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# Digital Twin in Architecture

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## ABSTRACT

The built environment is increasingly complex, driven by demands for sustainability, energy efficiency, and smart city integration. To address these demands, the architecture and construction industries are undergoing a digital transformation. Central to this shift is the concept of the digital twin (DT). A digital twin is regarded as a virtual representation of a physical object or system that uses real-time data to accurately reflect its real-world counterpart. It incorporates real-time data from Internet of things (IoT) sensors, artificial intelligence (AI), and machine learning to enable dynamic monitoring, simulation, prediction, and control across the asset's entire lifecycle. By bridging the physical and virtual realms, digital twins empower the AEC industry to design more efficiently, build more safely, and operate more sustainably. This essay explores the applications of digital twins in architecture.

***KEYWORDS:*** *digitalization, digital twin, data twin, architecture; architecture, engineering, and construction (AEC) industry.*

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## INTRODUCTION

The integration of advanced digital technologies into the architecture, engineering, and construction (AEC) industry has catalyzed a paradigm shift from traditional methodologies toward intelligent, data-driven processes. Central to this transformation is the concept of the digital twin (DT). A digital twin is a virtual replica of a physical asset, process, or system that uses real-time data, simulation, and machine learning to enable decision-making throughout a building's lifecycle. In the context of the AEC industry, a digital twin is an interactive, multidimensional virtual representation of a physical building or infrastructure project. 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 AEC sector. Figure 2 shows the conceptual model of a digital twin [2].

Traditionally, architectural design has relied heavily on assumptions and static simulations. Architects have always designed buildings based on assumptions about how spaces will be used. Digital twins fundamentally alter this process by enabling data-driven design decisions. They reveal how buildings actually behave once people move in, systems run, and conditions shift. The integration of digital twins into architecture represents a paradigm shift from static, fragmented processes to dynamic, data-driven lifecycle management. By bridging the gap between physical structures and their digital representations, digital twins empower architects, builders, and facility managers to optimize performance, enhance sustainability, and improve occupant experiences. The predictive capability ensures that design choices are grounded in measurable performance data rather than intuition alone [3].

## 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 ARCHITECTURE

For decades, the architecture, engineering, and construction (AEC) sector has grappled with persistent challenges: low productivity, fragmented communication, cost overruns, and a lack of predictability. The advent of Building Information Modeling (BIM) provided a significant leap forward by creating detailed 3D representations of structures. Building upon the foundations laid by Building Information Modeling (BIM), the digital twin (DT) has emerged as a revolutionary concept, offering a continuous, bidirectional flow of information between a physical building and its virtual counterpart. A digital twin is a dynamically synchronized, data-driven virtual representation of a physical system characterized by continuous cyber-physical data exchange. Unlike static 3D models, a digital twin in architecture is a living, adaptive entity that evolves alongside the physical structure, continuously updated by real-time data from sensors, Internet of things (IoT) devices, and operational systems [3].

A digital twin in the context of architecture is a dynamic, living model that evolves alongside its physical counterpart. By integrating Internet of Things (IoT) sensors, artificial intelligence (AI), and advanced analytics, digital twins provide a continuous flow of data regarding a building's structural health, energy consumption, occupancy patterns, and environmental conditions. This bidirectional flow of information allows architects, engineers, and facility managers to monitor, simulate, and optimize building performance in real-time, fundamentally altering how structures are conceived, constructed, and maintained. Figure 6 shows a representation of DT in architecture [9].

## APPLICATIONS OF DIGITAL TWIN IN ARCHITECTURE

Digital twins offer transformative potential across all phases of a construction project's lifecycle, moving beyond fragmented silos to provide a unified data ecosystem. From optimizing energy consumption to preserving irreplaceable cultural heritage, the applications are vast and transformative. Common applications of DT in architecture include the following [3,10]:

- *Design and Construction*: During the design phase, digital twins enable architects and engineers to move beyond static visualization. In the early design phases, digital twins serve as powerful simulation engines. Architects can test how a building will perform under various conditions before physical construction begins. By simulating various design scenarios—such as energy performance, spatial utilization, and structural integrity—professionals can optimize building parameters before ground is broken. In the construction phase, digital twins facilitate real-time monitoring of site progress. Technologies such as drones and 3D laser scanners capture the as-built conditions, which are then compared against the digital model. This continuous verification helps identify deviations early, mitigating risks, reducing rework, and ensuring that the project adheres to schedule and budget constraints. Figure 7 shows a building under construction [11].
- *Facility Management*: The operation and maintenance phase is the longest and most costly period in a building's lifecycle. Traditional facility management relies on reactive maintenance, responding to equipment failures after they occur. Digital twins enable predictive maintenance. Digital twins revolutionize facility management by providing operators with a centralized, real-time dashboard of the building's health. Sensors monitor occupancy levels, temperature, air quality, and equipment performance. This data enables predictive maintenance—identifying when a component, such as an HVAC system, is likely to fail and scheduling repairs before a breakdown occurs, thereby reducing downtime and maintenance costs.
- *Heritage Preservation:* Beyond modern smart buildings, digital twins are proving invaluable in the preservation of architectural heritage. The preservation of historical architecture presents unique challenges due to the fragility of materials and the impact of environmental degradation. Digital twins offer a non-invasive methodology for monitoring heritage sites. For example, in Genoa, Italy, digital twins integrated with IoT sensors and satellite data are utilized to monitor the impact of pollution, acid rain, and temperature fluctuations on UNESCO World Heritage buildings. This predictive capability allows conservationists to prioritize interventions and mitigate structural decay before it becomes irreversible.
- *Structural Health Monitoring:* During construction, spatial digital twins allow for the real-time monitoring of progress by synchronizing with the physical site via Internet of things (IoT) sensors, drones, and laser scanners. Digital twins are increasingly vital for Structural Health Monitoring (SHM). By embedding wireless sensors that measure strain, vibration, and displacement, engineers can continuously monitor the integrity of bridges, tunnels, and skyscrapers. This real-time surveillance detects material fatigue and seismic stress, preventing catastrophic failures.
- *Spatial Analysis:* Digital twins support spatial analysis by visualizing circulation paths, density, and activity patterns over time. This directly informs space planning, helping architects organize layouts based on real movement patterns rather than assumptions. Digital twins also facilitate advanced spatial analysis by visualizing circulation paths, density, and activity patterns. This information is invaluable for space planning, allowing architects to organize layouts based on real movement patterns. For example, in a healthcare facility, spatial analysis can identify potential congestion points, enabling early design modifications that improve flow and efficiency. Spatial analysis becomes more dynamic through real time performance data, helping designers refine circulation, zoning, and layout efficiency.
- *Urban Environments*: The principles of digital twins are increasingly being applied at the macro level, scaling from individual buildings to entire urban environments. At the urban scale, digital twins will help planners understand movement, infrastructure, and environmental behavior using real-time data. Urban digital twins integrate data from diverse city systems—transportation, energy grids, water management, and public services—to create a holistic virtual replica of a city. A pioneering example is Virtual Singapore, a high-resolution, data-rich 3D model of the city-state. This urban digital twin allows planners to simulate the impact of new developments, analyze solar energy potential, and test disaster

response scenarios. By breaking down data silos between government agencies, urban digital twins facilitate participatory governance and data-driven policy-making, essential for managing the complexities of modern urbanization and achieving carbon-neutrality goals. Figure 8 illustrates a typical urban environment [11].

## BENEFITS

Digital twins enhance resource allocation and site safety by tracking the movement of machinery and personnel, simulating potential hazards, and optimizing logistics. Digital twin technology holds transformative potential for the architecture and construction industries, offering a pathway to smarter, more sustainable, and highly efficient built environments. It offers a wide range of benefits that can hugely enhance the productivity and effectiveness of architecture and construction projects. Other benefits of DT in architecture include the following [3]:

- *Predictive Maintenance:* Traditional building maintenance is often reactive or scheduled based on fixed intervals. Digital twins enable a shift towards predictive maintenance. By analyzing data from sensors embedded in building systems, the digital twin can identify anomalies and predict potential failures before they occur. This proactive approach reduces downtime, lowers maintenance costs, and extends the lifespan of the building's assets.
- *Sustainability*: Sustainability in construction is one of the most significant points of debate nowadays. Buildings are major consumers of global energy. The built environment is a major contributor to global energy consumption and greenhouse gas emissions. Digital twins play a pivotal role in optimizing energy performance by analyzing real-time consumption data and simulating the impact of various operational strategies. Research indicates that integrating digital twins into building management can yield energy savings of up to 30%. By continuously monitoring environmental conditions and adjusting building systems accordingly, digital twins contribute significantly to the decarbonization of urban environments and the realization of smart, sustainable cities.
- *Improved Collaboration:* Digital twin platform architecture helps improve teamwork and interaction between project managers and team members. They serve as a single source of truth, fostering collaboration among architects, engineers, contractors, and clients. This shared virtual environment reduces miscommunication and ensures that all parties are aligned.
- *Improved Visualization:* Digital twins improve visualization and planning by providing a mesmerizing and communicative 3D model. With this, the stakeholders are able to discover multiple design options, identify errors beforehand, and make more wise decisions that align with the project goals. This helps reduce errors and the need for expensive methods to tackle the issues. Hence, digital twins help reduce time and cost and improve efficiency.
- *Improved Decision-making:* Digital twin provides organizations with a comprehensive view of their assets, products, processes, relationships, systems, or organizations, allowing them to make better-informed decisions. The comprehensive data and predictive analytics available to decision-makers allow them to make more informed decisions. These analytics are also helpful for careful testing and validation of designs before the construction process begins. Hence, by identifying and addressing the possible risks and threats in the building projects, the project team can avoid issues and costly maintenance during the construction phase
- *Risk Mitigation:* Safety is a paramount concern in construction. Digital twins enhance job site safety by simulating potential hazards and allowing teams to devise appropriate safety protocols. Real-time data on structural stability and environmental conditions enable engineers to monitor stress levels and prevent accidents. Additionally, digital twins provide a risk-free virtual environment for training workers on safety procedures.

Figure 9 shows some advantages of DT architecture [9].

## CHALLENGES

In spite of the profound benefits, the widespread adoption of digital twins in the AEC industry faces significant hurdles. While challenges such as data quality, interoperability, cybersecurity, lack of standards, complexity, and high implementation costs persist, the potential benefits far outweigh the hurdles. Other challenges of DT in architecture include the following [3]:

- *High Implementation Costs*: Developing a comprehensive digital twin requires substantial upfront investment in hardware (sensors, scanners), software infrastructure, and cloud computing resources.

- *Data Quality*: A digital twin is only as effective as the data it processes. Poor data quality, incomplete sensor integration, and the inability to harmonize disparate data types remain major challenges. The AEC industry relies on a multitude of proprietary software platforms. Filtering the "noise" and integrating disparate data formats from various legacy systems and proprietary software remains a technical challenge. The quality, accuracy, and consistency of the data collected are critical. Poor data quality or "static" building data can render the predictive capabilities of a DT ineffective. Achieving seamless interoperability and data exchange across these platforms requires universal adherence to open standards, which is still an ongoing process.
- *Data Interoperability:* A building's digital twin must aggregate data from various sources: geometric data from BIM, environmental data from IoT sensors, and operational data from Building Management Systems (BMS). Achieving interoperability among these disparate systems is a major hurdle. A significant percentage of early adopters report difficulties in unifying diverse data sources.
- *Cybersecurity Risks*: As buildings become hyper-connected, they become vulnerable to cyber threats. A digital twin centralizes vast amounts of sensitive data regarding a building's design, operational vulnerabilities, and occupant behavior. Ensuring robust cybersecurity measures to protect against unauthorized access, data breaches, and potential sabotage of physical systems via the digital interface is a critical concern that must be addressed .
- *Complexity:* The complexity of integrating systems demands highly specialized technical expertise, which is currently in short supply within the traditional construction sector. For team members unfamiliar with digital technologies, implementing digital twins can be very challenging. This limits the initial set-up and ongoing processes and, thereby, requires continuous support and assistance in entirely elevating the benefits of digital twins.
- *Skills Gap*: The successful deployment of DT technology necessitates a highly skilled workforce proficient in data analytics, AI, IoT integration, and advanced 3D modeling. The construction industry currently faces a severe knowledge and skills gap regarding these emerging technologies. The transition from traditional 2D workflows or static BIM to dynamic digital twins requires new skill sets in data analytics and systems integration. Overcoming this barrier requires significant investment in training existing personnel and attracting new talent with interdisciplinary expertise in both computer science and civil engineering.
- *Lack of Standards*: The absence of standardized data protocols and interoperability frameworks exacerbates the conceptual ambiguity. The AEC industry relies on a multitude of software platforms, sensors, and proprietary systems. Without universal standards (such as those proposed by IEEE or ISO specifically tailored for architectural DTs), integrating diverse data sources becomes a formidable task. This lack of standardization hinders the seamless exchange of information between different stakeholders, from architects and structural engineers to facility managers.

Figure 10 shows some disadvantages of DT architecture [9].

## FUTURE OF DIGITAL TWINS IN ARCHITECTURE

Digital twins are not just simple tools; they are, in fact, the next steps in developing the cognitive infrastructure of the built environment. The evolution of digital twins in architecture will be deeply intertwined with advancements in artificial intelligence, particularly generative AI and machine learning. Generative AI can significantly accelerate the deployment of digital twins. It can synthesize vast amounts of unstructured data—such as maintenance logs and operational videos—feeding this information into the digital twin to uncover hidden patterns and anomalies. The shift toward autonomous twins will enable buildings to not only predict issues but to self-correct and optimize their own systems without human intervention. Self-learning twins will autonomously manage energy, occupancy and maintenance—intervening only when human intervention is required. For example, an agentic digital twin could autonomously reroute HVAC loads in response to real-time occupancy data or independently schedule maintenance for a failing elevator component, moving building management from a reactive to a proactive, autonomous paradigm [3].

## CONCLUSION

The digital twin represents a profound evolution in how the architecture and construction industries design, build, and manage the built environment. By bridging the physical and digital realms, digital twins offer unprecedented visibility, predictive capabilities, and operational efficiencies. Ultimately, the transition toward digital twins is not merely a technological upgrade, but a fundamental shift toward a more intelligent, sustainable, and resilient built environment.

The adoption of digital twin technology is rapidly increasing in the architecture and construction industry. The digital twin market in the AEC sector is experiencing rapid growth. Digital twins allow architects, designers, and project managers to see, analyze, and maximize every stage in a building's life cycle, from planning and development to upkeep and operation. As the technology matures—bolstered by the integration of AI and expanding to the scale of smart cities—digital twins will not merely reflect the built environment; they will actively shape its future, ensuring that the architecture of tomorrow is resilient, adaptive, and profoundly connected to the needs of its inhabitants. More information about digital twin in architecture can be found in the books in [12,13].

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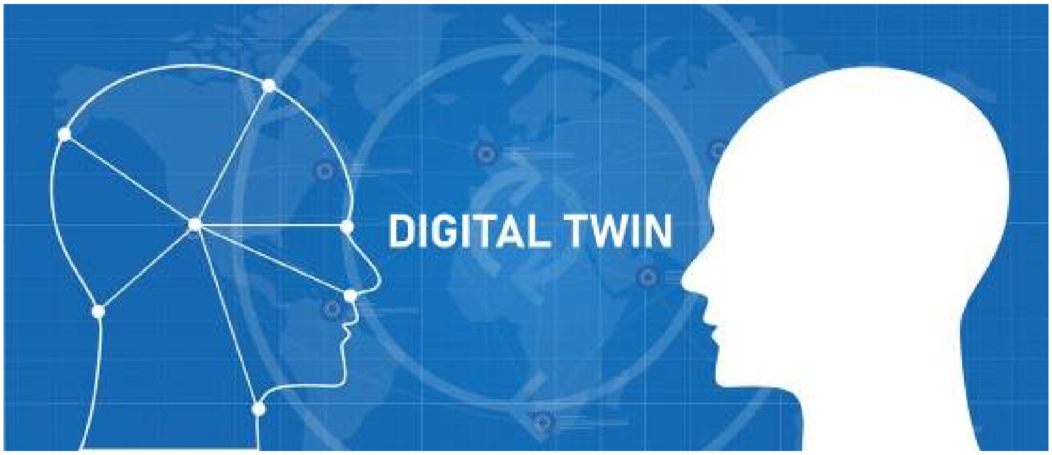

**Figure 1 A typical digital twin [1].**

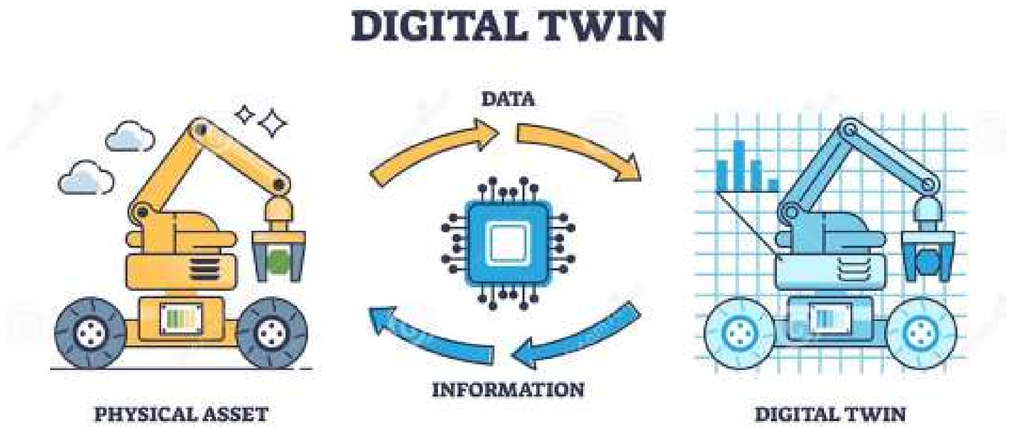

Figure 2 Conceptual model of a digital twin [2].

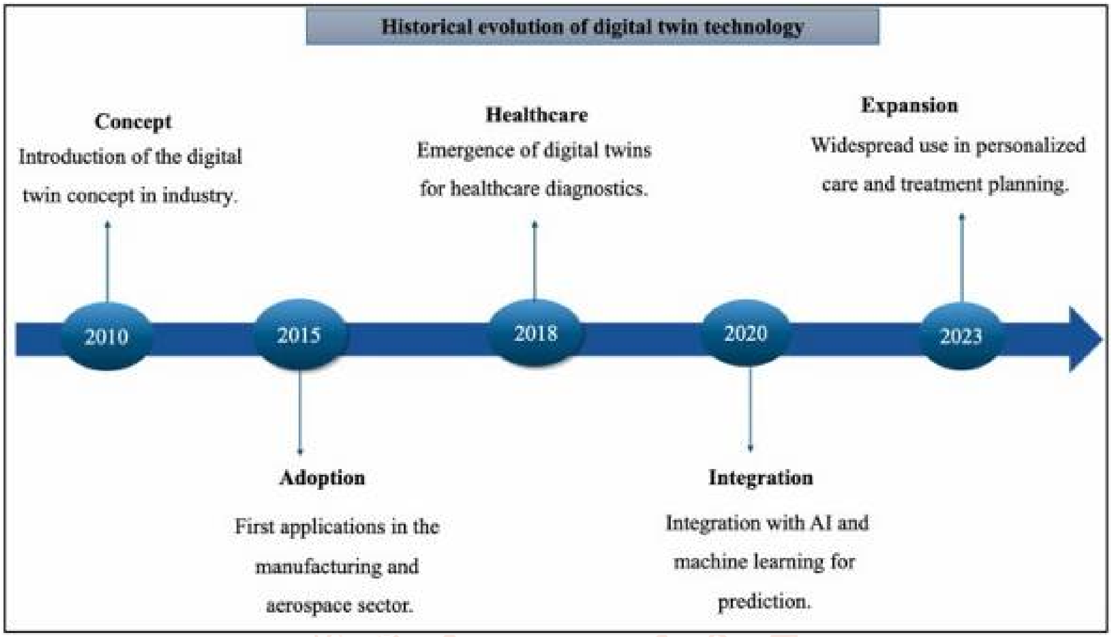

Figure 3 The historical evolution of DT technology [5].

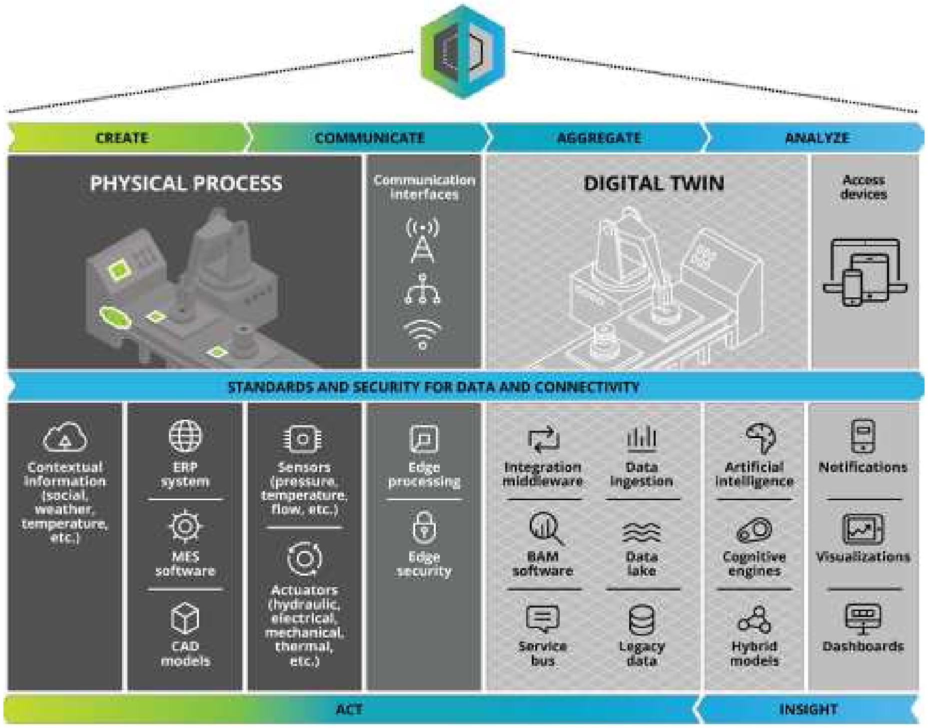

Figure 4 The digital twin conceptual architecture [6].

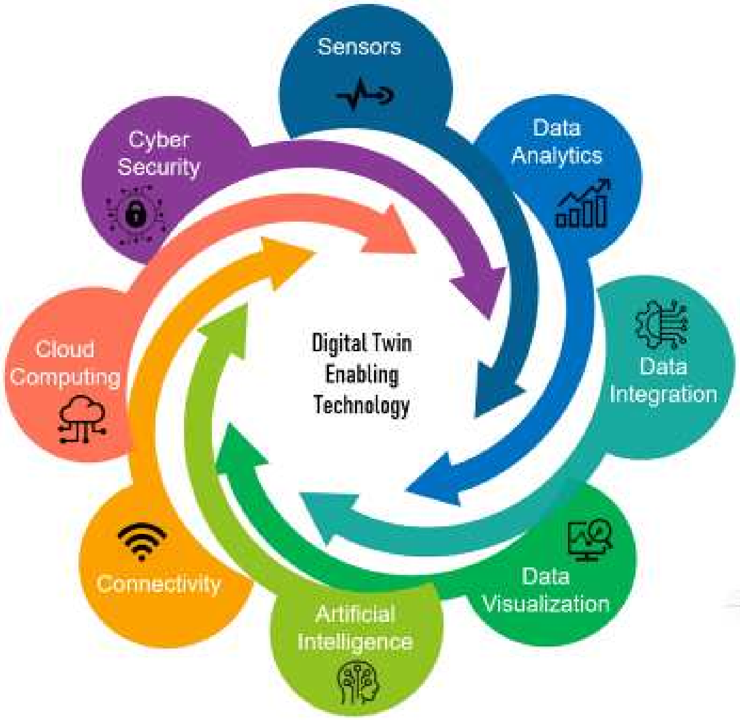

**Figure 5 DT enabling technology [7].**

**Figure 6 A representation of DT in architecture [9].**

**Figure 7 A building under construction [11].**

**Figure 8 A typical urban environment [11].**

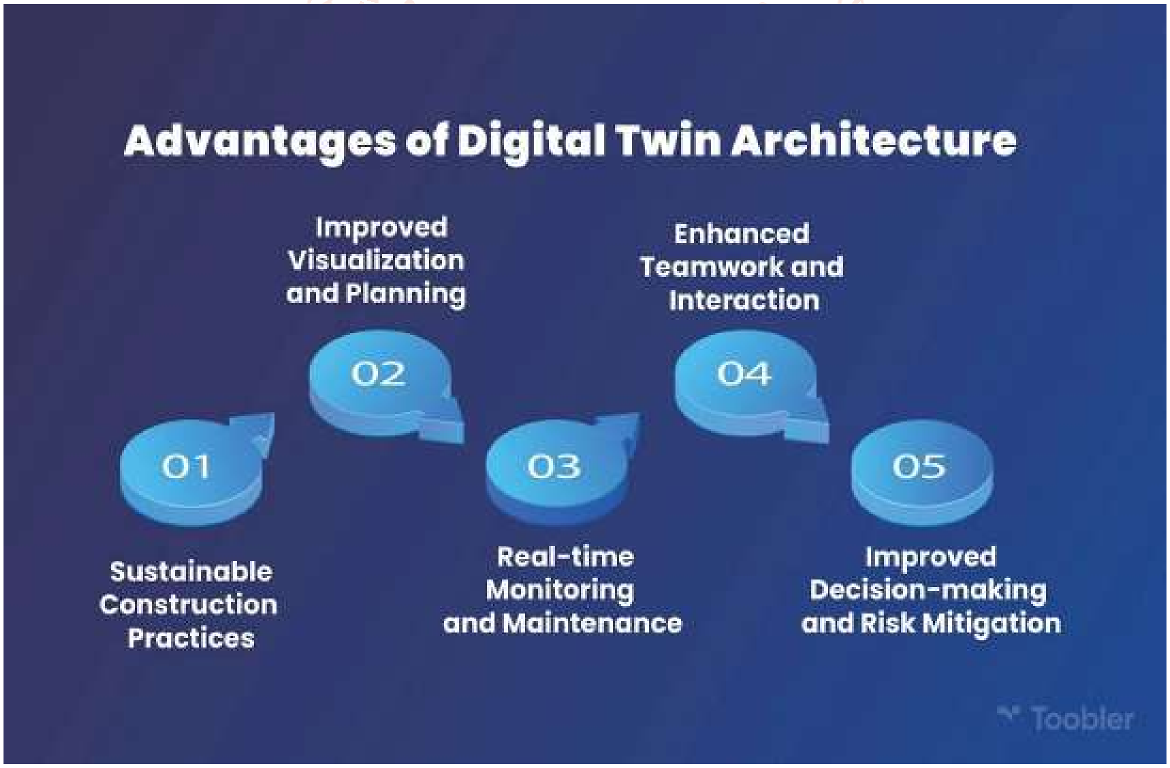

**Figure 9 Some advantages of DT architecture [9].**

**Figure 10 Some disadvantages of DT architecture [9].**