technology [7].

Figure 6 A representation of DT in aerospace [9].

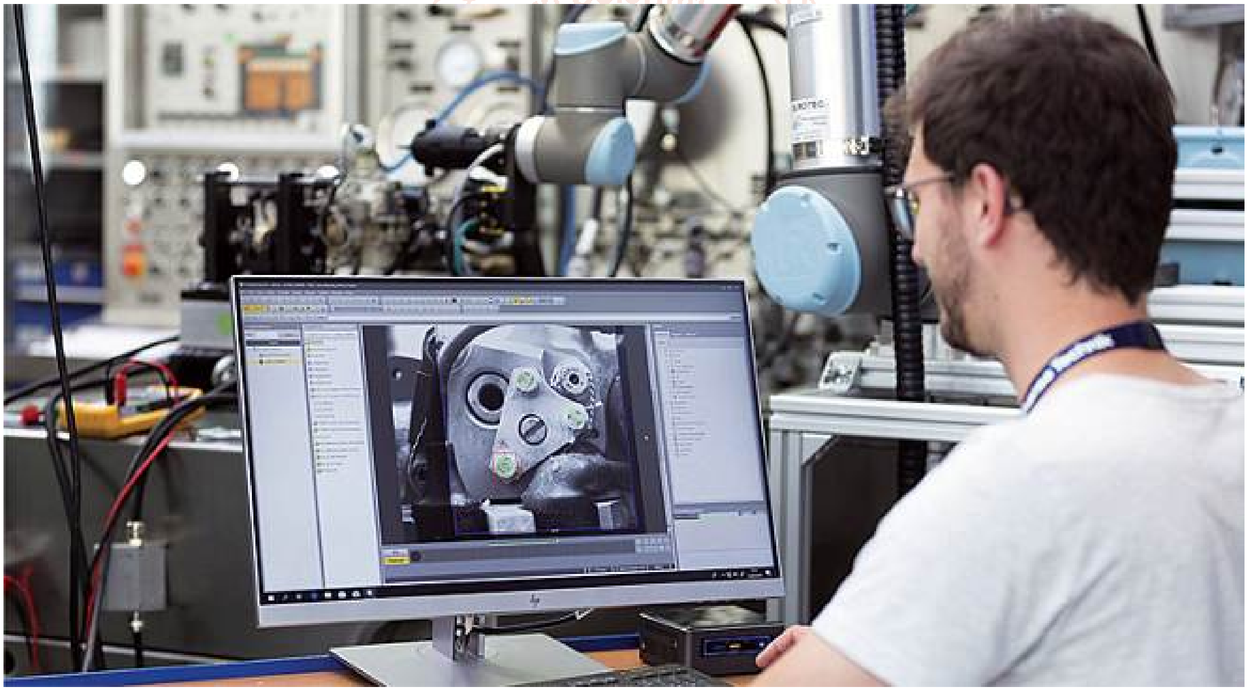


Figure 7 An aerospace engineer [10].

Figure 8 Aerospace manufacturing facility [12].

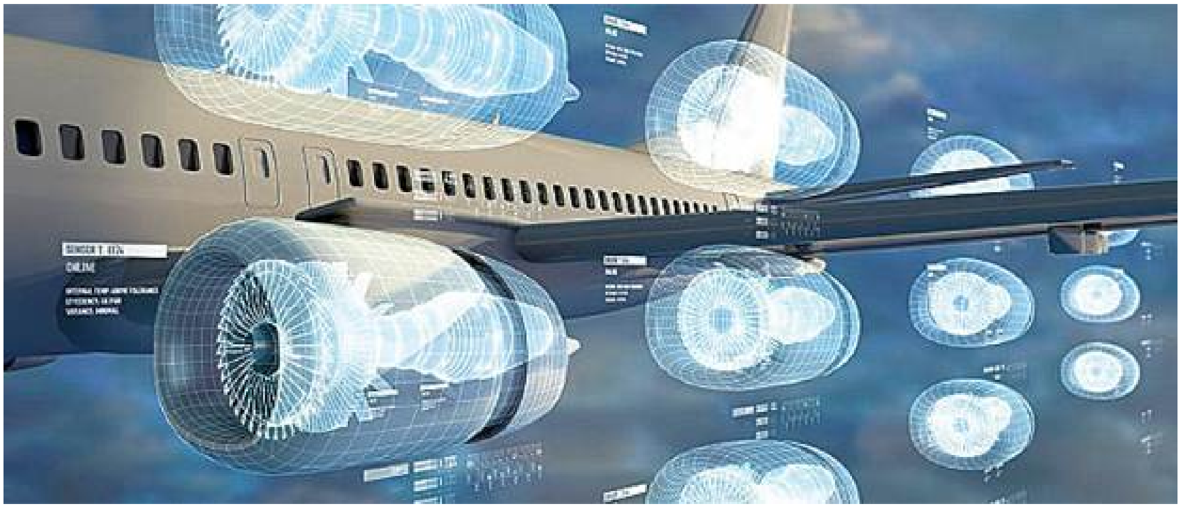


Figure 9 Design of an aircraft [10].