

## Digital Twin Construction

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### ABSTRACT

The construction industry is undergoing a fundamental digital transformation, and digital twin technology stands at its vanguard. A digital twin in the context of construction is regarded as an interactive virtual representation of a physical building or infrastructure project. It is emerging as an essential tool in construction and the built environment. It integrates real-time data from Internet of things (IoT) sensors, BIM models, artificial intelligence (AI), and other sources to mirror the physical entity. This bidirectional data flow allows stakeholders to monitor, simulate, and optimize the performance of the asset throughout its entire lifecycle. The DT technology enhances project visualization and stakeholder collaboration, optimizes planning and cost efficiency, strengthens safety and risk management, and supports long-term sustainability and facility management. A digital twin in construction is a living, real-time virtual replica of a physical building or infrastructure project. This paper presents a comprehensive understanding of current digital twin (DT) implementations in the construction industry.

**KEYWORDS:** digitalization, digital twin, data twin, construction, construction industry.

### INTRODUCTION

The construction sector is a cornerstone of the global economy. The global construction industry is a cornerstone of economic development, contributing approximately 10% to the global gross domestic product (GDP) and representing an output of nearly USD 10 trillion. The construction industry, traditionally characterized by fragmented workflows, low productivity, and a slow pace of technological adoption, is undergoing a profound digital transformation. Central to this paradigm shift is the concept of the “digital twin” (DT). A digital twin, also called data twin, is a dynamic, virtual replica of a physical asset, process, or system that bridges the physical and digital realms through continuous data exchange. Initially adopted by the aerospace and manufacturing sectors, the digital twin has increasingly permeated the construction industry. 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 construction sector. Figure 2 shows the conceptual model of a digital twin [2].

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The construction industry has long been associated with cost overruns, schedule delays, and fragmented communication. Complex projects involve dozens of disciplines, hundreds of subcontractors, and thousands of interdependent decisions — all of which must be coordinated across extended timescales and geographically dispersed teams.

Digital twin technology marks the next evolutionary step. A digital twin is a dynamic, virtual replica of a physical asset, process, or system that mirrors its real-world counterpart in real-time through the continuous integration of live data. Digital Twin technology represents a profound socio-technical transformation for the construction industry, promising significant advancements in productivity, lifecycle optimization, and sustainability [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 CONSTRUCTION

The construction industry has, for too long, been slow to embrace the digital revolution that has transformed other sectors. It is at a critical juncture, facing persistent challenges related to productivity, efficiency, safety, and sustainability. The industry is increasingly looking toward Industry 4.0 technologies to drive digital transformation. Among these, digital twin (DT) technology has emerged as a promising paradigm. Digital twins offer a compelling and evidence-based pathway to a future in which construction projects are delivered on time, within budget, with greater safety, and with a dramatically reduced environmental footprint. Digital twin technology represents a watershed moment for the construction industry. It holds transformative potential for the Architecture, Engineering, and Construction (AEC) industry [3]. Figure 6 shows a representation of DT in construction [9], while Figure 7 shows some construction workers [10].

In construction, a digital twin is an exact digital replica of a construction project or asset: a building or group of buildings, a bridge, a highway, a city block, or even an entire city. Digital twins are created by gathering and combining real-world information about the building or structure using technologies such as 3D laser scanners, drones, sensors, cameras, and other IoT-related devices. They can be accessed through specialized software, such as Trimble Connect, Quadri, Agile Assets or Tekla. These systems give project stakeholders a centralized, single source of truth for digital twin storage and sharing.

### APPLICATIONS OF DIGITAL TWIN CONSTRUCTION

DT technology is increasingly being recognized as an important tool for asset management and maintenance

in the construction industry. The application of digital twins spans the entire lifecycle of a construction project, offering distinct advantages at each phase. Common applications of digital twin construction include the following [3,11]:

- *Predictive Maintenance:* Digital twins enable predictive maintenance, which represents a transformative shift in how buildings and infrastructure are managed over their operational lives. By leveraging AI and real-time sensor data, digital twins can forecast when building components or machinery are likely to fail. This shift from reactive to predictive maintenance significantly reduces downtime and repair costs. Instead of relying on reactive repairs or fixed maintenance schedules, digital twins enable predictive maintenance. By analyzing sensor data from HVAC systems, elevators, and structural components, the twin can predict when a part is likely to fail, allowing for maintenance to be performed proactively. This reduces downtime and extends the lifespan of the asset.
- *Risk Management:* Construction remains one of the most hazardous industries in the world. Falls, structural collapses, equipment failures, and exposure to hazardous materials continue to cause thousands of fatalities and injuries annually. Digital twins offer a powerful and increasingly sophisticated toolkit for identifying, simulating, and mitigating these risks. The fundamental safety advantage of digital twins lies in their ability to simulate hazardous scenarios in a virtual environment before workers are exposed to them in the physical one. This proactive approach to risk management aligns with the principle that safety is most effectively managed through design and planning rather than reactive response.
- *Energy Optimization:* Digital twins continuously monitor energy consumption, occupancy patterns, and environmental conditions. AI algorithms can automatically adjust lighting, heating, and cooling systems to optimize energy efficiency without compromising occupant comfort, contributing significantly to sustainability goals.
- *Space Utilization:* Facility managers use digital twins to analyze how spaces are being used in real-time. This data informs decisions regarding office layouts, cleaning schedules, and future renovations.
- *Smart Cities:* Digital twin technology is scaling up to encompass entire infrastructure networks and smart cities. On a larger scale, digital twin technology is being used to create virtual replicas of entire cities. Urban digital twins integrate data from transportation systems, utility grids, and public services. City planners utilize these macro-level twins to simulate traffic flows, assess the impact of new developments on existing infrastructure, and plan for disaster mitigation. A city can simulate the addition of a new commercial district to understand its potential impact on local traffic congestion and energy demand, allowing for preemptive infrastructure upgrades. For example, Siemens created a digital twin for Singapore to simulate urban environments and optimize traffic flow, energy distribution, and environmental sustainability.
- *Infrastructure:* In the context of civil infrastructures, such as bridges, dams, and buildings, sensors can be deployed to continuously monitor the health and condition of these structures. By collecting data on factors like vibrations, temperature, and structural movements, these sensors provide real-time insights and enable proactive measures to be taken when necessary [49,52]. By analyzing the data collected with these sensors, anomalies that indicate potential structural issues can be identified. By bridging the physical and digital worlds through the continuous integration of real-time data, digital twins transform how buildings and infrastructure are designed, built, operated, and maintained. Figure 8 shows the digital twin of a building [12].
- *Safety Management:* Safety is a paramount concern on any construction site. DT technology is being increasingly used in the construction industry, with safety and risk management being one of the key areas where its implementation can bring significant benefits. The implementation of this technology enables the creation of a virtual replica of a physical structure, facilitating the identification of potential safety hazards and risks at construction sites using constant monitoring prior to their materialization. This can subsequently result in improvements in safety practices, leading to the prevention and minimization of incidents on construction sites. Studies have shown promising outcomes when DT technology is applied toward such an end.
- *Lifecycle Management:* The value of a digital twin extends far beyond the construction phase. Once a project is complete, the digital twin serves as a comprehensive virtual manual for the building's entire lifecycle. By continuously monitoring the performance of assets through IoT sensors, it can predict maintenance needs before

failures occur, reducing downtime and repair costs. This predictive maintenance capability ensures the long-term operational efficiency and sustainability of the asset. Figure 9 shows the lifecycle DT in construction [13].

## BENEFITS

The integration of digital twins into the construction industry yields substantial benefits, fundamentally altering how projects are managed and executed. One of the most immediate and tangible benefits of digital twin technology is the transformation of project visualization. A major benefit of digital twins within construction is that they help improve the analytical capabilities of building information modeling (BIM). Other benefits of digital twin construction include the following [3,14-16]:

- *Cost Reduction:* The use of digital twins can help reduce costs by helping more efficient project planning and execution. Early visibility of potential problems means teams can address issues before they escalate and cause extra expense. Additionally, digital twins help reduce waste, improve resource management, and avoid rework, lowering overall project costs.
- *Improved Collaboration:* Serving as a single source of truth, the digital twin breaks down information silos among architects, engineers, contractors, and owners. This centralized data environment ensures that all parties have access to the most current information, thereby reducing errors and miscommunication. By establishing a common data environment — a single, authoritative source of truth — digital twins ensure that all parties, from lead designers to on-site subcontractors, are working from the same, most current information. This eliminates the version-control problems and information silos that have historically plagued large construction projects.
- *Energy Efficiency:* To truly increase efficiency, you need to know how the facility is being used. The adoption of DTs within the construction sector offers a robust means to enhance energy efficiency and promote sustainability. Digital twins play a critical role in optimizing energy consumption. For example, by analyzing HVAC performance and occupant behavior, facility managers can adjust systems to reduce carbon emissions and lower energy costs.
- *Quality Control:* The implementation of DT technology within the construction industry offers significant potential for enhancing quality control and management processes. By utilizing DT applications, construction companies can revolutionize their approach to assuring quality. DTs enable real-time monitoring and analysis of construction processes, providing a comprehensive understanding of the project at each stage.
- *Sustainability:* The construction industry bears a disproportionate share of responsibility for global environmental degradation. It accounts for approximately 40% of global energy consumption, one-third of carbon emissions, and a quarter of global waste generation. As governments and organizations worldwide commit to ambitious net-zero targets, the industry faces an urgent imperative to reduce its environmental footprint. Digital twins are emerging as one of the most powerful tools available to meet this challenge. During the design phase, digital twins enable detailed energy modeling and environmental simulation, allowing designers to evaluate the performance of different materials, orientations, and building systems before construction begins. Digital twins also support the broader sustainability agenda by aligning with the United Nations Sustainable Development Goals (SDGs).
- *Streamlined Facility Management:* Digital twins can offload much of the burden of asset management. For example, when a repair is needed, a digital twin can pinpoint problem areas and share necessary specs with techs. It can even keep track of who to bill for the work.
- *Better Planning:* Digital twins are a *proactive* planning tool, allowing clients or building owners to provide feedback before the jackhammering begins or the sheetrock is installed. Engineers can also perform more extensive assessments for items like duct locations and utility placements, while architects can anticipate aesthetic concerns, such as paint color or lighting layouts. The use of digital twins in construction empowers the improvement of design risk assessments and condition surveys, effectively enabling collaborators to shift away from PDF reports and photos by providing an immersive view to more effectively understand site conditions and potential issues.
- *Improved Safety:* Remote virtual inspections allow project managers to oversee safety procedures better. With continuous updates on site conditions, equipment usage, and worker locations, digital twins support safety planning and real-time risk management, helping teams identify hazards earlier and take proactive steps to

prevent incidents. Also, digital twins enrich construction documentation with accurate, virtual measurements of hard-to-reach or dangerous environments, meaning employees do not have to take unnecessary risks while on-site.

- *Reduced Rework:* Digital twin helps construction project managers simulate designs virtually to identify errors and deviations early on. This reduces rework, avoids last-minute changes, and helps to ensure that projects stay on schedule.
- *Enhanced Decision-making:* With real-time data integrated into the model, digital twins give project teams a better understanding of how assets are performing or developing, enabling more informed, data-driven decisions at every stage.

## CHALLENGES

In spite of the profound benefits, the widespread adoption of digital twins in the construction industry faces several challenges. The primary challenges include the high initial costs of implementation, data security and privacy concerns, data governance, interoperability issues, the complexity of integrating diverse data systems, and a lack of standardized contractual frameworks regarding data ownership and liability. Other challenges of digital twin construction include the following [3,14]:

- *Data Quality:* A digital twin is only as reliable as the data it ingests. In the dynamic environment of a construction site, ensuring continuous data accuracy is difficult. If BIM models are outdated, field conditions are not properly recorded, or IoT sensors malfunction due to power loss or environmental factors, the digital twin quickly loses its credibility. The static nature of much building data, coupled with the physical challenges of maintaining sensor networks on active construction sites, leads to data uncertainties that severely limit the predictive capabilities of the DT.
- *Interoperability:* The construction industry relies on numerous disparate software systems and data formats. Integrating these siloed data sources into a cohesive digital twin remains a major technical challenge. Construction projects rarely operate on a single, unified software platform. Design teams utilize various BIM software, contractors rely on distinct project management tools, and facility owners employ separate asset management systems. Integrating these disparate systems into a cohesive digital environment is a profound technical challenge.
- *High Initial Costs:* Developing a comprehensive digital twin requires substantial upfront

investment in IoT hardware, software platforms, and skilled personnel. For many contractors and developers operating on tight profit margins, this investment is prohibitive. The challenge is exacerbated by the fact that the return on investment (ROI) is rarely immediate. This disconnect between who pays for the DT and who benefits from it stifles investment.

- *Lack of Standardization:* There is currently a lack of universal standards and protocols for digital twin development and data exchange in construction, complicating collaboration across different organizations. The lack of universal data standards and inconsistent data structures mean that DTs often struggle to act as a “single source of truth,” instead reflecting fragmented information that undermines trust in the system.
- *Cybersecurity:* As digital twins aggregate vast amounts of sensitive data regarding building operations and occupant behavior, they become attractive targets for cyberattacks. The construction industry is increasingly vulnerable to ransomware attacks, IP breaches, and project disruptions. Ensuring robust data security is paramount.
- *Skills Gap:* The implementation and management of digital twins require expertise in data analytics, AI, and IoT—skills that are currently in short supply within the traditional construction workforce. There is a pronounced shortage of professionals who possess a deep understanding of both traditional construction workflows and advanced digital twin technologies (such as IoT systems, data mapping, and analytics). This skills gap results in DT platforms being implemented but underutilized, as teams do not fully understand how to maintain the models or translate the data into actionable decisions.
- *Resistance to Change:* The construction industry's project-based structure relies on temporary collaborations among diverse stakeholders—architects, engineers, contractors, and owners. This fragmentation creates misaligned incentives and a lack of clear DT value propositions across different phases of the project. Without strong stakeholder alignment and cultural readiness, DT initiatives struggle to gain traction.
- *Governance Issues:* Traditional construction contracts do not adequately address the nuances of digital twin ownership, data rights, and liability. If a predictive maintenance algorithm within a DT fails, determining liability among the software provider, the contractor who installed

the sensors, and the facility manager is legally complex. Clear governance frameworks that dictate data management, ethical considerations, and long-term ownership are urgently needed to mitigate these risks.

## FUTURE OF DIGITAL TWINS CONSTRUCTION

Digital twin is a revolutionary technology gaining traction in the construction industry. Looking ahead, the digital twin market is poised for exponential growth. Future trends suggest a deeper integration of autonomous AI, enabling digital twins to not only predict issues but also independently execute corrective actions. The future of digital twins in construction is intrinsically linked to advancements in AI and machine learning, which will enhance the predictive capabilities of digital twins, enabling more autonomous decision-making. It extends beyond individual buildings to encompass entire urban ecosystems. As these algorithms become more sophisticated, digital twins will evolve from passive monitoring tools into autonomous systems capable of self-optimization and self-correction. As technology continues to mature, digital twins will undoubtedly become a foundational element of modern construction, driving efficiency, safety, and sustainability in the built environment. The adoption of digital twin technology will transition from a competitive advantage to an industry standard. The future of digital twin construction is bright, with ongoing advancements in technology poised to unlock even greater potential. It lies in these intelligent, evolving virtual replicas, paving the way for smarter buildings, resilient infrastructure, and sustainable cities [3]. Figure 10 shows the future state of construction [14].

## CONCLUSION

Digital twins represent a paradigm shift in the construction industry, moving beyond static blueprints to dynamic, data-driven replicas of the physical world. By bridging the gap between physical assets and digital models, this technology enhances every stage of the construction lifecycle—from conceptual design to long-term facility management.

The technology offers unprecedented opportunities to enhance efficiency, safety, and sustainability across the entire lifecycle of built assets. Embracing this technology is not merely an option; it is an imperative for an industry that must build the sustainable world of tomorrow. Digital twins are expected to keep transforming the construction industry.

The digital twin represents far more than an incremental technological upgrade; it is a fundamental reimagining of how the built

environment is designed, constructed, and managed. Its use is becoming a key differentiator for firms in the AEC industry.

Digital twins in construction are becoming important for managing modern construction and infrastructure projects. They offer benefits like improved planning and design, enhanced safety, real-time monitoring, better resource and cost management, and streamlined operations. By bridging the physical and digital realms, digital twins offer unprecedented visibility, predictive foresight, and operational efficiency. More information about digital twin in construction can be found in the books in [17-21] and a related journal: *Automation in Construction*.

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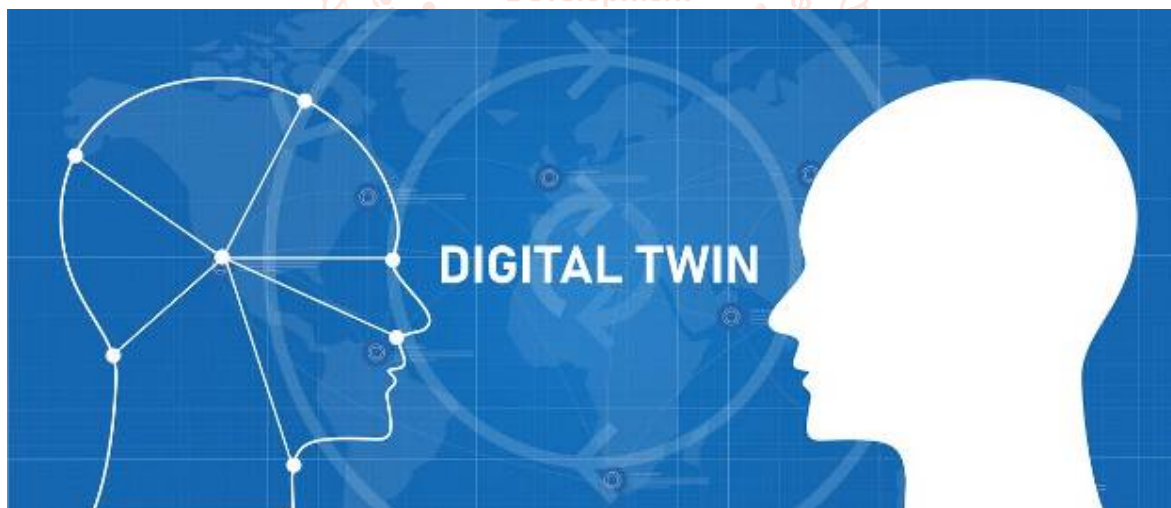


Figure 1 A typical digital twin [1].

## DIGITAL TWIN

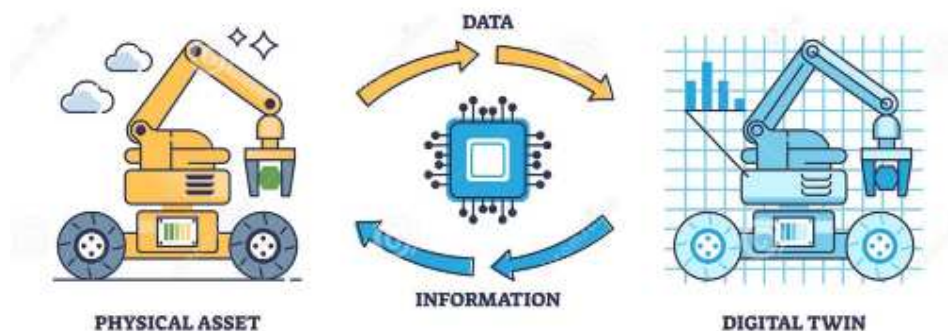


Figure 2 Conceptual model of a digital twin [2].

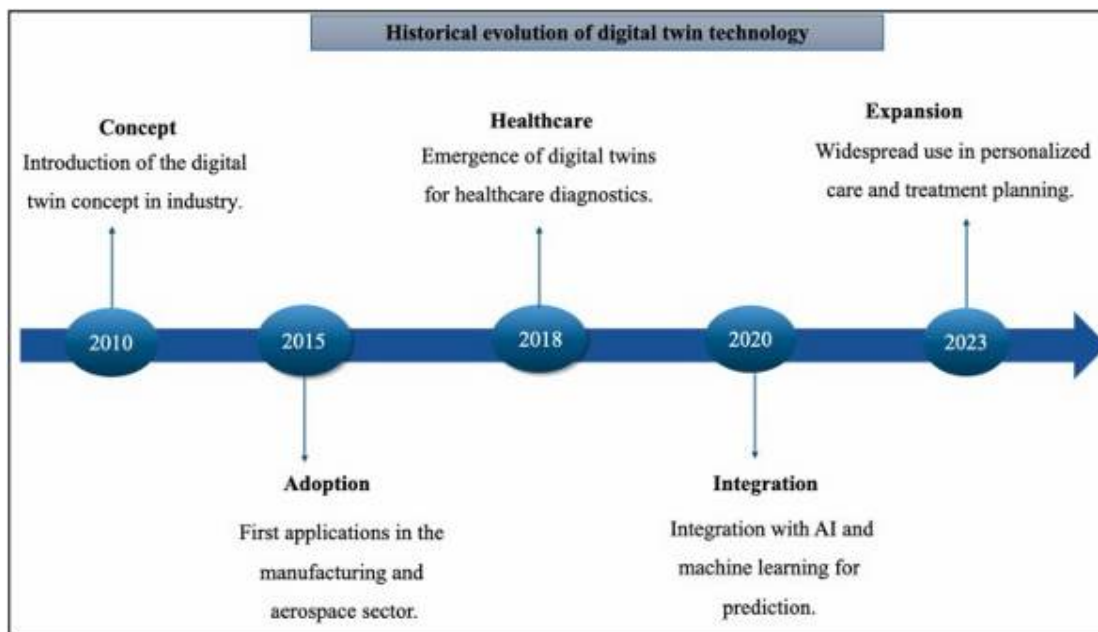


Figure 3 The historical evolution of DT technology [5].

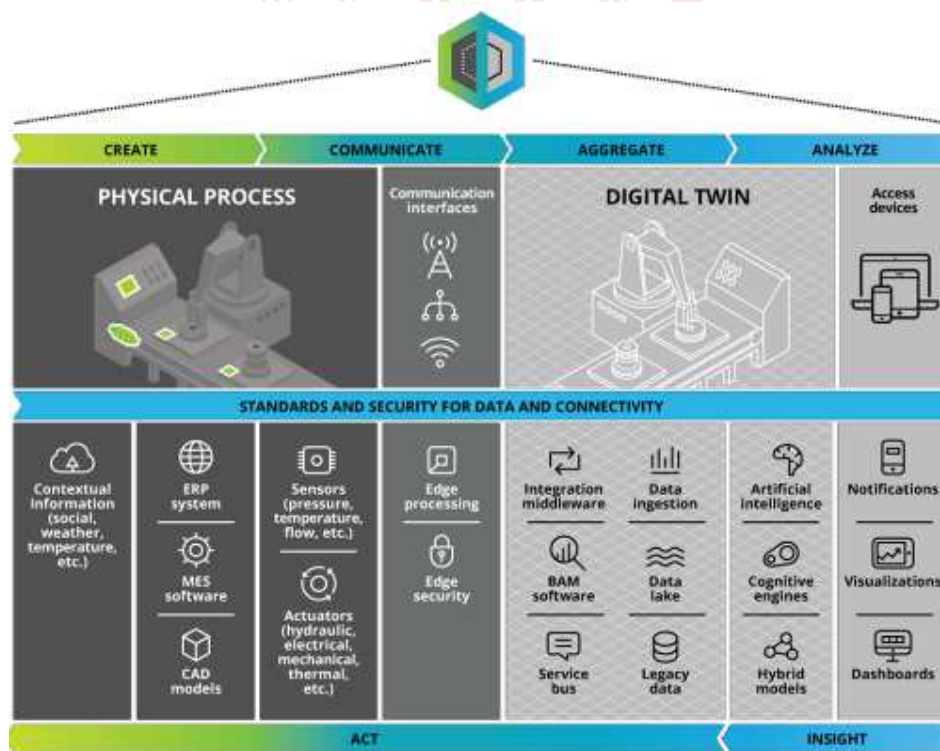
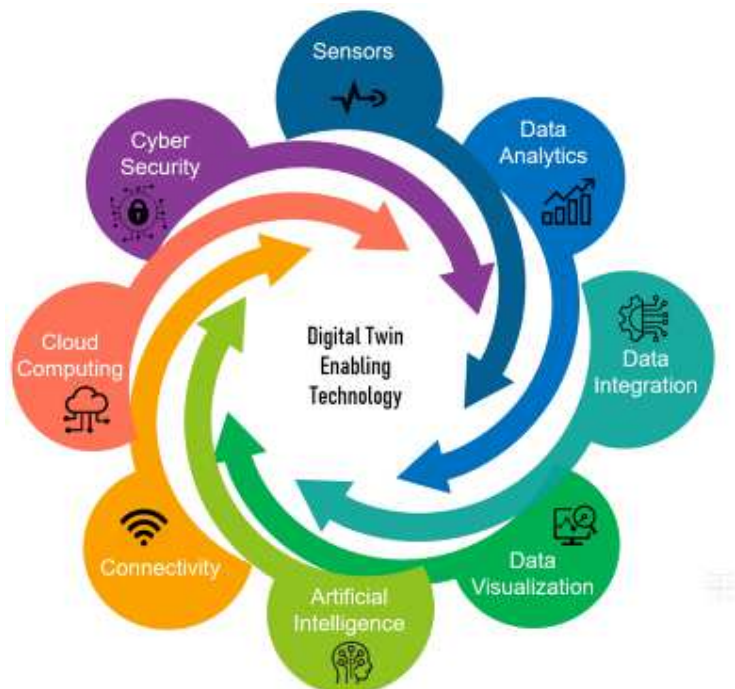


Figure 4 The digital twin conceptual architecture [6].



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



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



**Figure 7 Some construction workers [10].**

