Open Access Research Journal of
Engineering and Technology
Journals home page: https://oarjpublication/journals/oarjet/
ISSN: 2783-0128 (Online)

OARJ OPEN ACCESS RESEARCH JOURNALS

(REVIEW ARTICLE)

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Evaluation of product lifecycle management and digital twin integration in aviation field

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Open Access Research Journal of Engineering and Technology, 2024, 07(02), 060–069

Publication history: Received on 21 August 2024; revised on 29 October 2024; accepted on 31 October 2024

Article DOI: https://doi.org/10.53022/oarjet.2024.7.2.0054

Abstract

In today's world, digital transformation is becoming increasingly crucial in industry. The Digital Twins and simulations become much more important with growing complexity of products, the need to accelerate product development processes while reducing costs. The increasing value of Digital Twins is prompting organizations in the aviation industry to actively utilize them in research and development efforts. However, due the idea of difficulties of using Digital Twins in the industries, product developers don't have a clear idea where to begin. This article provides readers with a general overview of the current situation by offering an examination of the aviation sector. Initially, the concept of Digital Twin, its evolution, and relevant studies are explored, followed by an examination of the impact of creating Digital Twins for companies operating in aviation on the product development process. In this study, unlike other published works, the concept of Digital Twin is explained under three subheadings. These include the Design Digital Twin for design steps, the Production Digital Twin for manufacturing processes, and the Performance Digital Twin for post-delivery work related to the product. The final section of the study evaluates the contribution of Product Lifecycle Management (PLM) systems to the process of creating Digital Twins and the advantages they provide to companies in product development processes.

The present research work does not contain any studies performed on animals/humans subjects by any of the authors.

Keywords: Digital Twin; Product Lifecycle Management (PLM); Design Digital Twin; Production Digital Twin; Performance Digital Twin; Aviation

1. Introduction

The aircraft design process typically occurs in five steps. First, after understanding the needs, the requirements and technical constraints are determined, and conceptual designs are created at this stage [1]. Then, based on the identified requirements, three-dimensional (3D) models of the aircraft are created using computer-aided design (CAD) and computer-aided engineering (CAE) software, and simulations are conducted under various scenarios [2]. Once the design is approved, a prototype is manufactured. This prototype is used to test the performance of the design under real-world conditions. Prototype tests are generally conducted in various areas such as aerodynamic testing, structural durability testing, engine performance testing, and flight testing. These tests are crucial for determining whether the design meets the targeted performance [3]. If the prototype tests are successful, the aircraft moves on to the certification process. The certification process involves comprehensive tests conducted by relevant authorities to verify the safety and suitability of the aircraft [4]. After the completion of the certification process, serial production begins, and the aircraft is introduced to the market. The aircraft design process continues even after production and delivery. Maintenance and support services must be continuously provided during the aircraft's usage. Providing maintenance and support services is essential to maintain the aircraft's safety, efficiency, and mission performance [5]. The outlined process is summarized in Figure 1.

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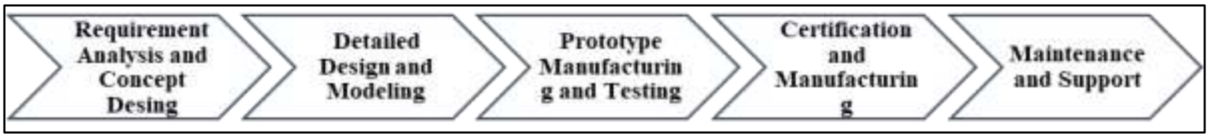

Figure 1 Aircraft Project Lifecycle

The aircraft design process generally requires a multidisciplinary approach, integrating engineering, technology, and industrial design disciplines [6]. This process is continually evolving, leading to more efficient and innovative aircraft through the integration of new technologies and methods [7]. Nowadays, the tracking and linking of these processes are attempted using PLM software. PLM systems help identify the impact area of problems in the processes and retroactively detect points for improvement [8]. Due to increased competitive conditions, the concept of Digital Twin is also coming to the forefront alongside PLM systems to ensure that products are quickly brought to market and cost advantages are realized in the aerospace industry.

2. Digital Twin

The Digital Twin is a digital replica of a physical object or process. The concept of a Digital Twin is defined as the digital representation of a physical entity and even more [9]. A Digital Twin is used to predict the complete characteristics, behaviors, and performance of an object or process. This technology is widely used, especially in the manufacturing sector, and is effectively applied in areas such as real-time production scheduling [10]. Digital Twins are used to better understand, optimize, and simulate future outcomes of physical objects or processes [11]. A Digital Twin should include a virtual process definition and, most importantly, create all the physical conditions that the product will encounter throughout its lifecycle virtually. When this goal is achieved, the Digital Twin can create new business models that provide companies with new revenue streams and business opportunities [12]. As shown in Figure 2, the Digital Twin emerges from the concept phase and evolves and persists alongside the product throughout its lifecycle.

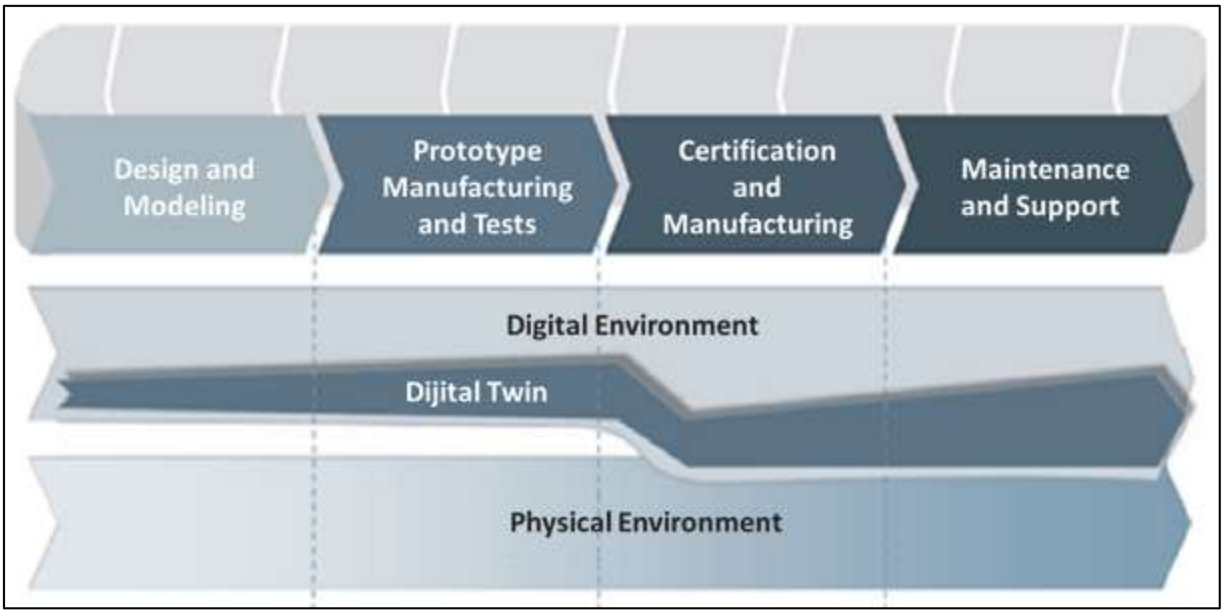

Figure 2 Relationship Between Digital Twin, Process, and Physical Environment [13]

2.1. Digital Twin in Aerospace Industry

In aviation, Digital Twins are utilized across various fields such as space science, security and defense, commercial aircraft, and aviation manufacturing, encompassing activities from design to product delivery [13] These digital replicas are crucial for predicting the lifespan of aircraft structures, ensuring structural integrity, and analyzing wear and fatigue throughout the aircraft's operational life [17]. Furthermore, Digital Twins significantly contribute to cost savings and reliability improvements, especially in the analysis of high-value equipment like jet engines [18].

The concept of the Twin was first introduced during NASA's Apollo 13 program. NASA created at least two spacecraft for the program, testing them under various conditions on Earth, and referred to them as twins [13]

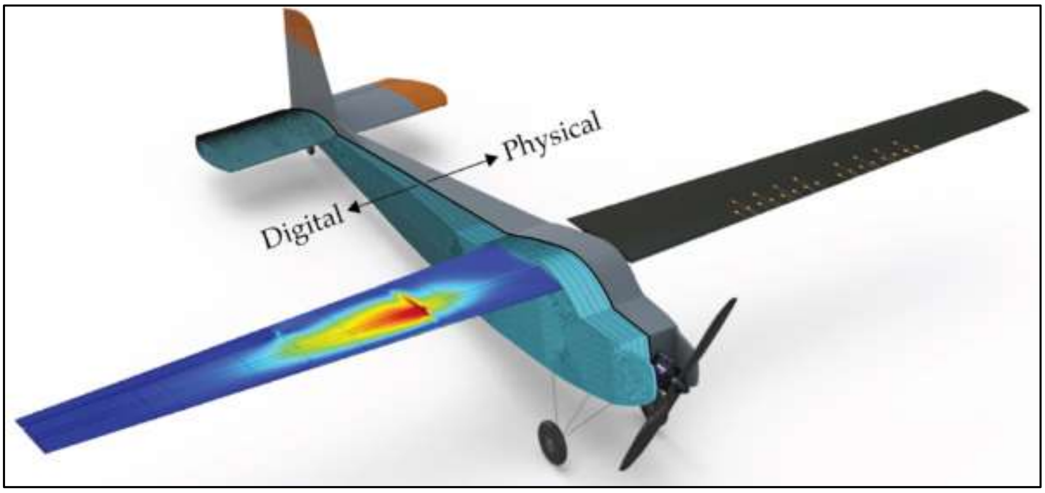

Figure 3 Digital Twin and Physical Model [16]

Figure 4 Apollo 13 Twin: Green Section Main Module, Brown Section Command Module [19]

Another well-known example of a hardware twin is the "Iron Bird," used in the aviation industry to test and optimize the critical systems of an aircraft [2]. The Iron Bird is a test setup that simulates loads the aircraft will encounter under operational conditions, allowing testing in a laboratory environment. This setup provides advantages by allowing many tests to be conducted on physical models, thereby facilitating the development of the final product.

In 2002, Professor Michael Grieves [33] from the University of Michigan proposed an idealized lifecycle management approach for smart manufacturing and future factories, referring to it as Digital Twin. However, this concept was rarely mentioned in the research conducted between 2002 and 2010 [20].

With the maturation and industrialization of Internet of Things (IoT) and Big Data technologies in the early 2010s, Digital Twin usage became practically viable. During this period, NASA and the U.S. Air Force made significant contributions to the R&D of Digital Twins in the aviation sector [13].

Today, the increasing power of simulation technologies and the use of High-Performance Computing (HPC) systems have enhanced the importance of creating Digital Twins, as many tests now provide results very close to those obtained from real models. These tests have shortened design and production processes and significantly reduced costs.

In the digital transformation process, it has become possible to benefit from digital models in various ways across each process in the aviation sector. Different digital models are used throughout the product’s lifecycle, from the conceptual phase through design, production, and maintenance. Each of these models can be considered a Digital Twin. Therefore, it is not accurate to describe the Digital Twin concept through a single model.

In this study, the concept of the Digital Twin will be elaborated and explained under three main headings.

2.1.1. Design Digital Twin

In the aviation sector, the Design Digital Twin refers to the integration of various digital models throughout the process from conceptual design to production. The Design Digital Twin functions as a digital representation of a physical aircraft, facilitating the integration of different digital models during this process [20]. This concept encompasses a broad range of activities, starting from shaping the external shell geometry of the aircraft, extending to structural design and system integration.

In the initial phase, the external shell geometry of the aircraft is defined according to operational requirements. Aerodynamic analyses are performed to optimize the external shell geometry for different mission conditions. These analyses are crucial for enhancing the aircraft's performance and efficiency [21]. Digital models used to simulate aerodynamic performance play a significant role in evaluating airflow and aerodynamic forces [22].

In addition to the external shell geometry, manufacturable structural designs are created to ensure structural integrity. At this stage, detailed three-dimensional models of the aircraft are designed and analyzed. These digital representations of structures are used for pre-production testing and evaluations [14]. These structures form the structural components of the Digital Twin and reduce the need for physical prototypes.

The Design Digital Twin can be expanded to include all components of the aircraft. This scope includes the aircraft's systems, control mechanisms, and other functional components, which are also digitally modeled. Software used to analyze system behaviors is a crucial tool for improving the accuracy and reliability of these models. This allows the entire system to be considered as a whole and potential issues in system integration to be detected in advance [23].

2.1.2. Production Digital Twin

Unlike the three-dimensional model of the product, the Production Digital Twin enables the creation of a digital copy of the production line, allowing for the optimization of production processes and improvement of efficiency. This concept provides the ability to simulate the production process through its digital representation, identifying potential bottlenecks and efficiency issues in advance [24].

With the Production Digital Twin, digital copies of production lines can be created. These digital models allow for the simulation of production processes in a virtual environment, thereby identifying potential issues, bottlenecks, and inefficiencies in the production line beforehand. Simulations contribute to optimizing the process and improving resource utilization [28]. This includes the integration of real-time data flow and performance analysis in the production process.

Today, the use of sensors on production machines and the interpretation of data collected from these sensors enable the integration of digital and physical data. Real-time data provided by sensors, when combined with Digital Twins, allows for more accurate monitoring and control of the production process. This data integration facilitates the rapid detection and correction of abnormalities and efficiency declines in the production process [27].

Digital twins allow for continuous monitoring and optimization of production processes. By digitally representing each stage of the production process, they make production lines and processes more efficient. Additionally, Production Digital Twins contribute significantly to managing maintenance and repair processes, improving production line performance, and enhancing overall production efficiency [29].

2.1.3. Performance Digital Twin

In the aviation industry, processes such as maintenance, training, and performance management continue after the delivery of products. The Performance Digital Twin plays a critical role in these processes by monitoring the operational performance of aircraft and optimizing maintenance and training procedures [20].

Flight training is typically conducted using simulators. These simulators provide pilots with opportunities to experience various scenarios by replicating real flight conditions. When supported by digital twin technology, simulators can offer more realistic and effective training. The Performance Digital Twin enhances the accuracy of simulators and the effectiveness of pilot training, improving pilots' abilities to handle emergencies and various flight conditions [23].

In maintenance processes, augmented reality (AR) and Digital Twin technologies are used together to make maintenance operations more efficient. AR models provide real-time information and instructions to maintenance personnel, helping to prevent errors [25]. The Performance Digital Twin supports these models by ensuring maintenance processes are conducted accurately and effectively. During aircraft operation, data obtained from various sensors can be analyzed to preemptively identify maintenance needs. For example, Boeing has used sensors placed on the engines of a two-engine 737 to collect 300,000 parameters during a 6-hour flight, generating 20 terabytes of data per engine, which was used to optimize maintenance processes [26]. This type of data analysis allows the Performance Digital Twin to adopt a proactive approach in maintenance processes and predict maintenance needs in advance [27].

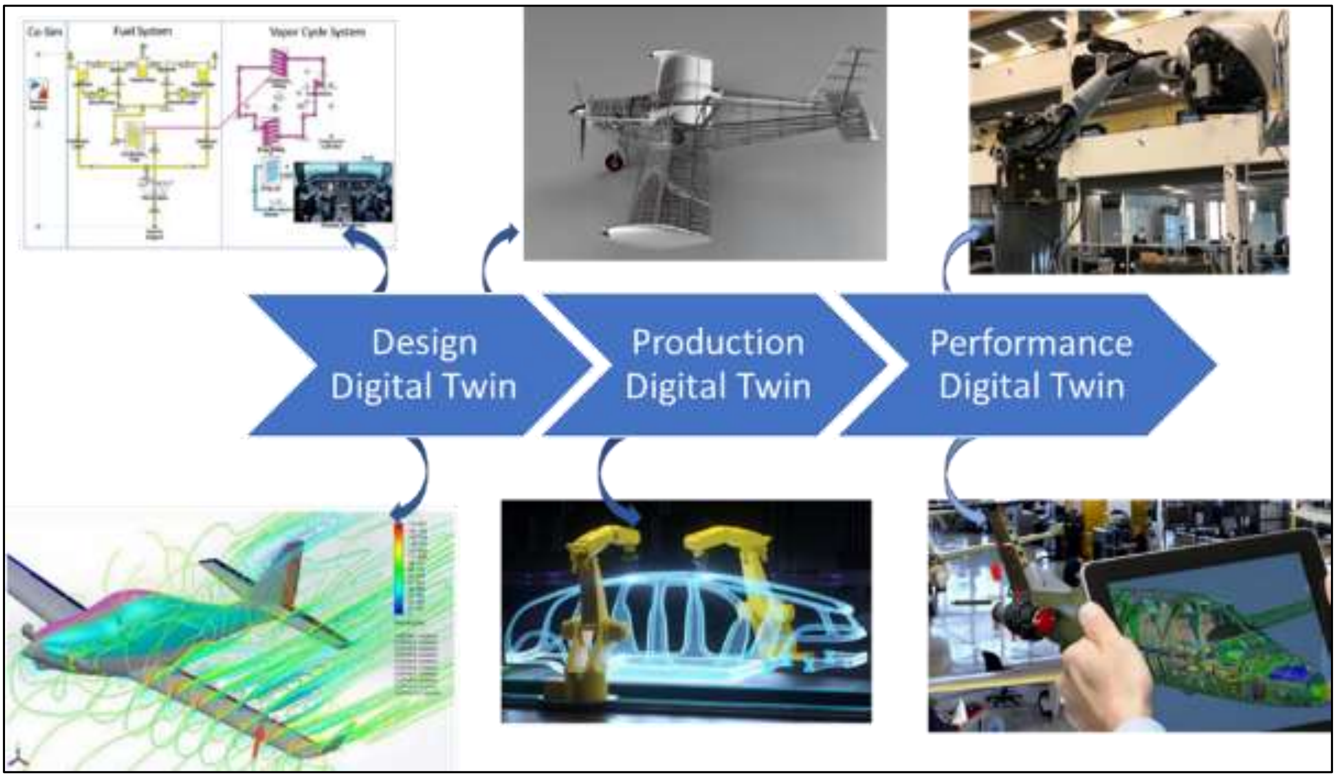

Figure 5 Different Digital Twin Models [30, 31, 32]

A Digital Twin is a digital representation of a physical entity, and this representation is updated and integrated throughout the physical object's lifecycle. The primary function of a Digital Twin starts with the product development process and continues through the product's operational and service phases. In other words, a Digital Twin not only describes the behaviors of the product but can also be used to optimize these behaviors and enhance performance [33]. For a Digital Twin to function effectively, the entire process must be part of an integrated Digital Thread. The Digital Thread can be defined as a structure where multiple digital entities interact with each other and the physical world. This structure is crucial for increasing efficiency and monitoring performance throughout the product lifecycle [20].

Efficient operation of the Digital Twin throughout its lifecycle is made possible through this integration. The connection provided by the Digital Thread facilitates identifying the sources of problems and making necessary adjustments [34]. Structures used to ensure the Digital Thread include Product Lifecycle Management (PLM) systems, which play a significant role. PLM systems collect and manage product information, processes, and data in a central location, enhancing the effectiveness of the Digital Twin [35]. PLM systems are used to increase efficiency and ensure data integrity across all stages from product design to manufacturing and service. Integration of the Digital Twin with these systems enables real-time updates and optimization of product data [36].

2.2 Product Lifecycle Management (PLM)

The aerospace industry is a sector characterized by high safety standards, complex engineering processes, and a constant need for innovation. In this context, Product Lifecycle Management (PLM) systems play a critical role for aerospace companies. PLM is an integrated approach that comprehensively manages all phases of a product's lifecycle, from design to retirement. The significance of PLM in the aerospace sector stands out for several key reasons:

- **Advanced Design and Engineering Management:** The aerospace sector is characterized by designs requiring complex engineering knowledge. PLM systems collect and manage engineering data on a centralized platform, allowing engineers to easily track and coordinate design changes. This helps minimize errors and enables more efficient management of design processes [37].
- **Regulation and Compliance:** The aerospace industry is subject to strict regulations and standards. PLM systems store necessary documents, approvals, and test results in a central data repository to ensure that products are developed in compliance with these regulations. This facilitates audit processes and ensures ongoing compliance [15]. Specifically, adherence to standards set by organizations such as the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA) can be more effectively managed with PLM systems.
- **Enhanced Collaboration and Communication:** Aerospace projects often involve multiple stakeholders and suppliers on an international scale. PLM systems enable effective communication and collaboration among all these stakeholders. This ensures that projects are completed on time and meet quality standards [38]. A central PLM platform provides all stakeholders with access to real-time data and project updates, improving collaboration processes.
- **Data Management and Traceability:** Aerospace products are often composed of long-lasting and complex parts. PLM systems allow detailed tracking of product data, including the history, maintenance records, and changes of each part. This optimizes maintenance processes and part replacements [39]. Additionally, PLM systems enhance product traceability, providing a rapid resolution process in case of any issues.
- **Process Efficiency and Innovation:** PLM automates and standardizes business processes, resulting in time and cost savings [40]. It also supports the faster realization of innovative design ideas. Aerospace companies gain a competitive advantage from this increased efficiency. The integration of PLM systems provides improvements at every stage of the manufacturing process, fostering innovation and enhancing the ability to quickly bring new products to market.
- **Customer Satisfaction and Reliability:** PLM systems collect customer feedback and performance data, enabling continuous improvement of products to meet customer needs [41]. This increases customer satisfaction and reinforces brand reliability. Integrating customer feedback into product development processes ensures that customer expectations are better met.

The integration of PLM systems in the aerospace sector not only enhances operational efficiency but also helps meet safety and quality standards in the industry. Therefore, PLM systems can be considered a strategic investment for aerospace companies.

PLM plays a significant role in the product design and development process. It aids in digitizing the entire process and improving efficiency. In product design, PLM provides a solution for designers and engineers to collaborate and share design data. As shown in Figure 6, the design and production of different structures for the Airbus A400M project in various countries and the coherence of the entire process have been achieved through the use of PLM systems. Additionally, changes made in design through PLM are reflected throughout the entire workflow, minimizing the error rate.

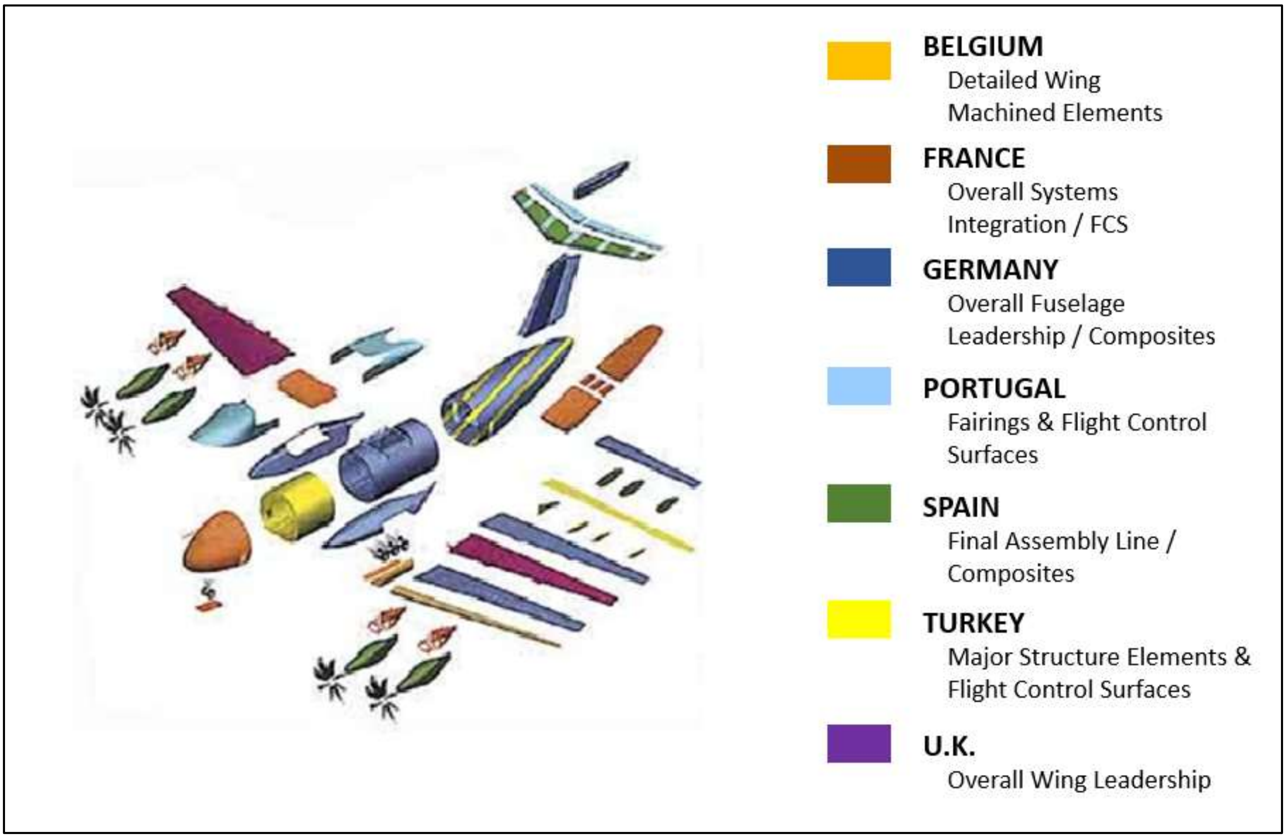

Figure 6 Countries Involved in the Airbus A400M Project [42]

3. Discussion

PLM is a critical tool for managing product development processes in the complex and dynamic nature of modern industry. The importance of connections between these processes is vital for increasing efficiency, quality, and innovation at every stage of the product lifecycle. PLM facilitates access to the same data for all stakeholders by establishing connections between processes and accelerating decision-making processes. Consequently, any changes, such as design modifications, production updates, or service requests, can be quickly communicated to other processes and managed appropriately.

In PLM processes, a significant amount of data is utilized from models and digital representations. The digital copy of the product enables the simulation of processes in a digital environment, the pre-identification of problems within processes, and access to the root causes of issues through the Digital Thread provided by PLM systems. The Digital Twin is used at every stage of PLM processes, but it would not be accurate to describe the Digital Twin as a single concept throughout the entire process. To better understand the Digital Twin concept, we need to consider all structures reflecting the behavior of the physical product throughout the processes as Digital Twins.

3D models used from the concept stage to production are referred to as the Design Digital Twin; digital factory simulations that model production processes are referred to as the Production Digital Twin; and data simulating maintenance activities and operational processes after the product is delivered to the customer constitute the Performance Digital Twin. These three types of Digital Twins are managed in a connected manner through PLM, and as shown in Figure 7, the tracking and integration of all these processes are ensured. This integration allows for the storage of data at a single point within the PLM environment, making the flow of information more organized and accessible.

While PLM and Digital Twins individually provide many benefits, their combined management results in much more efficient product management. Digital Twins support the data and process management provided by PLM systems, leading to better decision-making and more efficient process execution throughout the product lifecycle. Therefore, the integration of PLM and Digital Twins is a powerful tool for optimizing product management in modern industrial applications.

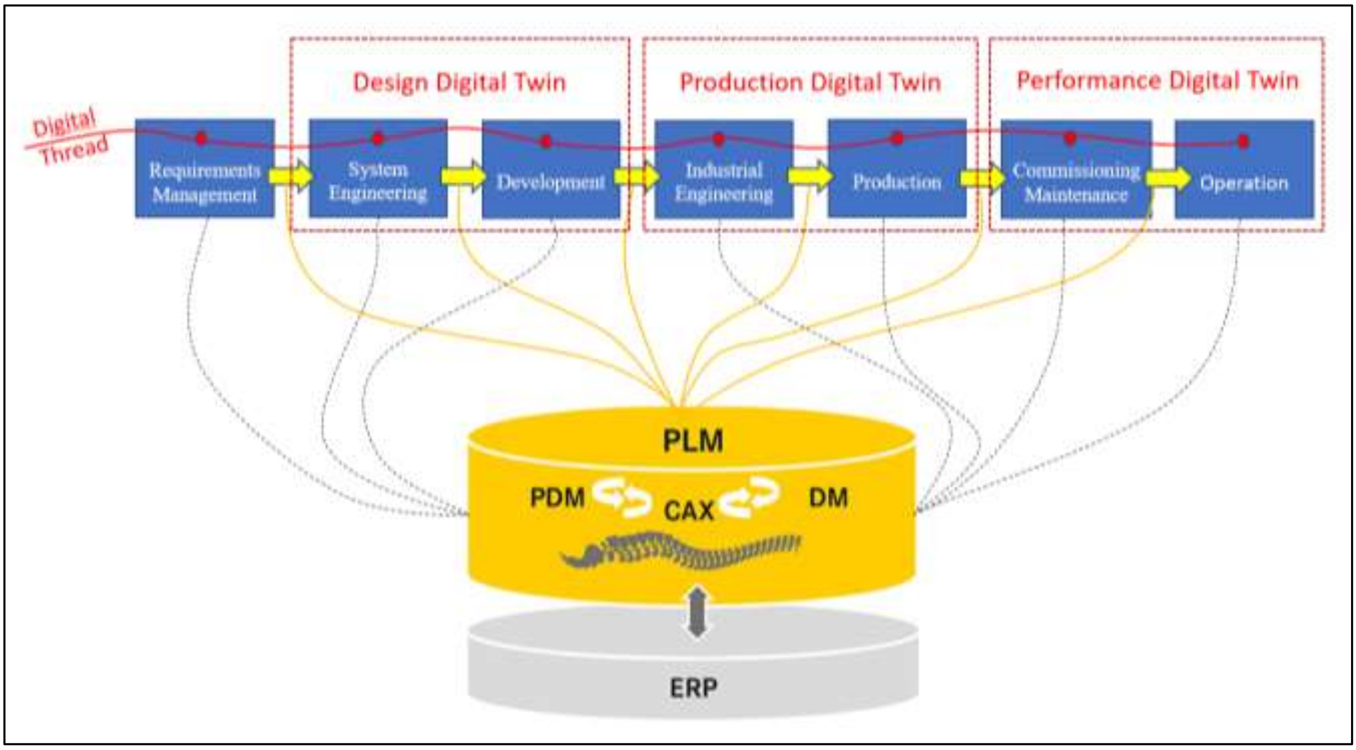

Figure 7 PLM Processes and Digital Twin Connection [43]

4. Conclusion

This study highlights the importance of Digital Twins in the aerospace industry and their critical role in Product Lifecycle Management (PLM) systems. The study offers a different perspective on the Digital Twin concept by evaluating it through three distinct areas: Design, Production, and Post-Delivery product models, rather than viewing it as a single concept. Additionally, the study underscores the importance of creating data within the PLM platform and aggregating data within a unified system across all these Digital Twin models. It emphasizes that the integration of PLM systems with Digital Twins allows companies to access more rapid and reliable information throughout the product lifecycle, make faster decisions, and manage their processes more effectively. Furthermore, the study highlights that this integration has the potential to enhance product quality, increase customer satisfaction, and improve the competitive advantage of companies.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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