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Digital Twins in Manufacturing

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ABSTRACT

A digital twin is an evolving virtual representation of a physical object, system, or process that utilizes real-time data to accurately reflect and simulate its real-world counterpart's behavior. It bridges the physical and virtual realms, enabling real-time, bidirectional data exchange to optimize production processes, enhance product design, and facilitate predictive maintenance. A digital twin in manufacturing is a detailed virtual model of a physical asset, such as a product, equipment piece, or an entire production system. Digital twins can represent individual machines, production lines, or entire factories, enabling simulation, prediction, and optimization without disrupting real operations. The digital twin can allow companies to have a complete digital footprint of their products from design and development through the end of the product life cycle. The integration of digital twins into manufacturing has accelerated rapidly with the convergence of the Internet of things, cloud computing, and artificial intelligence. This paper explores operational applications of digital twin technology in the manufacturing sector.

KEYWORDS: *digitalization, digital twin, manufacturing, smart manufacturing.*

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INTRODUCTION

The manufacturing sector is undergoing a profound structural evolution driven by rapid digitization, hyper-connectivity, and the imperative for operational resilience. The global manufacturing sector operates in an era defined by unprecedented volatility. Manufacturers are forced to navigate persistent labor shortages, rising material and energy costs, and highly fragmented supply chains, while simultaneously meeting stringent regulatory demands for decarbonization and environmental accountability. To survive and thrive, industrial leaders are turning to cyber-physical systems that bridge the physical and virtual worlds in real time. Of particular fascination of late seems to be the notion of a *digital twin*: a near-real-time digital image of a physical object or process that helps optimize business performance. A virtual representation of a physical procedure or product is called digital twin which can enhance efficiency and reduce costs in manufacturing process [1].

The concept of the digital twin (DT) has emerged as a revolutionary paradigm shift. A digital twin is a virtual representation of a physical thing - a machine, a process, a production line, or an entire factory - that uses real data to mirror what is happening in reality. This technology represents a significant departure from traditional computer-aided design (CAD) or isolated sensory monitoring. Digital twin represents a living, dynamic bridge between physical assets and virtual environments. Figure 1 shows a typical digital twin [2]. 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 manufacturing sector, turning conventional medical practice into a smart and data-driven model. Figure 2 shows the conceptual model of a digital twin [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].

There are numerous requirements to describe “digital twin.” To be considered a digital twin, the model must have some specific characteristics such as [7]:

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.
2. 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.
3. Scalability (ability to analyze different scales of information);
4. Interoperability (ability to convert, match and establish equivalence between representation models);
5. Expansibility (ability to integrate models);
6. Fidelity (ability to conform to the physical model); the core of any DT is a high-fidelity virtual model.
7. 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 MANUFACTURING

The manufacturing sector faces unprecedented pressure to scale capacity, enhance resilience, and drive operational efficiency amid severe labor constraints, rising material costs, and supply chain disruptions. With a strained supply chain, a shortage of blue-collar workers, and a turbulent economy, the strain on manufacturers is compounding. Digital twin technology has emerged as a cornerstone innovation to address these challenges. It enables manufacturers to move from reactive decision-making to proactive, data-driven optimization. Rather than acting as a static CAD model or a one-way data shadow, a digital twin represents a dynamic, bidirectional, real-time virtual counterpart of a physical asset, process, or system. Digital twins are exact virtual replicas of objects, products, equipment, processes, supply chains, and people. In other words, a digital twin can copy an entire company’s business ecosystem.

Digital twins rely on data gathered by Internet of Things (IoT) sensor technologies embedded or attached to the original object, whether it is a person, machine, or anything else. Serving as both an interactive simulation and a set of administrative tools, digital twins manage facilities, systems, and machines, while gathering data to drive performance. By bridging the physical and virtual worlds through a real-time, bidirectional data loop, digital twins unlock massive value across the entire product and operational lifecycle [1]. Figure 5 shows manufacturing process DT model [6]. The model of Figure 5 specifically finds expression through five enabling components—sensors and actuators from the physical world, integration, data, analytics, and the continuously updated digital twin application. Figure 6 shows examples of DTs in manufacturing [8].

In a complex manufacturing environment, digital twins are deployed at different levels of granularity and scope. A robust industrial digital twin cannot function as a standalone software application; rather, it requires a sophisticated, multi-layered technological architecture to collect, process, analyze, and act upon data. A benefit of a digital twin is that it can provide a virtual replica of a physical system, allowing for testing and analysis without disrupting the actual system. Figure 7 shows the digital twin for manufacturing [8].

APPLICATIONS OF DIGITAL TWIN IN MANUFACTURING

A digital twin is a virtual representation of a physical system or process that allows for real-time monitoring, analysis, and optimization. The digital twin application continuously analyzes incoming data streams. Digital twins revolutionize three core areas of manufacturing: predictive maintenance, process optimization, and quality control. Common applications of DT in manufacturing include the following [1,9,10]:

- *Predictive Maintenance:* Predictive maintenance is an approach that uses data analysis tools and techniques to monitor equipment and predict when maintenance is required, with the goal of minimizing downtime and reducing maintenance costs. Unplanned downtime is one of the most significant cost drivers in industrial manufacturing, costing capital-intensive industries millions of dollars annually in lost productivity and emergency repairs. Traditional maintenance strategies rely on reactive "break-fix" approaches or conservative, schedule-based preventative maintenance, both of which are highly inefficient. Asset-level digital twins address this vulnerability by shifting maintenance strategies from reactive or preventative (schedule-based) to predictive (condition-based). Digital twins enable a transition to predictive and condition-based maintenance. The early warning system allows maintenance teams to schedule repairs during planned maintenance windows. Digital twins in predictive maintenance can increase productivity, identify issues early, and continue to provide fresh perspectives in addition to process optimization.
- *Process Optimization:* On the production floor, maintaining high throughput and minimizing bottlenecks is a constant challenge. Process and factory digital twins provide a real-time, comprehensive view of the entire manufacturing line. In traditional manufacturing, deploying a new production line or introducing a new product is a highly risky, capital-intensive process. Physical commissioning often reveals unforeseen design flaws, spatial clearance issues, or PLC programming errors, leading to costly delays. Digital twins facilitate virtual commissioning, allowing engineers to build, program, and test entire production lines in a risk-free virtual environment before purchasing physical equipment. During ongoing operations, digital twins continuously optimize processes. Ultimately, the digital twin is not merely a tool for localized process optimization; it is the foundational architecture of the future.
- *Quality Control:* In the manufacturing sector, digital twin technology revolutionizes product development by eliminating the need for traditional prototyping stages. Rather than allocating resources to construct physical models, manufacturers increasingly adopt digital twins, which offer a more flexible and manageable approach. Ensuring consistent product quality is critical for protecting brand reputation and minimizing waste. When integrated with industrial AI, digital twins enhance quality control through automated, real-time inspection. The digital twin compares these real-time images against the high-fidelity "as-designed" digital model.
- *Smart Factory:* Leading factories around the globe have seamlessly integrated cutting-edge technologies into their daily operations, underlining the manufacturing sector's commitment to achieving a higher level of automation and digitalization. The concept of the "smart factory" is no longer a futuristic aspiration but a contemporary operational reality. At the heart of this transformation is the digital twin, which is defined as a highly scalable, real-time virtual representation of a physical object, process, or system. Unlike traditional computer-aided design (CAD) models or static simulations, a digital twin is continuously updated with real-time data from its physical counterpart, establishing a continuous feedback loop that mirrors the physical entity's characteristics, behaviors, and environmental conditions. The modular, scalable architecture ensures that data flows seamlessly from the factory floor to the analytical models and back. Modern smart factories organize digital twin applications into four distinct integration levels: Machine (Asset), Cell (Line), Shop Floor (Factory), and Enterprise (Supply Chain). Shop floor digital twins integrate data feeds from manufacturing execution systems,

enterprise resource planning systems, and human-machine interfaces to create a comprehensive model of the entire factory floor. Figure 8 shows DTs blend physical assets and factory technologies in a single view [11].

- *Virtual Prototyping:* Virtual Prototyping is an area in which DT can help companies identify and resolve potential issues before manufacturing the final product, reducing engineering costs and improving operational procedures. Traditionally, product development is a slow, iterative, capital-intensive process characterized by iterative physical prototyping. It involves the creation of multiple physical prototypes, rigorous testing, and subsequent design modifications. Digital twins revolutionize this workflow by serving as virtual prototypes during the initial design phase. By testing designs in a high-fidelity virtual environment, companies can identify structural flaws, optimize material usage, and validate performance characteristics early in the lifecycle. This virtual validation drastically reduces the number of physical iterations required, significantly lowering R&D costs.
- *Supply Chain Synchronization:* The value of digital twins extends far beyond the four walls of the factory. End-to-end supply chain digital twins integrate supplier inventory levels, logistical tracking, and market demand forecasts to build a resilient operational ecosystem. Modern manufacturing relies on highly synchronized, global supply chains where disruptions at a single supplier can halt production lines thousands of miles away. Supply chain digital twins create an end-to-end virtual model of the entire logistics network, integrating real-time data from suppliers, warehouse inventory levels, transit times, and customer demand forecasts. This comprehensive visibility allows manufacturers to optimize just-in-time (JIT) and just-in-sequence (JIS) production.
- *Environmental Sustainability:* In the 21st century, sustainability is no longer a corporate social responsibility checkbox. It is a core business metric driven by carbon taxes, resource scarcity, and consumer preferences. Digital twins are proving to be one of the most powerful tools in the path toward net-zero manufacturing. They are emerging as one of the most powerful technological levers for driving decarbonization and resource efficiency in manufacturing. By creating high-fidelity thermal and thermodynamic models of factories, sustainability digital twins allow operators to optimize energy consumption. Digital twins contribute to circular economy initiatives by minimizing material waste.
- *Smart Manufacturing:* Smart manufacturing is a manufacturing approach that incorporates advanced technologies such as artificial intelligence, the Internet of things, robotics, and big data analytics to optimize production processes and increase efficiency. Smart manufacturing also provides opportunities for product customization and personalization, as well as real-time supply chain management. It enables manufacturers to respond quickly to changes in demand, market trends, and customer preferences, and to create products that are tailored to individual customers' needs. Digital twin technology represents a paradigm shift in smart manufacturing, offering a powerful “virtual mirror” to optimize operations, predict failures, and drive continuous innovation. In the context of smart manufacturing, a digital twin can be used to simulate and optimize the production process, predict and prevent equipment failures, and improve efficiency and quality of part production. The digital twin provides several benefits to smart manufacturing. For one, it enables real-time monitoring of manufacturing processes, allowing for quick identification and resolution of issues. Additionally, it allows for the testing and optimization of products and processes before they are physically produced, which can save time and resources. Moreover, production digital twins are employed to verify the effectiveness of a manufacturing process prior to component manufacture. Figure 9 shows DT in smart manufacturing [12].

BENEFITS

DT technology is an indispensable tool for achieving autonomous, highly efficient, and sustainable manufacturing ecosystems. Companies can utilize digital twins to model, anticipate, and improve products and manufacturing processes in different industries. As a result, digital twins can help manufacturing businesses make better decisions, reduce costs, and improve performance across a range of applications. Other benefits of DT in manufacturing include the following [1,9,13]:

- *Sustainability:* With growing regulatory pressure and consumer demand for green manufacturing, digital twins will play a critical role in sustainability. Future digital twins will model not only physical throughput and machine wear but also real-time energy consumption, water usage, and carbon emissions. By simulating energy-intensive processes, the twin can identify operational schedules that maximize the use of renewable energy, reduce waste, and minimize the overall environmental footprint of the manufacturing process.

- *Efficiency:* Digital twins are revolutionizing how decisions are made within factories, and forward-thinking manufacturers are getting ahead of the technology curve to drive efficiency. In a resource-constrained environment where talent gaps and supply chain shortages are the norm, digital twins are emerging as a frontrunner technology for rapidly scaling capacity, increasing resilience, and driving more efficient operations. By implementing demand-response strategies and optimizing production schedules to align with off-peak energy rates, manufacturers can significantly reduce their greenhouse gas emissions. By leveraging these top digital twin technologies, manufacturers can enhance efficiency, reduce costs, and drive innovation in their operations.
- *Collaboration:* Digital twins are virtual replicas of physical assets or processes that can be used to simulate and optimize performance. They can be particularly useful in manufacturing, where they can help teams collaborate more effectively and improve efficiency. Digital twins can be accessed from anywhere, allowing teams to collaborate remotely. This can be particularly useful for global teams or teams that are working from home. By using digital twins, teams can collaborate in real-time, even if they are in different locations. Digital twins can facilitate collaboration and communication between different stakeholders in the manufacturing process, including designers, engineers, operators, and managers.
- *Water Conservation:* In sectors such as food and beverage manufacturing, water is a critical resource. Digital twins of bottling lines and liquid processing plants enable precise tracking of water usage, allowing manufacturers to optimize clean-in-place cycles, detect micro-leaks instantly, and maximize water recycling opportunities.
- *Training:* Training new employees in manufacturing environments can be challenging due to complex automation systems, safety risks, and ongoing production demands. Digital twins offer a more effective approach, allowing workers to train in a risk-free virtual environment that mirrors real-world operations. Figure 10 shows some manufacturing workers [14].
- *Production Monitoring:* The digital-twin strategy can be used to improve quality of products, production methods, or even whole value chains. In the context of part production, a digital twin can be created for a specific machine or production line, allowing for real-time monitoring of production processes. This includes tracking variables such as temperature, pressure, and flow rate, which can impact the quality of the final product. By analyzing data from the digital twin, manufacturers can identify areas where production processes can be optimized or modified to improve efficiency and product quality. Continuous improvement at manufacturing sites can also be implemented by using digital twins.
- *Safety Enhancement:* One of the underused implementation cases is leveraging digital twins to improve safety on-site. Identifying hazards and risks is a critical step in enhancing safety in the manufacturing process. By recognizing dangers and risks through preventative maintenance, digital twins can increase safety in prat production process. A digital twin can be used to identify hazards in the manufacturing process by simulating the behavior of the system under different conditions. Once hazards have been identified, a digital twin can be used to assess the risks associated with them.
- *Reduction of Time-to-market:* Digital twin technology can help reduce the time to market for a product by providing a virtual model of the product that can be tested and optimized before the physical product is built. This can help to identify potential problems early on in the design process and make necessary changes before production begins. By creating a digital twin of the product, designers can test different configurations and optimize the design for performance and efficiency. This can help to reduce the number of physical prototypes needed and speed up the design process.

CHALLENGES

The widespread adoption of digital twins remains constrained by several formidable technical, financial, methodological, and organizational barriers. Formidable challenges—such as data fragmentation, high implementation costs, data complexity, legacy integration, interoperability, lack of standardization, and cybersecurity risks—currently hinder widespread adoption. Manufacturers frequently struggle with data silos, where legacy machines, proprietary software, and disparate databases. Other challenges of DT in manufacturing include the following [1,13,15]:

- *High Initial Cost:* Implementing a digital twin requires substantial initial capital expenditure. Developing a comprehensive digital twin requires significant capital investment in IoT sensors, high-performance computing, simulation software, and systems integration. For small and medium-sized enterprises, justifying this upfront cost can be difficult, especially when the return on investment (ROI) is not immediately visible. Companies should avoid attempting to build an all-encompassing "factory twin" from day one. Instead, they should adopt an iterative, modular approach and use the returns to fund the gradual expansion of the digital twin ecosystem.
- *Data Quality:* The digital twin is based on massive, cumulative, real-time, real-world data measurements across an array of dimensions. Modern manufacturing facilities generate vast volumes of high-velocity, heterogeneous data from Industrial Internet of things (IIoT) sensors, programmable logic controllers (PLCs), and enterprise software. A digital twin is only as accurate as the data that feeds it. On a typical factory floor, data is generated by thousands of sensors at varying frequencies, formats, and protocols. Managing this complexity and ensuring high data quality is a monumental task. Manufacturers must establish robust data governance frameworks.
- *Legacy Systems:* Many factories operate with legacy machinery that was manufactured decades before the Internet era. These machines lack modern connectivity and utilize proprietary communication protocols, making it difficult to integrate them with cloud-based IT platforms. The use of industrial middleware, IoT gateways, and modern APIs is crucial. These technologies act as translators, converting legacy protocols into modern, open standards.
- *Cybersecurity Risks:* By establishing a real-time bidirectional connection between physical machinery and cloud networks, digital twins expand the attack surface of a manufacturing facility. A cybersecurity breach could allow malicious actors to not only steal sensitive intellectual property but also send unauthorized control commands to physical machinery, risking physical destruction and worker injury. Manufacturers must adopt a "zero-trust" security architecture. This involves implementing end-to-end encryption for all data in transit and at rest.
- *Talent Shortage:* The development and maintenance of digital twins require a highly interdisciplinary skill set that sits at the intersection of operational technology (OT) and information technology (IT). In the current labor market, there is a severe shortage of professionals who bridge these distinct domains. There is a severe global shortage of specialized talent capable of designing, deploying, and maintaining digital twin architectures, which require a rare combination of skills in systems engineering, data science, industrial automation, and software development.
- *Interoperability*: Perhaps the most persistent technical barrier is the lack of interoperability. A typical manufacturing plant operates as a heterogeneous ecosystem of legacy machinery, proprietary hardware, and siloed software applications. These systems often use incompatible communication protocols, proprietary data formats, and localized semantics. Integrating these disparate components into a cohesive System of Digital Twins (SoDT) requires standardizing how data is represented and exchanged.
- *Cultural Resistance:* Introducing digital twins fundamentally alters established workflows, decision-making processes, and organizational hierarchies. On the factory floor, operators and technicians may exhibit deep skepticism toward AI-driven recommendations or automated physical adjustments, viewing them as threats to their autonomy or job security. If senior management treats the digital twin as a siloed IT project rather than a core strategic initiative, the technology will fail to achieve the cross-departmental integration required to deliver its full value.
- *Lack of Standardization:* The manufacturing industry often relies on standardized processes and regulations. It faces complications due to the absence of a unified framework for DT. With a huge range of DT models and architectures in existence, the lack of standardization can lead to compatibility issues.

FUTURE OF DIGITAL TWINS IN MANUFACTURING

The future of digital twins in manufacturing represents a fundamental paradigm shift in how physical goods are designed, produced, and maintained. As digital twin technology matures, its future will be shaped by two powerful, converging forces: the integration of cognitive artificial intelligence and the global mandate for sustainable, green manufacturing. As technology continues to advance, digital twins will become more intelligent, immersive, and accessible, driving the future of smart manufacturing toward autonomous self-optimization.

The future of digital twins in manufacturing lies in their transition from passive, analytical representations into active, prescriptive, and ultimately autonomous agents of factory optimization. It is not about replacing human workers, but rather about enabling a highly collaborative, safe, and efficient human-machine teaming environment. The digital twin is poised to evolve from an emerging dispensable luxury for technology leaders into an indispensable operational standard for the global manufacturing ecosystem. The next generation of digital twins will evolve from predictive models into autonomous, cognitive twins [1].

CONCLUSION

Digital twin technology is revolutionizing manufacturing by enabling real-time simulation, predictive maintenance, and process optimization. It represents one of the most transformative innovations in the history of modern manufacturing. Digital twin technology is not merely an incremental upgrade to manufacturing software, but a fundamental redesign of industrial operations. It has emerged as a cornerstone technology, bridging the gap between physical operations and virtual intelligence. However, realizing this potential requires navigating complex technological and organizational hurdles, including severe data fragmentation and high setup barriers.

A digital twin is a dynamic, virtual representation of a physical product, process, system, or enterprise, characterized by a bi-directional data connection that enables real-time data exchange between the physical and virtual entities. It has gained great interest as an innovative technology in Industry 4.0 that enables advanced modeling, simulation, and optimization of service and manufacturing systems. While DTs offer transformative capabilities for enhancing efficiency and decision-making, overcoming some challenges is crucial for realizing their widespread adoption and impact across service and manufacturing sectors. More information about digital twin in manufacturing can be found in the books in [16-21].

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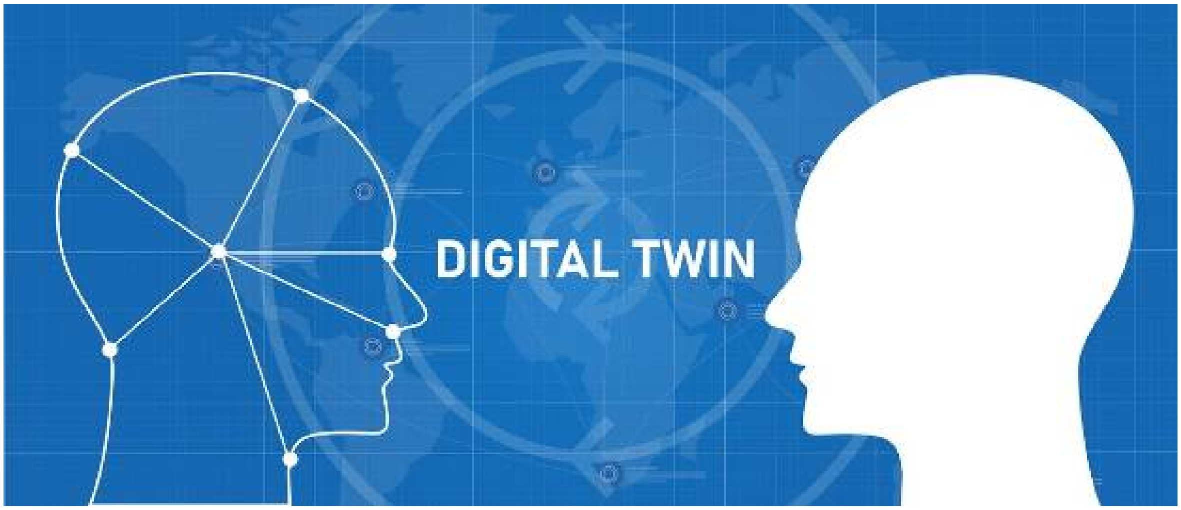

Figure 1 A typical digital twin [2].

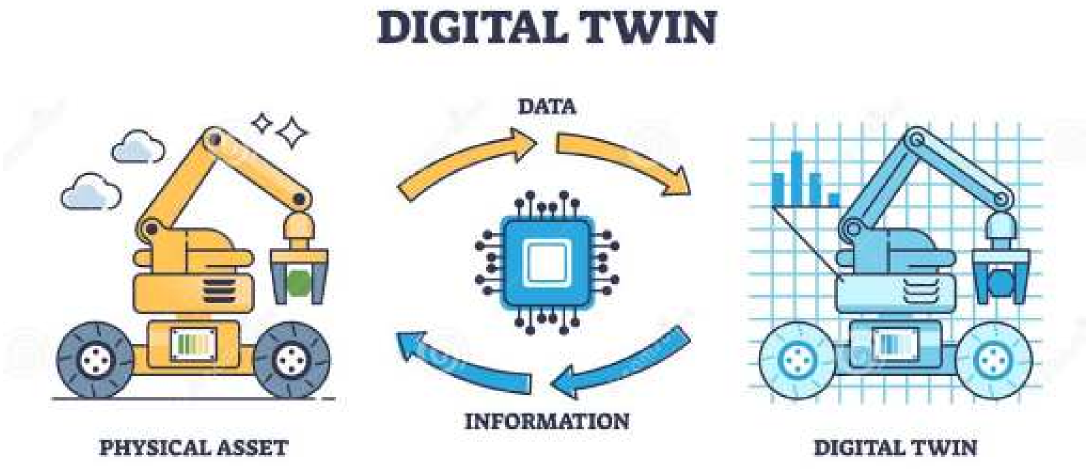

Figure 2 Conceptual model of a digital twin [3].

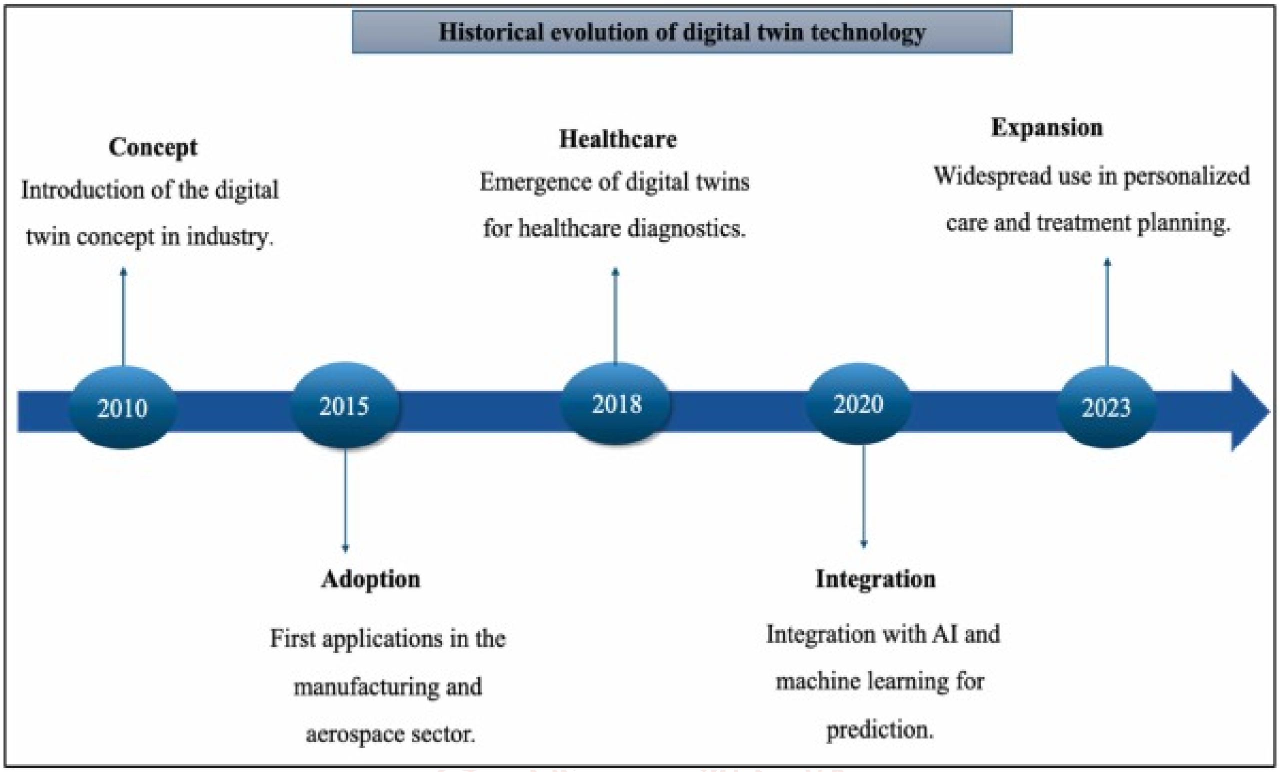

Figure 3 The historical evolution of DT technology [5].

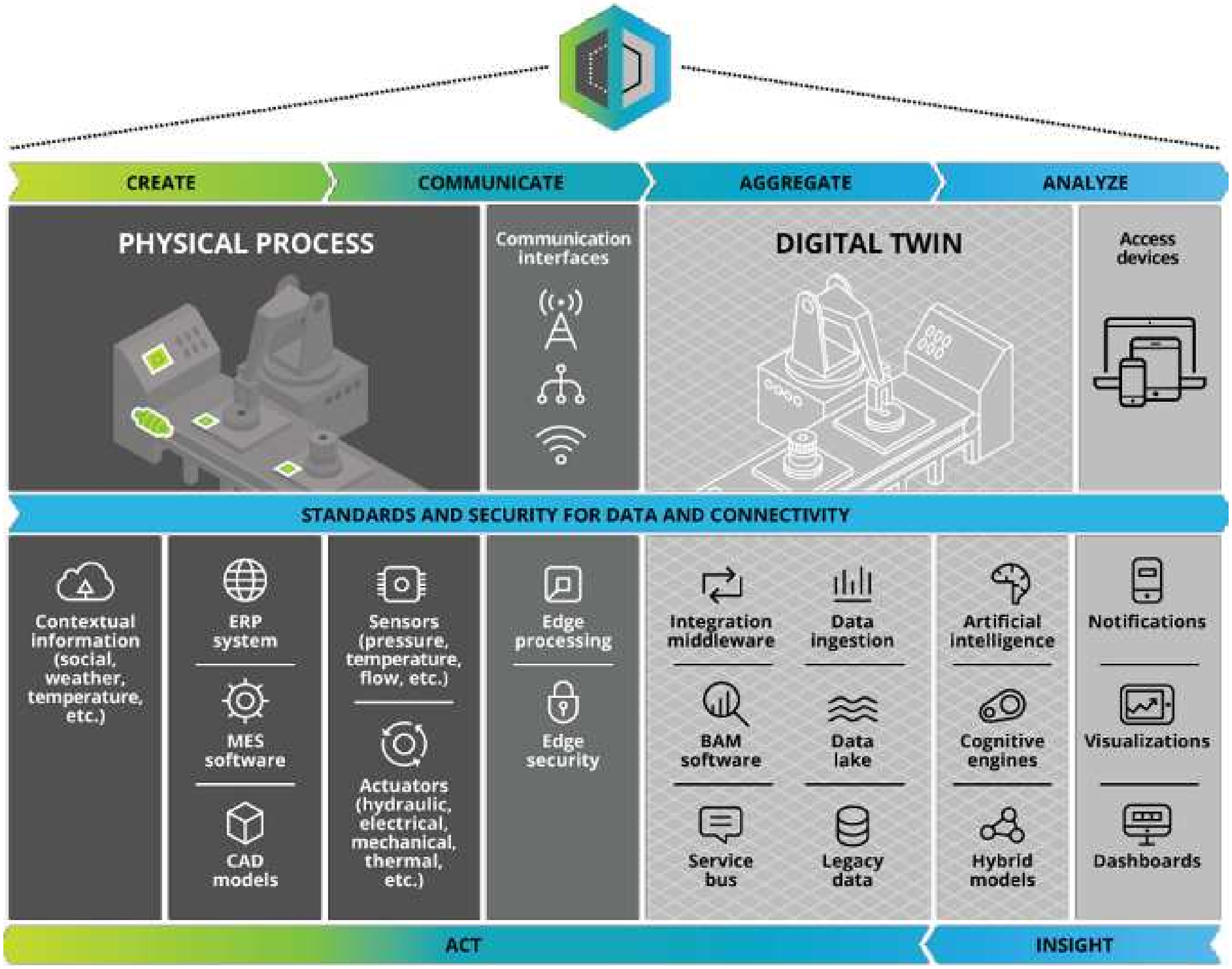

Figure 4 The digital twin conceptual architecture [6].

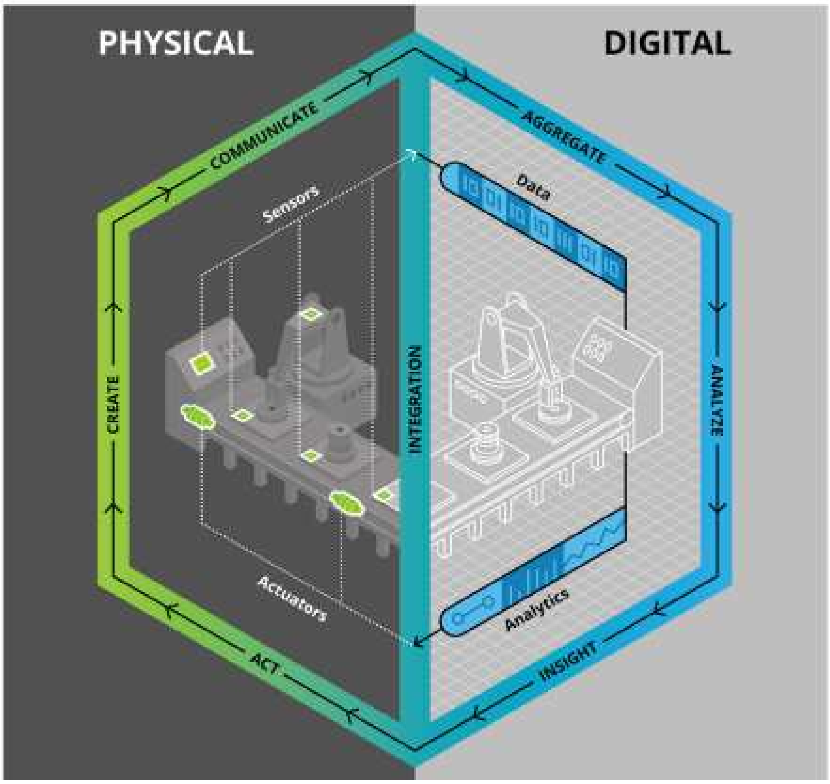

Figure 5 Manufacturing process DT model [6].

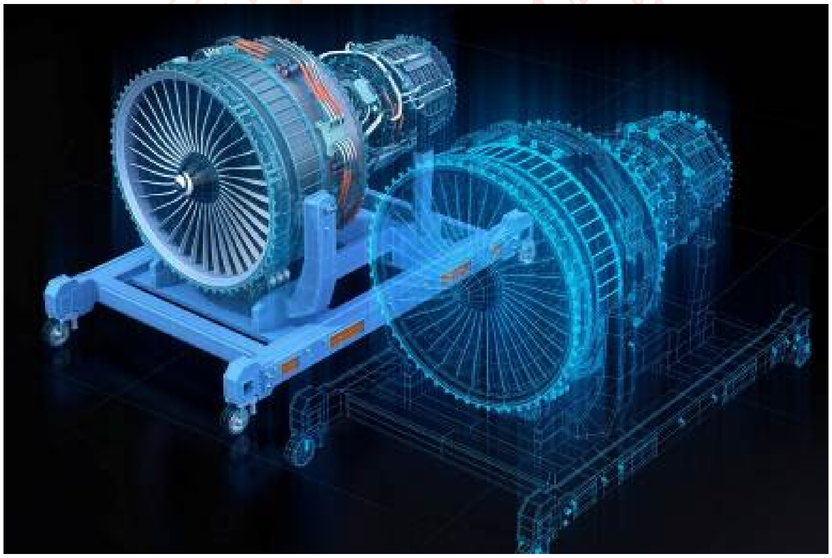

Figure 6 Examples of DTs in manufacturing [8].

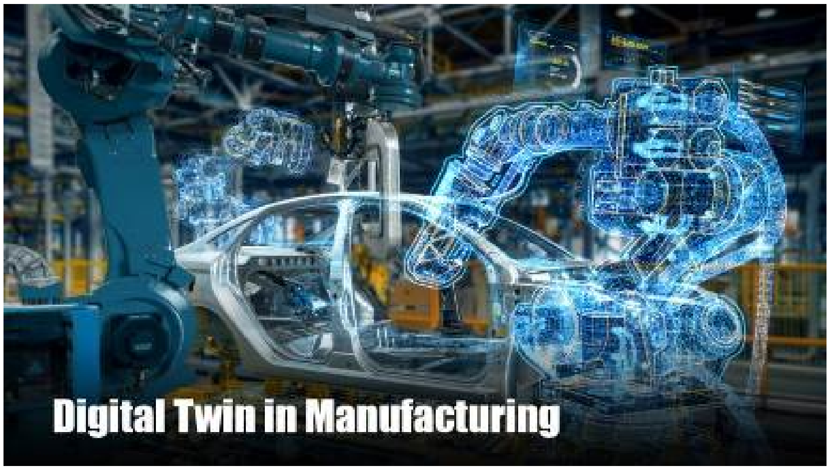

Figure 7 Digital twin for manufacturing [8].

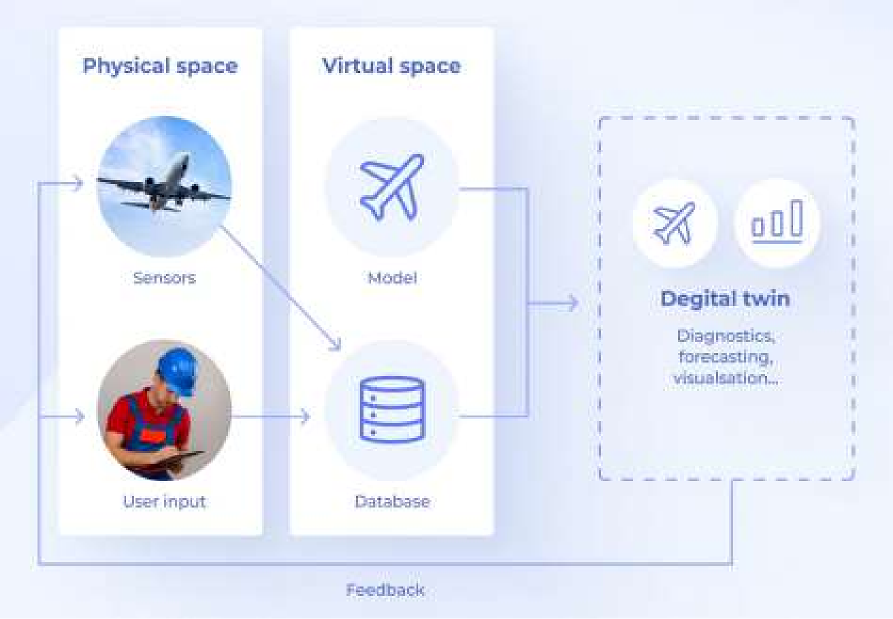

Figure 8 DTs blend physical assets and factory technologies in a single view [11].

Figure 9 DTs in smart manufacturing [12].

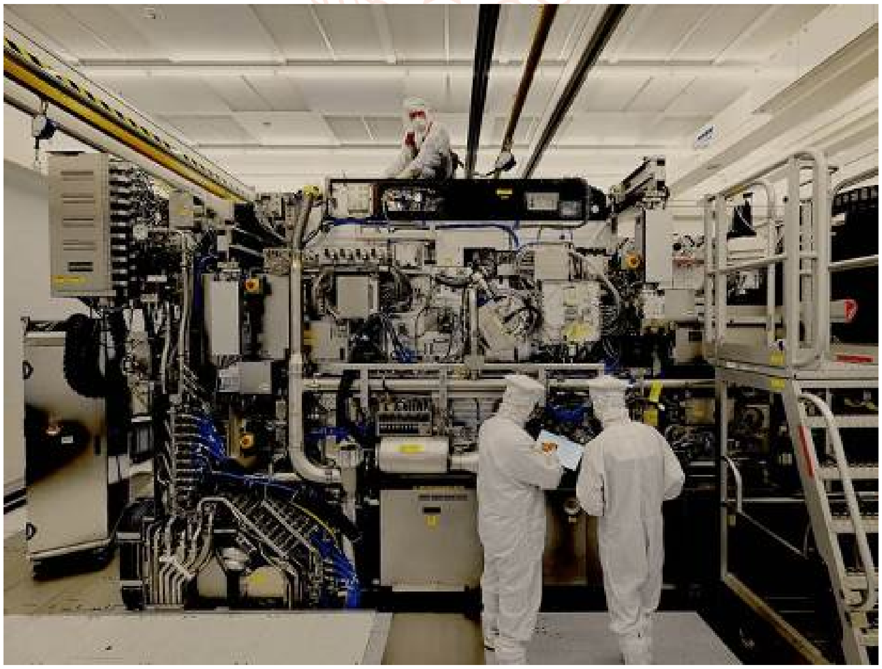

Figure 10 Some manufacturing workers [14].