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# A COMPREHENSIVE SURVEY ON DIGITAL TWIN TECHNOLOGY: CONCEPTS, FRAMEWORKS AND INDUSTRIAL USE-CASES

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**ABSTRACT**
Digital Twin technology links physical systems with virtual models for real-time monitoring and simulation. This paper presents an overview of Digital Twin concepts, evolution and key adoption drivers. It discusses benefits, objectives, and requirements for improving product lifecycle management. Different Digital Twin types are reviewed along with the required technology integration. Industrial use cases from manufacturing, healthcare, smart cities, and aerospace demonstrate broad applicability. The paper categorises domains supported by Digital Twin solutions. It introduces reference frameworks including three-dimensional product lifecycle management, cloud-based cyber-physical systems, intelligent twins, and Industry 4.0 applications. The Digital Twin lifecycle is summarised from creation to decommissioning, providing a complete view of system management. This study also highlights the role of Digital Twin technology in shaping scientific culture by enabling advanced documentation, preservation, and interpretation of cultural heritage assets. The integration of AI-driven twins in heritage sites, museums, and smart cultural infrastructures demonstrates their potential in supporting sustainability, policy-making, and public engagement in the digital age.

**Keywords:** Digital twin, Industry 4.0, Digital Twin Lifecycle, Multi-Domain Applications, Digital Twin Framework

## 1. INTRODUCTION

The idea of a Digital Twin traces back to NASA's space programs in the 1960s. Engineers built physical replicas of spacecraft on Earth to study failures during missions. The formal Digital Twin concept was introduced by Michael Grieves in 2002 during a Product Lifecycle Management presentation. He proposed linking a physical system with a virtual representation through continuous data exchange. Early models were called the Mirrored Spaces Model and later the Information Mirroring Model. The term "Digital Twin" was first clearly used in 2011 in the book Virtually Perfect.

A Digital Twin (DT) is a virtual model of a real object, process, or system. It mirrors physical behavior using real-time and historical data. This technique helps in monitoring, simulation and analysis of physical object without having direct interaction. Prediction of failure and improvements in system performance can be done by Digital Twins. They reduce cost, time, and operational risk. DT plays an important role for controlling and optimization of physical system when its complex.

DT was first originated in Aerospace engineering and later extended to other domains such as manufacturing, healthcare, agriculture, energy sector, smart cities and industrial automation. Technologies such as Internet of Things (IoT), cloud computing, artificial intelligence and data analytics part of Industry 4.0 plays an important role in DT. Data gathered using these technologies would help DT to provide predictive analytics, optimization of resources and provide data-driven decisions. This paper highlight technologies, industrial use-cases, domains that are supported, supported architectures and Digital Twin lifecycle (Grieves & Vickers, 2017).

Traditional methods applied for static models uses manual inspection that doesn't capture real-time behaviour and doesn't predict future states whereas modern systems are complex, data-rich and are difficult to inspect or monitor using traditional methods. This gap can be addressed by Digital Twin technology by adding a link between physical systems and data-driven virtual models. Industry 4.0 advanced technologies help in continuous monitoring and prediction using effective DT architectures, its lifecycle and respective domains. Motivation of a comprehensive study includes DT & its concepts, evolution and types, different frameworks and lifecycle management. This is essential for supporting design, reduce risk in operational level and enable its adoption across industries.

Outside the industrial sphere, Digital Twin technology is becoming more and more applicable in the field of cultural heritage and scientific culture. Online versions of monuments, archaeological sites, museums, and intangible cultural resources make it possible to preserve, plan restoration, and gain access virtually. Such developments play a part in the transformation of digital culture within society by harmonizing natural sciences, engineering and humanities. Digital Twins Enhance interdisciplinary research, policy formulation and sustainable heritage management through the use of AI-based Digital Twins in cultural contexts.

Following this introduction, Section 2 includes the integration technologies about DTs. Industrial use cases are reviewed under Section 3 and Domains and its applications are highlighted as part of Section 4. Innovative architectural frameworks are covered in Section 5. Section 6 explores the digital twin lifecycle and the paper concludes with final insights.

### 1.1 What is Digital Twin - Definition

Digital twin is virtual representation of its physical counterpart which is an integrated and data-driven system. Grieves and Vickers describe feedback loop using three core elements: a physical entity, its virtual model and data link between them, which supports prediction, monitoring and optimization throughout its lifecycle. The data-driven links enables continuous exchange of data between physical and its digital counterpart. Digital Twins are unique, data-driven replicas of physical or living entities. They rely on sensors, historical data and analytics to reflect real-world behaviour in near real time. Multiple Digital Twins can be combined to represent complex systems such as factories, power plants or cities. DT's are "probabilistic simulations and multi-physics of models" that mirrors real operational life as defined by NASA, thus improves insight of the system, controlling information and performance as shown in Figure 1 ("Definition of a Digital Twin," n.d.; Gartner, n.d.).

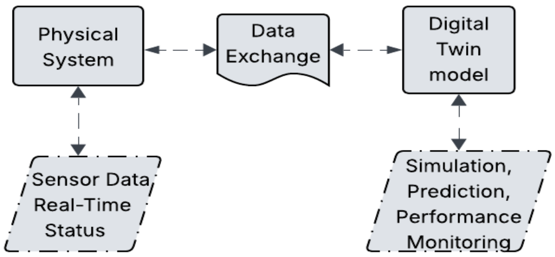


**Figure 1: Interaction between Physical System and Digital Twin Model**

### 1.2 History of Digital Twin

The growth of Digital Twin technology is clearly shown in Figure2 timeline. In early 1960s and 1970s CAD tools enabled virtual representations of physical objects. During this period NASA replicated the spacecraft to analyze system faults as part of Apollo program. In the 1980s, advances in simulation supported virtual prototyping in engineering. Gelernter's *Mirror Worlds* in 1991 introduced virtual models that reflect real systems. The term "Digital Twin" was introduced by Michael Grieves in 2002 to link physical products with digital models. During the 2010s, IoT, cloud computing, and AI enabled real-time data-driven twins. General Electric applied Digital Twins in industry in 2012, and Gartner recognized the technology as strategic in 2017. From 2018, Digital Twins expanded into smart cities and urban systems. During the 2020s, healthcare and supply chains adopted Digital Twins for remote monitoring and prediction. Recent work integrates AI and AR/VR, with growing use in renewable energy and future expansion toward metaverse and quantum-based Digital Twins (Agnusdei et al., 2021; Hananto et al., 2024; Mostaq Hossain et al., 2023; Yao et al., 2023).

### 1.3 Evolution of DT

The development of Digital Twin technology can be divided into clear evolutionary phases, as shown in Figure3. In the traditional phase, products were designed using sketches for physical models, with limited digital support. During transitional phase 3D modeling and digital mockups were introduced in the early 2000s thus reducing physical prototypes. Basic virtual testing of product behaviour is enabled with an improvement in computing. In 2010s the conceptual phase was emerged, where DT's supported "what-if" analysis and virtual experimentation. Industry paradigm shift in testing from physical to digital systems. Current phase depths the shift to intelligent virtual systems that operate across multiple domains in integration with different technologies such as IoT, machine learning and artificial intelligence that enables real-time data handling and faster decisions for system analysis and optimization.

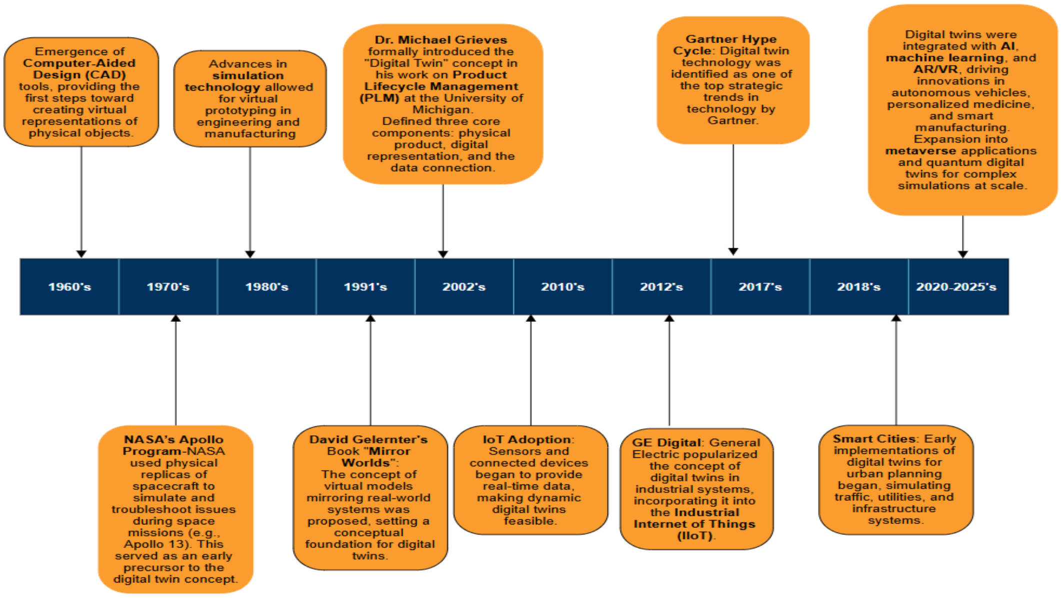


**Figure 2:** Timeline highlighting its significant milestones

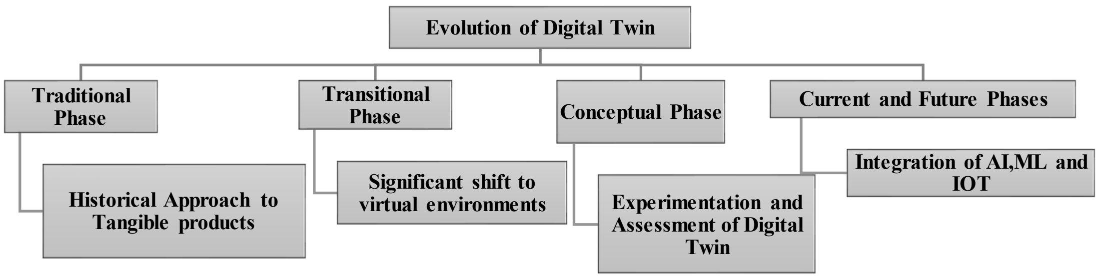


**Figure 3: Evolution of Digital twins**

### 1.4 Why Digital Twin, Benefits and its needs

Short term and long-term industrial challenges like detecting early faults and preventing unexpected failures can be solved using Digital Twin technology with real-time monitoring. Thus equipment life can be extended and reduces the maintenance cost. DT's improve resource use, reduce waste and increase operational speed. Virtual models enable faster product design and testing, reducing development time and overall cost. Scenario-based simulation supports risk planning and prepares systems for changing operating conditions.

In supply chains, Digital Twins provide live visibility and enable quicker responses to disruptions.

Digital Twins also support energy savings, emission reduction, and effective waste control. Data-driven services improve product quality and enhance customer experience through consistent performance.

Safety improves through virtual testing and training in high-risk operating environments. Integrated data views support informed and coordinated decisions across the enterprise.

### 1.5 Different types of Digital twin

Digital twins exist in different forms, each tailored to serve specific functions and applications (Capegemini, n.d.). Product and Asset Twins are responsible to maintain continuity from design till long term engineering operation. Production data is analysed or enhanced inorder to improve quality, efficiency and throughput in case of Manufacturing Twins. Measurable processes are model in Process Twins to optimize resource use, scalability and system output.

Supply chain, logistics and transport networks performance and resilience can be improved by Network Twins. Real-time operational scenarios are focused by Operational Twins and are widely used for mission planning and decision support. Environmental Twins model external conditions like weather or terrain to support planning and risk assessment. Skill development and scenario-based learning are provided by Training Twins through virtual environments. Large facilities can be replicated by Infrastructure Twins to improve maintenance and operational efficiency. These different categories demonstrate the adaptability of Digital Twin technology across product, process and system levels.

**2. Digital Twin Technology Integration**

Digital Twin technology integrates with many digital tools like CAD tools. Without interrupting physical real machines DTs can test systems and try out ideas using simulation software. This helps in identifying issues at early stage. When DTs are combined with machine learning, they learn data over time. This improves prediction accuracy and usefulness. Using DTs and CAD software integration transforms design into smart digital models thus simplifies design, testing and product life management. These tools together enable smooth transition from idea to real use (Yao et al., 2023).

**2.1 Association of DT with simulation software**

Simulation software is a central component of Digital Twin for prediction and testing. Tools combine historical and real-time sensor data to reflect physical behaviour. DT's can evaluate system responses under different conditions using simulation reducing the prototype costs and development efforts without real-world risk. Physics-based modeling is supported by engineering tools such as ANSYS, Simulink and COMSOL. Factory simulations are supported by platforms like Siemens Simcenter and 3DEXPERIENCE that enable process. Simulation helps find faults early and reduces energy loss. Models need frequent updates and reliable data support. The major limitation is computational load and validation efforts.

**2.2 Association of DT with machine learning**

The integration of Digital Twin and Machine Learning enhances prediction, analysis and system understanding. DT provide real-time and historical data to train machine learning models. Trained models helps in detecting patterns and predict future system behaviour. Safe environments are provided by DT's to test Machine Learning models for fault detection and prediction without real-world risk. This reduces unexpected failures and improves accuracy of DT. Frequent data updates help models adjust to changes and poor data quality hinders model reliability and prediction accuracy. Retraining of machine learning models are required to prevent performance degradation over time.

**2.3 Association of DT with CAD**

The integration of Computer-Aided Design (CAD) with Digital Twin technology build virtual replication of physical objects. DT is formed by defining CAD geometry, materials and its structural properties. These models are created before production to support early simulation and design testing. CAD twins when applied to manufacturing sectors enables machine monitoring, planning of maintenance and optimization of processes. Construction with CAD and BIM models helps to manage lifecycle of buildings and its infrastructure. CAD-based twins in Aerospace and automotive sector provide safety and performance. Medical device twins and implants for surgical planning depends on Healthcare with CAD models. Smart cities with CAD-based twins helps in infrastructure planning. CAD provides collaboration through shared and accurate model view. Complex CAD models increase computing cost and require skilled data integration to maintain real-time updates.

**3. Industrial Use Cases of Digital Twins**

Digital Twin technology is applied in software and hardware domains to integrate physical and digital components. Software-based DT's provide simulation, predictive evaluation and performance testing without affecting live environments. Virtual replicas of cloud platforms and enterprise applications support fault identification and optimization of workload. Digital Twins model network behavior in cyber-physical systems to enhance reliability and security. Digital Twins are used in industries such as automotive, aerospace, and manufacturing, to monitor the performance of equipment and predict maintenance. Process twins are applied by semiconductor companies to enhance yield and defect minimisation. To control energy consumption and identify failures, consumer electronics manufacturers use device twins. These applications demonstrate how Digital Twins can enhance development, lifecycle management, and operational insight as highlighted in Fig. 4. Few curated lists as given in Table 1 of real-time software-level Digital Twin use-cases, highlighting projects and applications being developed or deployed by the software industry:

**Table 1: Software Industry – Digital Twin Use Cases / Real-Time Scenarios**

| Company | Use Case / Scenario |
|---|---|
| **Microsoft Azure Digital Twins** | **Smart Building Management**: Provides a platform to model physical environments (like buildings) digitally to optimize energy, space usage, and maintenance (Microsoft Azure, n.d.). |
| **IBM Digital Twin Exchange** | **Industrial IoT Systems**: Software platform for creating digital twins of machinery, offering insights for predictive maintenance and operational efficiency. |
| **PTC ThingWorx** | **Manufacturing & Production Simulation**: ThingWorx platform allows real-time creation and management of digital twins for industrial equipment to improve productivity and reduce downtime (PTC ThingWorx, n.d.). |
| **Siemens MindSphere** | **Industrial Automation Twin Management**: Software platform to connect digital twins of factory machines and production lines with analytics and AI tools. |
| **ANSYS Twin Builder** | **Simulation-Driven Product Development**: Enables engineers to build simulation-based digital twins of physical products to optimize performance and reliability. |
| **Autodesk BIM 360** | **Construction Project Management**: BIM 360 allows the creation of digital twins of buildings and infrastructure to improve project collaboration and lifecycle management. |
| **Dassault System's 3DEXPERIENCE** | **Product Lifecycle Management**: Used in aerospace, automotive, and healthcare industries to simulate and manage the entire product lifecycle using digital twins. |
| **Oracle Digital Twin Platform** | **Asset Management & Cloud Integration**: Provides cloud-based digital twin services for predictive maintenance, asset tracking, and operational optimization. |

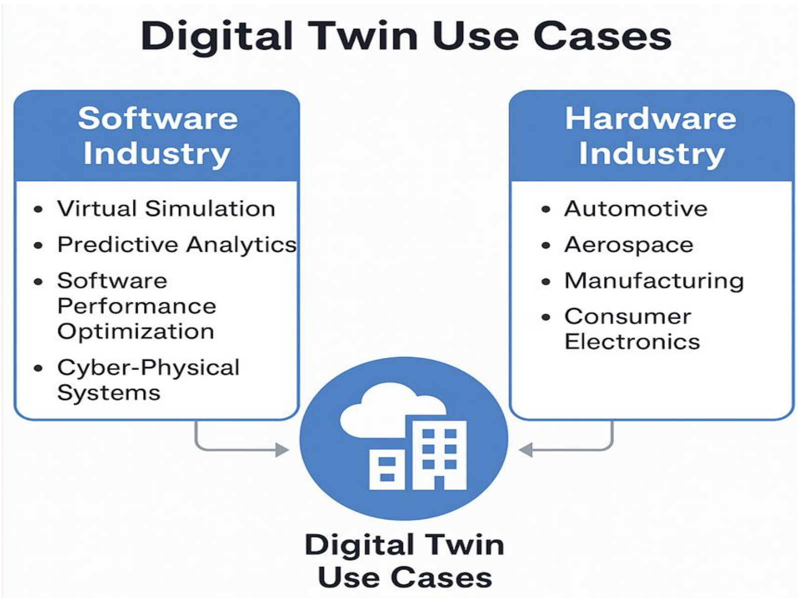


**Figure 4: Digital Twin use cases**

Detailed list of Hardware-Level Digital Twin Use-Cases and Real-Time Projects worked on by industries (in collaboration with software providers) that bridge the physical (hardware) and digital (software) worlds is given in table 2.

**Table 2: Hardware-Level Digital Twin Use Cases**

| Company | Use Case / Scenario |
|---|---|
| **GE (General Electric)** | **Jet Engine Digital Twins**: GE uses digital twins to monitor real-time engine performance, predict wear & tear and reduce unscheduled maintenance in aircraft engines. |

| | |
|---|---|
| **Siemens AG (Industrial Machinery)** | **Factory Equipment Digital Twins**: Siemens applies digital twins to motors, drives and manufacturing equipment to predict failures and optimize production processes. |
| **Tesla** | **Electric Vehicle Battery Management**: Tesla creates digital twins of EV battery packs to optimize charge cycles, thermal control and lifetime prediction. |
| **ABB Robotics** | **Robotic Arm Simulation & Control**: ABB employs digital twins to simulate and optimize robotic arms in production lines, improving precision and energy efficiency. |
| **Rolls-Royce (Aerospace)** | **Aero-Engine Maintenance Prediction**: Rolls-Royce uses digital twins of airplane engines for remote diagnostics, failure prediction, and servicing recommendations. |
| **Bosch Rexroth** | **Hydraulic System Twin**: Bosch creates digital twins for hydraulic and automation components to simulate system behaviours and optimize energy use in industrial plants. |
| **Caterpillar** | **Heavy Equipment Monitoring**: Caterpillar integrates digital twins in construction and mining equipment to monitor wear and optimize operation and maintenance. |

**4. Different Domains supported by Digital Twins**

Digital Twins support many domains by creating virtual replicas of physical assets, processes, or systems. Major domains include manufacturing, healthcare, transportation, energy, smart cities, agriculture and others as shown in Figure 5.

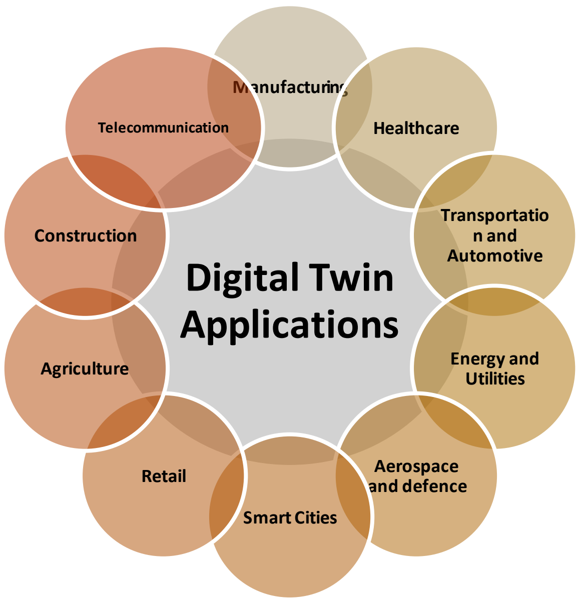


**Figure 5: Applications supported by Digital Twin**

**Aerospace and Defence Industry**: Digital Twins have a strong impact on aerospace and defence systems. They support product design, performance analysis, and predictive maintenance (Li et al., 2022). Virtual models reduce physical testing and improve safety. Jet engine twins track health and predict failures in real time. Airframe twins analyze stress and fatigue to extend service life. Space mission twins test scenarios before real execution. Satellite twins monitor subsystems during long missions. Examples includes Digital twins for Rolls-Royce, Airbus and NASA simulators (Geletko et al., 2019; Lockheed Martin, n.d.; Olavsrud, n.d.; Patrizio, 2002; Sudeep Srivastava, 2025), these DT's increase reliability, reduce operational downtime and extend asset service life.

**Smart Cities:** Digital Twins enable real-time modelling of Smart Cities to represent urban systems in real time. City DT's integrate data from multiple sources like traffic, energy, buildings and sensors (El-Agamy et al., 2024) to control traffic, disaster planning and energy optimization. Virtual Singapore and Helsinki's 3D city models enables planning and sustainability goals (Helsinki 3D, n.d.; "Virtual Singapore," 2025; Yuting, 2022) and improve service quality and strength urban resilience. In addition to infrastructure and services, Digital Twins in smart cities are increasingly used for cultural heritage preservation. Historic districts, monuments, and culturally significant landscapes can be digitally modeled to monitor structural health, simulate environmental impacts, and support conservation strategies. These applications enhance cultural sustainability while integrating heritage into modern urban planning.

**Manufacturing**: Manufacturing is one of the leading area for Digital Twin use-cases. Factory twin's uses real time data to model machines, production lines and workflows thus reducing downtime required for predictive maintenance. Design cycles are shortened, reduction in physical prototypes and improve quality and sustainability (Altair, n.d.; Altair Engineering, 2023). Examples includes Siemens manufacturing plants, GE Factory and automotive production twins (Siemens, n.d.).

**Healthcare**: DT's representation in case of healthcare sector can be a patient or an organ. Data is integrated from clinical, imaging and physiological (El-Warrak & de Farias, 2024; Katsoulakis et al., 2024; Vallée, 2023; Zhang et al., 2024). DT's help in predicting the treatment response, organ twins is simulated to find the disease progression, heart twins help in diagnosing and device planning and patient twins provide personalized care system. This improves accuracy and reduce trial-and-error treatment (Albrecht, n.d.; Dassault Systèmes, 2023; FEops, n.d.; Philips, 2018; *Twin Health*, n.d.).

**Transportation and Automotive:** Vehicles and transport data is integrated virtually via Digital Twins models which support design, testing and lifecycle management. Before manufacturing vehicle twins helps in testing the designs ("Digital Twin Technology in Automotive Design and Prototyping," 2024). To predict maintenance needs component twins are used and production DT's helps in optimizing assembly lines. Safe training can be implemented in autonomous driving uses virtual twins (Kang, 2024). Logistics and Inventory is improved in Supply chain using twins (Sharma, 2025). EV battery life and efficiency is extended using battery twins. DT's tools improve safety, cost control, and sustainability (Arff et al., 2023; A. Kumar, 2025; Singh, 2025).

**Energy and Utilities:** DT's play an important role in this sector like efficiency of power plant is improved by creating its twin (GE Vernova, n.d.; Kobayashi & Alam, 2024). Supply and demand in real time is balanced by creating grid twins and turbine performance is optimized by having wind farm DT's(GreenPowerMonitor, 2026; Hitachi, n.d.). Twins increases production safety (SCS Tech India, 2025). Detecting leakages and managing its quality in cases of water network twins (Rodríguez-Alonso et al., 2024). Charging cycles and its aging is optimized by creating battery storage twins (Reniers & Howey, 2023). This reduces the cost and increases the efficiency.

**Retail:** Retail Digital Twins helps improve product placement and movement flow, optimize layout and inventory, identifying shortage of stocks or overstock by simulating stores, customers and supply chains. Customer twins enables personalized recommendations. Online shopping and reduced returns is improved by using virtual stor twin.

**Agriculture:** Soil, crops climate and equipment twins are created in agriculture sector. These twins improves precision farming and optimization of resource. Crop yield and its growth is predicted using crop twins. Use of fertilizer is guided using soil twins. Climate is controlled by creating greenhouse twins for improving the quality. Health of livestock and its productivity can be tracked using twins. Agri-farm system efficiency is improved when all these kinds of twins are applied.

**Construction:** Construction Digital Twins connect design models with site data. They track progress, safety, and structural health. Concrete curing twins monitor temperature and strength (Lee et al., 2022). Bridge twins detect early structural defects. Tunnel twins improve lifting and transport safety. Geotechnical twins manage soil uncertainty (Hagen & Andersen, 2024). Project twins reduce errors, delays, and rework (Cotoarbă et al., 2025).

**Telecommunication:** Telecom Digital Twins model networks, sites, and coverage.

They support planning, monitoring, and optimization. Network site twins reduce deployment time and field visits (S. Kumar, 2024). Radio twins improve indoor and outdoor signal planning (Park, 2025). Event-based twins manage traffic surges (Ericsson, n.d.). AI-driven twins predict failures and reduce downtime (Greve, 2024; S. Kumar, 2024). City-scale twins support smart city connectivity (Kerris, 2021).

## 5. Innovative framework for digital twins

The Digital twin is advancing and it's been applied to wide range of industries. This section we will cover the four types of DT framework- PLM, Cloud CPS, Intelligent twin and Industry 4.0 that have been proposed in recent years in figure 6.

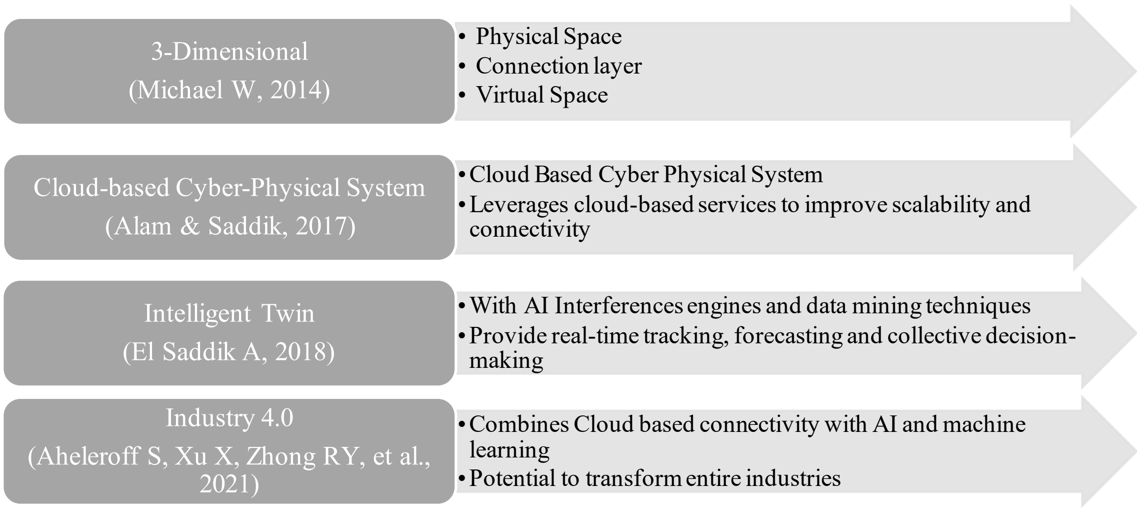


**Figure 6: Four Significant Digital Twin Framework Evolution**

### 5.1 Three-Dimensional Product Lifecycle Management

Three-dimensional Product Lifecycle Management (PLM) is an information-driven approach that manages a product from concept to retirement. PLM integrates product data across design, manufacturing, distribution, use, and end-of-life stages. It ensures shared access to current and consistent information among all stakeholders. PLM also coordinates processes and practices across departments to improve efficiency and collaboration. A general structure helps in organizing product information to provide faster responses and better decisions to support market needs. To reduce development time and cost, PLM contributes to strategic goals which improves product quality and competitiveness. The Product Lifecycle Implementation Maturity Model (PLIMM) framework evaluates PLM through five levels: inputs, processes, outputs, outcomes and impacts. These levels measures resource investment, performance of process, quality of product, operational improvement and return on investment. Performance of PLM is measured using literature review, expert interviews, factor analysis, pilot surveys, focus groups and repeated testing. This framework support systematic assessment of PLM maturity and alignment with organizational strategy (Lehner et al., 2024; Walton et al., 2013).

### 5.2 Cloud-Based Cyber-Physical Systems

A structured framework is presented by Alam and El Saddik includes an integration of Cloud-based cyber-physical systems (C2PS) with Digital Twin technology (Alam & El Saddik, 2017). It’s a three operating modes framework: physical sensor–fusion, cyber digital-twin services and deep sensor–service integration. Physical and cyber layers provides distributed computation, communication and control. Real-time data is collected from physical devices that support analysis and decision making through DT’s. This creates a continuous feedback loop between cyber models and physical systems that improves accuracy and response time. The validation of framework is done using a telematics driving assistance application that generates location-based speed warnings and penalty estimates from live data. They discussed extending the model to smart homes, offices and cities, highlighting the need for shared data models and ontologies for cross-domain integration.

### 5.3 Intelligent Twin

Digital twins are defined as virtual replica to exchange data continuously with physical system (El Saddik, 2018). The framework applied in intelligent twin includes data integration, machine learning, cloud computing, interoperability, scalability and continuous feedback as shown in Figure7 (Abouzid & Saidi, 2023). These operation uses IoT for sensing, AI for decision support and high-speed communication such as 5G. This enable real-time interaction and improved service quality.

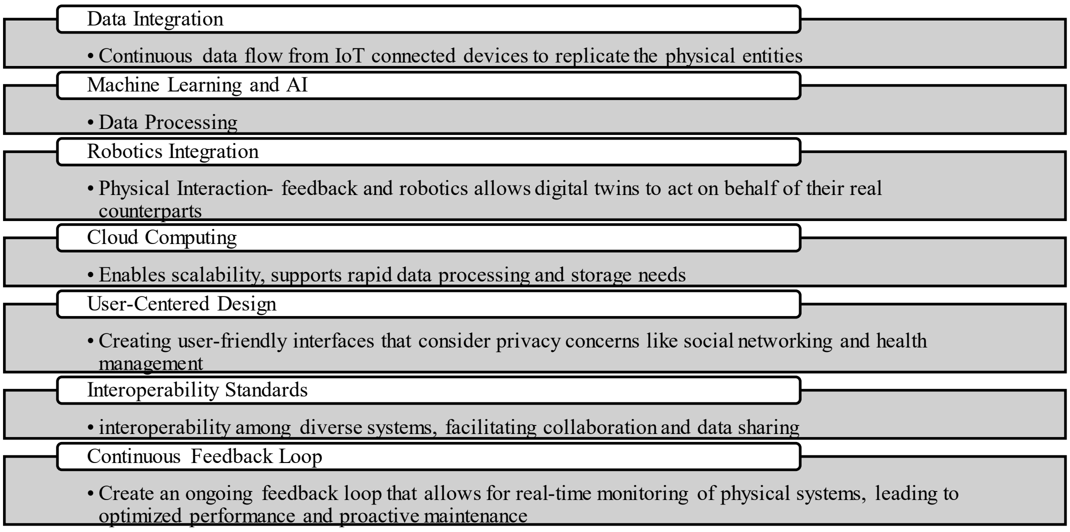


**Figure 7: Key elements of Intelligent Twin framework**

### 5.4 Industry 4.0

Digital Twin as a Service (DTaaS) in the Industry 4.0 framework is a combination of physical and digital systems that aid in monitoring (Aheleroff et al., 2021). Authors proposed a Digital Twin reference architecture that provides cyber and digital layers and data collection. It is based on IoT, cloud, big data and augmented reality to facilitate real-time communication and transformation of raw sensor data to value knowledge that can be used to support better decision-making. DTaaS can be used to realize mass individualization since it allows customization of the product in the virtual space. Examples of benefits demonstrated by case studies include predictive maintenance and smart monitoring. Other limitation identified by the authors are system integration, organizational complexity, knowledge gaps and scalability challenges.

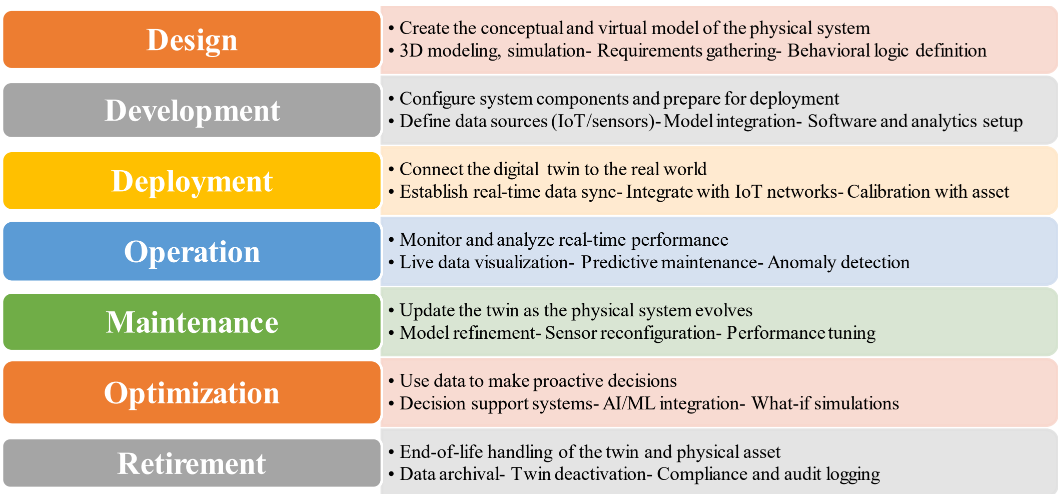


**Figure 8: Common Lifecycle Phases of a Digital Twin**

The Digital Twin of the future needs to include a cultural and ethical aspect, such as data governance, preserving the heritage, and access by the populace. Digital Twin architectures can be made more relevant to societal uses and policy-making with the integration of cultural datasets and models of participation.

## 6. Lifecycle of Digital Twin

A DT lifecycle has two primary scenarios: design stage creation and the post-deployment creation (Barricelli et al., 2019). Here, in the design-stage case, the DT is constructed with the product design to facilitate preliminary analysis and optimization. In the post-deployment case, the DT is developed once the physical asset is deployed into service. In both cases, the digital and physical twins constantly exchange information to aid in monitoring, prediction and optimization of performance. According to previous research, there are four phases of the lifecycle: design, development, operation and dismissal (Macchi et al., 2018; Pronost et al., 2024). A prototype DT is developed during design based on system requirements. The development phase bridges between the DT and the physical asset and confirms its behaviour. During the functioning stage, live data allows controlling the condition and predicting the maintenance. Dismissal stage kills both twins and the lifecycle information can be used in future design enhancements, which is shown in Figure 8. In cultural heritage, a Digital Twin lifecycle goes beyond efficiency in operations to long-term preservation and archival worth. Lifecycle information can be used to aid in restoration of artifacts, documentation, and intergenerational knowledge.

## 7. Digital Twin Applications in Cultural Heritage

Digital Twin technology has been extensively applied to the industrial systems and less commonly to cultural heritage, archaeology, museums and heritage oriented urban environments. Digital Twins are used in such contexts as data-rich virtual models of heritage buildings, archaeological sites, museum collections, and culturally important places. They are significant through their integration of engineering, natural sciences, digital tools, and humanities-based interpretation in a common framework of preservation, monitoring, accessibility, and dissemination of knowledge. The interdisciplinary nature of Digital Twins ensures its relevance to the digital culture of the scientific community of the digital era, where technological systems are not only efficient in their work but also help preserve and share cultural memory (Dang et al., 2023; Luther et al., 2023; Mazzetto, 2024).

### 7.1 Digital Twins in Cultural Heritage Preservation

Digital Twins can be used in heritage preservation to offer dynamic virtual equivalents of monuments, historic buildings, heritage landscapes. They are not limited to the 3D models as opposed to the static ones, but they can merge geometry, sensor data, environmental conditions, material behavior and archival records into a single system. This facilitates ongoing observation, structural evaluation, and modeling of decay, and conservation intervention strategy. This is particularly useful with sensitive assets in need of proactive conservation and extended monitoring of the condition (Dang et al., 2023; Mazzetto, 2024; Sugiyama et al., 2025). These systems may integrate photogrammetry, laser scanning, BIM-oriented documentation, and sensor networks to enhance the accuracy of conservation in heritage buildings and enhance multidisciplinary decision-making. Digital Twins based on simulation have also been demonstrated to be useful to historical masonry buildings, where numerical and experimental measurements can be combined to evaluate structural behavior and predict future weaknesses (Angjeliu et al., 2020; Karatzas et al., 2026; Mazzetto, 2024).

### 7.2 Archaeological Applications

Digital Twin technology is also highly relevant in archaeology in the fields of documentation, reconstruction, interpretation and risk management. Environmental exposure, urban growth, tourism, and material decay are the main factors that threaten archaeological sites. A Digital Twin is capable of incorporating excavation documentation, topography, remote sensing, spatial models and conservation information into a dynamic digital image of the location. This enhances the quality of documentation and enables intervention strategies to be virtually tested prior to their use in the field (Dang et al., 2023; Liu et al., 2024). It also contributes to the clear reconstruction of damaged or fragmented remains, extended storage, and enhanced academic and general knowledge of complex archaeological settings.

### 7.3 Museums and Digital Culture

Digital Twins can be used in museums to enhance the management of collections, exhibition planning, and visitor engagement. Objects in museums and spaces of exhibition can be modeled as intelligent digital objects linked to the metadata, conservation records, spatial context, and interaction data. This aids in preventing conservation, environmental surveillance, and coherent control of collections, particularly in historic buildings (La Russa & Santagati, 2020; Luther et al., 2023). Digital Twins are also a part of the digital culture as they allow people to experience online tours, interactive exhibits, and object-level interpretation to a greater number of viewers. These systems can be especially beneficial in cases where the physical access is restricted and may improve the appreciation and interaction of visitors to the virtual space (Wang et al., 2025). In such a manner, Digital Twins enhance institutional practice and cultural communication (La Russa & Santagati, 2020).

### 7.4 Smart Heritage Cities and Scientific Culture

The use of Digital Twin applications is also emerging as a significant part of heritage-conscious urban systems. Although the models of smart cities are usually concerned with infrastructure and services, historic areas, monuments, and culturally important public places may also be incorporated in urban twins. This facilitates the conservation of heritage in the context of the larger urban planning, sustainability, tourism, and resilience strategies

(Dang et al., 2023; Karatzas et al., 2026). A socially aware Digital Twin has the capacity to bridge the gap between the technical information and the trends of utilization and cultural significance, enhancing long-term management of heritage spaces (Karatzas et al., 2026).

Interoperability between geometric and sensor-based, archival, and semantic data is a critical necessity of successful heritage Digital Twins. Research on heritage ontology demonstrates that the integration, interpretation, and long-term preservation of knowledge assets can be enhanced by means of semantic structures (Niccolucci & Felicetti, 2024). At a larger scale, Digital twins facilitate the culture of science by providing platforms on which engineers, conservators, archeologists, historians, architects, and policymakers can cooperate via shared digitalizing images. Thus, they transform the way in which heritage is recorded, examined, handled, and consumed in modern society (Luther et al., 2023; Mazzetto, 2024; Niccolucci & Felicetti, 2024).

## 7. CONCLUSION

Digital Twin technology has become a strong data-driven method of connecting physical systems to virtual models by monitoring and simulating in real-time and predicting. The following paper has examined the fundamentals, history, applications, integration technologies, industrial applications, frameworks, and life cycles of Digital Twins demonstrating the wide-ranging value of Digital Twins in manufacturing, healthcare, transportation, energy, agriculture, telecommunications, and smart cities. It is confirmed in the discussion that Digital Twins enhance the understanding of the system, its operational efficiency and maintenance planning, decision-making through the integration of IoT, cloud computing, artificial intelligence, machine learning and simulation tools.In addition to industrial transformation, the Digital Twin technology is becoming increasingly significant in cultural heritage, archaeology, museums, and heritage-conscious urban environments. Its capacity to encourage dynamic documentation, structural monitoring, conservation planning, virtual reconstruction and accessibility by the general public illustrates its applicability within scientific culture in the digital era. Digital Twins in these situations provide a transdisciplinary connection between engineering, natural sciences, and the humanities, which allow more cohesive methods of preserving, interpreting, and sharing cultural knowledge. The studied articles suggest that Digital Twins are not a technological means of optimization only, yet they are growing platforms of sustainability, cultural continuity and evidence-based policy support. Their future relevance will be based on enhanced interoperability, effective data integration, ethical governance, and increased access to the rest of society. With the further growth in adoption both in the industrial and cultural sectors, Digital Twin technology is likely to become a larger and larger part of the formation of intelligent systems, the preservation of heritage assets, and empowering the global scientific culture.

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## CONFLICT OF INTEREST STATEMENT

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