

## Digital Twin in Supply Chain

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### ABSTRACT

In an era defined by global interconnectivity and unprecedented volatility, modern supply chains face mounting pressures. To build agility and resilience, organizations are increasingly turning to digital twin technology. In the context of supply chain management, a digital twin is regarded as a dynamic, virtual replica of a physical supply chain network, encompassing its assets, processes, inventory, and information flows. It is continuously updated with real-time data to mirror its real-world counterpart. This real-time synchronization enables organizations to simulate scenarios, predict disruptions, optimize inventory, and improve overall operational efficiency. This paper demonstrates how digital twins are reshaping supply chain resilience and operational efficiency.

**KEYWORDS:** *digitalization, digital twin, data twin, supply chain, supply chain management.*

### INTRODUCTION

The global supply chain landscape has undergone significant transformations in recent years, driven by rising consumer expectations, labor shortages, geopolitical conflicts, and extreme weather events. The modern supply chain is characterized by unprecedented complexity, globalization, and vulnerability to disruptions. In response, digital twin technology has emerged as a transformative solution, offering dynamic, real-time virtual replicas of physical supply chain networks. A digital twin is a virtual representation of a physical object, system, or process that uses real-time data to mirror physical behavior. In the context of supply chain management, a digital twin provides an end-to-end simulation of the entire network—from raw material sourcing and manufacturing to warehousing, logistics, and last-mile delivery. 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].

The era of managing supply chains through static spreadsheets and historical assumptions has passed. In a global economy defined by volatility and complexity, digital twins offer a vital strategic advantage. Digital twins are being deployed across various nodes of the supply chain to solve specific operational challenges. Traditional supply chain models, often reliant on static data and reactive strategies, are increasingly inadequate for navigating the complexities of modern commerce [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].

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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 SUPPLY CHAIN

In an era characterized by global economic volatility, extreme weather events, and rapidly shifting consumer demands, traditional supply chain management faces unprecedented challenges. Several competing forces are exerting pressure on the supply chain: consumer demand for low-priced products delivered via fast-and-free shipping; rising wages for manufacturing, warehouse, and delivery employees; and murky visibility into future macroeconomic disruptions. The static models and manual planning methods of the past are increasingly inadequate for navigating the complexities of modern, interconnected logistics networks. In response, digital twin technology has emerged as a transformative solution. Digital twins are virtual replicas of an object, system, or process used to simulate potential situations and outcomes. Digital twin technology is a dynamic, virtual replica of a physical supply chain that leverages real-time data, simulation, and advanced analytics to optimize operations, mitigate risks, and drive sustainability [3]. Figure 6 depicts digital twins in supply chain [9].

A supply chain digital twin is a precise virtual replica or virtual simulation of a physical supply chain system that utilizes real-time data obtained from sensors and IoT devices. It harnesses near-real-time data from multiple sources, such as ERP data, factory outputs, node lanes, inventory levels, vehicle locations, shipment schedules, market dynamics, and more, to give you an end-to-end view of your supply chain. Digital twins mimic the behavior and performance of the actual system, giving businesses the ability to simulate various scenarios, stress test newly developed systems, avoid risks, address problems in a timely manner, and make better and more data-driven decisions. Supply chain digital twins will mirror assets, transactions, and generally any communications and operations happening in the supply chain. This helps businesses to constantly monitor the processes, receive real-time updates, and

make quick and efficient adjustments [10]. Amazon represents perhaps the most sophisticated application of supply chain digital twins in the commercial world. The company employs AWS-powered simulation and digital twin technology to design and optimize its fulfillment centers.

## APPLICATIONS OF DIGITAL TWIN IN SUPPLY CHAIN

Digital twins can be used to model the interaction between physical and digital processes all along the supply chain—from product ideation and manufacturing to warehousing and distribution. The technology is proving its value across retail, automotive, aerospace, consumer goods, and logistics—wherever the complexity of physical operations demands the analytical power of a virtual counterpart. Figure 7 shows some applications of DTs in supply chain [10]. Common areas of application of DT in supply chain include the following [3,11]:

- *Real-Time Monitoring:* One of the primary applications of a supply chain digital twin is establishing complete transparency across complex networks. Traditional supply chains often suffer from siloed data, forcing managers to make decisions based on incomplete or outdated information. A digital twin consolidates data from various nodes—such as supplier performance, factory outputs, inventory levels, and transportation routes—into a unified platform. This real-time visibility allows organizations to track the flow of goods dynamically, instantly identifying bottlenecks or delays. For instance, a digital twin can monitor the condition and location of perishable goods in transit, enabling businesses to predict product spoilage and take corrective action before losses occur.
- *Asset Management:* When you document the exact location and condition of your inventory, equipment, and materials, you streamline operations and take full control of your asset management. This reduces inventory loss, boosts accountability, and helps you locate assets and materials quickly, even in the most complex facilities. By integrating digital twins with BIM systems and IoT sensors, you can track critical factors like temperature, humidity, and equipment status in real time. By connecting physical spaces with digital data, your team stays ahead of potential issues before they disrupt operations or cut into your revenue.
- *Demand Forecasting:* Digital twins leverage artificial intelligence (AI) and machine learning algorithms to enhance predictive capabilities significantly. By analyzing historical data alongside real-time external variables—such as market trends, weather patterns, and geopolitical events—digital twins generate highly accurate demand forecasts. This predictive power allows companies to align their production and inventory strategies more effectively with actual market needs. Traditional demand planning relies heavily on historical data, which can fail during unprecedented market shifts. Digital twins utilize real-time data and predictive analytics to create highly accurate demand forecasts. If a digital twin detects a demand surge in one region and excess stock in another, it can instantly recommend inventory reallocation. Retail giants like Walmart use digital twins to forecast deficits and optimize restocking cycles.
- *Warehouse Optimization:* Digital twin technology is revolutionizing warehouse management and logistics. Companies are creating digital replicas of warehouses to monitor operations in real time. A warehouse digital twin creates a virtual replica of the facility, including racking systems, automation equipment, and inventory placement. Managers can use this model to test different layouts, optimize picking paths, and simulate the introduction of new robotics or automation systems. By doing so, they can identify the most efficient configurations to maximize space utilization and reduce labor costs. Furthermore, digital twins optimize inventory positioning across the broader network, ensuring that the right products are stored in the optimal locations to meet regional demand while minimizing holding costs. Figure 8 shows a supply chain worker in a warehouse [12].
- *Transportation Planning:* In the logistics domain, digital twins are being used to simulate end-to-end transportation networks. Digital twin is the technology that can help logistics to react immediately to changes and quickly adapt to them. Digital twins allow companies to test alternative transportation routes during port blockages, severe weather, or geopolitical sanctions. By simulating different modes and lanes, organizations can balance delivery speed, cost, and carbon emissions. Logistics leader DHL implemented a digital twin of its network to optimize delivery schedules and routing, resulting in a 25% decrease in transportation expenses.
- *Cost-to-Serve Analysis:* Cost-to-serve analysis helps businesses understand the cost of delivering a product to a customer on a granular level, including transportation, warehousing, and labor costs. Strategic supply chain design—such as

determining the optimal location and size of a new distribution center—can be stress-tested using a digital twin. By modeling complex constraints, companies can optimize their physical footprint. Digital twins enable granular “cost-to-serve” analysis, helping businesses understand the exact cost of delivering a product to a specific customer, thereby protecting profit margins.

## BENEFITS

Digital twin technology has emerged as a transformative force in supply chain management, offering virtual replicas of physical networks to enable real-time monitoring, predictive analytics, and enhanced resilience. By creating a dynamic, real-time replica of physical operations, digital twins empower organizations with unparalleled visibility, operational efficiency, and predictive capabilities. They transform supply chains from rigid, reactive networks into agile, resilient ecosystems capable of withstanding global disruptions. Other benefits of DT in supply chain include the following [3,13]:

- *Automation:* AI-driven automation can handle routine tasks, like order processing and inventory management, to reduce employee workload and prevent errors. Today’s supply chain management (SCM) software has automated large parts of the supply chain in the past decade, dramatically streamlining how suppliers, buyers, and shippers intersect. Digital twins can integrate with existing SCM tools, functioning as an innovation layer that sits on top of the tech stack. They not only automatically predict what can happen but also provide perspective actions on what to do about it.
- *Better Decision-making:* By using digital twins, organizations will be able to make more informed decisions. This is because the data they receive is not theoretical, but genuine and up-to-date. Digital twins help organizations make smarter, faster, data-driven decisions to respond — not react — if and when something goes wrong. It also helps uncover areas for operational improvement. Automated decision making allows teams to focus their time and energy on areas where expertise can add the most value.
- *End-to-end View:* Supply chain digital twins enable organizations to visualize and optimize their end-to-end supply chain operations in one virtual environment, allowing for fast identification and resolution of inefficiencies and bottlenecks. Digital twins can connect SCM tools throughout the supply chain to provide an integrated view of performance and up- and downstream decision impacts. This eliminates a

siloes approach in which each tool only optimizes its local variables, with little coordination among them. For example, one retailer used digital twins to connect their planning, inventory deployment, and transportation management tools.

- *Efficiency:* The adoption of digital twins is revolutionizing supply chain efficiency by offering unprecedented visibility and predictive capabilities. Businesses can track inventory levels, production schedules and logistics operations in real time, allowing them to quickly identify and resolve bottlenecks. Digital twins are redefining supply chain management, offering real-time simulation, predictive analytics, and AI-driven insights that drive efficiency, reduce risks, and enhance sustainability
- *Sustainability:* Beyond efficiency, digital twins help contribute to sustainability by reducing waste, optimizing inventory management and improving energy consumption. Sustainability has become a non-negotiable pillar of corporate strategy, driven by regulatory pressure, investor scrutiny, and consumer expectations. Digital twins are uniquely positioned to support Environmental, Social, and Governance (ESG) objectives across the supply chain. By optimizing transportation routes, reducing energy consumption in warehouses, and minimizing material waste through better product lifecycle management, digital twins directly reduce the carbon footprint of supply chain operations. Organizations that have embraced digital twins are achieving measurable improvements in cost, service levels, resilience, and sustainability.
- *Team Collaboration:* Digital twins put everyone on the same page with a shared visual understanding of your operations. Staff from different countries can look at the same spot in your warehouse together. No more confusion about which location you are talking about — everyone sees the same visuals, documentation, and data.

## CHALLENGES

In spite of the profound benefits, scaling digital twin technology in supply chain management presents several significant challenges. Challenges in data integration, cost, organizational alignment, data silos, data quality, data privacy, interoperability, high implementation costs, workforce readiness, and cybersecurity remain. Studies indicate that a significant percentage of digital twin projects fail to meet their objectives, primarily due to technical complexities and organizational resistance. Other

challenges of DT in supply chain include the following [3]:

- *High Implementation Costs:* Developing a comprehensive supply chain digital twin is a capital-intensive endeavor. Implementing digital twins requires substantial capital expenditure for IoT sensors, advanced software platforms, AI tools, and robust data infrastructure. The cost of covering cloud infrastructure, IoT sensors, AI analytics, and software integration can be prohibitive, particularly for small and mid-sized enterprises.
- *Data Quality:* The foundation of any digital twin is data. Data quality remains the most fundamental obstacle. A digital twin is only as good as the data feeding it, and integrating disparate, siloed data from legacy systems, and external partners is technically demanding. Inconsistent or inaccurate data can lead to flawed simulations and poor decision-making. For a digital twin to function effectively, it requires a continuous flow of high-quality data. However, establishing robust data pipelines across organizational boundaries often encounters technical friction and requires complex middleware solutions. The “garbage in, garbage out” principle is acutely applicable here; poor data quality undermines the predictive analytics capabilities that make digital twins valuable.
- *Data Integration:* Supply chains are inherently fragmented, involving multiple tiers of suppliers, manufacturers, distributors, and logistics providers. Each entity typically operates its own legacy IT systems, databases, and data formats. Integrating these disparate, siloed data sources into a unified, real-time digital twin is a monumental task.
- *Lack of Standardization:* As supply chains involve multiple partners, using different systems and data formats makes end-to-end integration highly complex. A critical technical barrier is the lack of universal standards for digital twin development and data exchange. Without standardized protocols, creating a seamless flow of information between the physical supply chain and its digital counterpart is highly complex.
- *Interoperability:* The heterogeneous nature of IoT devices, communication networks, and software platforms means that systems often “speak different languages.” This lack of interoperability forces organizations to build custom integrations, which are costly, difficult to scale, and hard to maintain. As supply chains expand, the inability of different digital twin models to communicate effectively limits end-to-end visibility and collaborative optimization.
- *Cybersecurity Risks:* A successful cyberattack on a digital twin could have devastating consequences. Because a supply chain digital twin centralizes critical operational data and connects numerous vendors, it becomes a prime target for cyberattacks that could expose sensitive logistics data or disrupt physical operations. Because digital twins rely on vast amounts of real-time, interconnected data, they expand an organization's attack surface, making them potential targets for cyberattacks. Robust security protocols are essential.
- *Talent Shortage:* Operating and maintaining a supply chain digital twin requires a highly specialized skill set that bridges domain expertise in supply chain management with advanced technical proficiencies in data science, AI, IoT, and systems architecture. Currently, there is a significant global shortage of professionals possessing this interdisciplinary expertise.
- *Resistance to Change:* Technology alone cannot transform a supply chain; the human element is equally critical. End-to-end supply chain optimization requires more than just implementing technology; it also requires a mindset shift at the leadership level and throughout the organization. Organizational structures and corporate culture often present significant resistance to the adoption of digital twins. Change management is a persistent barrier, as implementing digital twins requires a cultural shift and a workforce skilled in data analytics and AI—capabilities that many organizations currently lack. The automation and predictive capabilities of digital twins may raise concerns about job displacement among staff.

## **FUTURE OF DIGITAL TWINS IN SUPPLY CHAIN**

The evolution of digital twins will fundamentally alter supply chain paradigms. The trajectory is clear: from visibility and prediction toward autonomous, self-healing supply chain ecosystems. As technology continues to evolve, the capabilities of supply chain digital twins will expand further. The efficacy of a supply chain digital twin depends on the seamless convergence of several advanced technologies that collectively facilitate data acquisition, modeling, and application. Artificial intelligence, machine learning, and IoT constitute the analytical intelligence of the digital twin. When integrated, these three pillars

endow digital twins and make it essential for modern logistics operations.

As we look to the future, AI will enhance the visual capabilities of digital twin technology, making it easier to understand disruption or policy changes with a 3D view of the supply chain. As AI and IoT capabilities continue to advance, digital twins will become an indispensable tool, transforming supply chains from reactive networks into resilient, autonomous, and highly efficient ecosystems. This future is being built today by organizations like Amazon, Walmart, and Siemens, and codified in emerging academic frameworks for agentic digital twins [3].

## CONCLUSION

Digital twins represent a paradigm shift in supply chain management. Their transformative potential is no longer theoretical. Leading organizations across retail, manufacturing, and logistics are already deploying these technologies at scale, generating measurable competitive advantages. By providing a dynamic, real-time mirror of physical operations, they empower organizations to navigate complexity, mitigate risks, and optimize performance at every node of the supply chain.

Digital twins (DTs) developments are still in the pilot stages of deployment in supply chain management (SCM), and their full integration with real-time synchronization and autonomous decision-making poses many challenges. While supply chain organizations recognize the value digital twins can provide, few have implemented them at scale. Despite the need for quicker and more dynamic supply chain planning, many companies are still hesitant to adopt digital twin technology. One reason may be the complexity of digital twin technology. Training time, implementation workload, and maintenance costs may deter companies from embracing the technology [14]. Unlike many SCM solutions that are plug and play, digital twins may require a customized build to implement. More information about digital twin in supply chain can be found in the books in [15-18] and the following related journals:

- Supply Chain Analytics.
- Journal of Emerging Technologies and Innovative Research

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Figure 1 A typical digital twin [1].

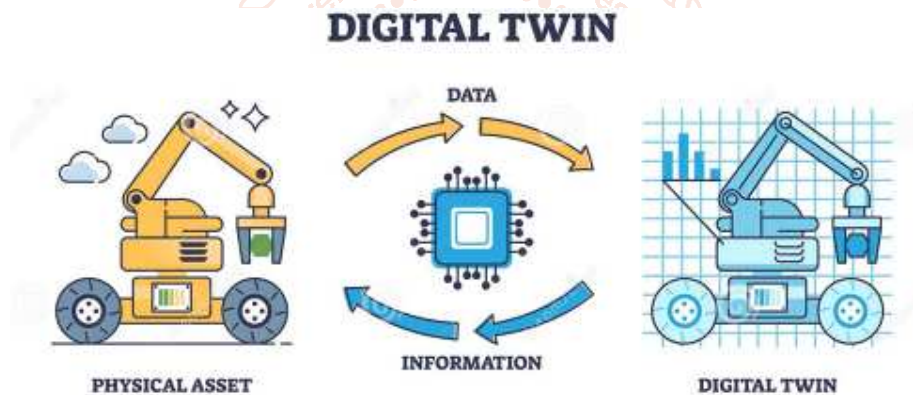


Figure 2 Conceptual model of a digital twin [2].

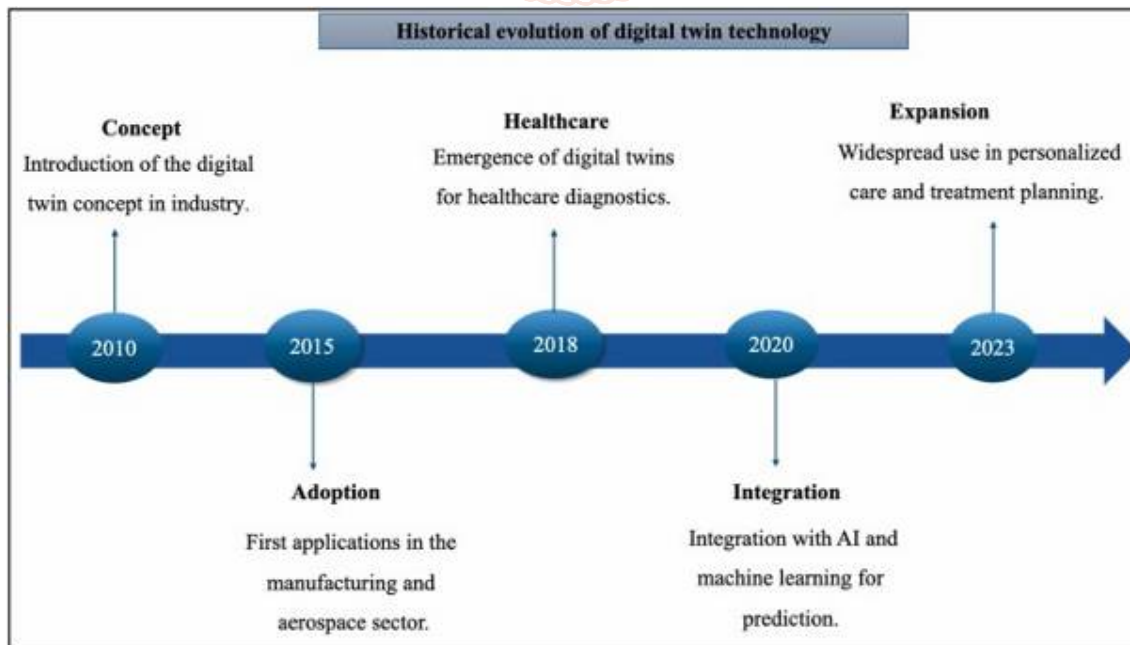


Figure 3 The historical evolution of DT technology [5].

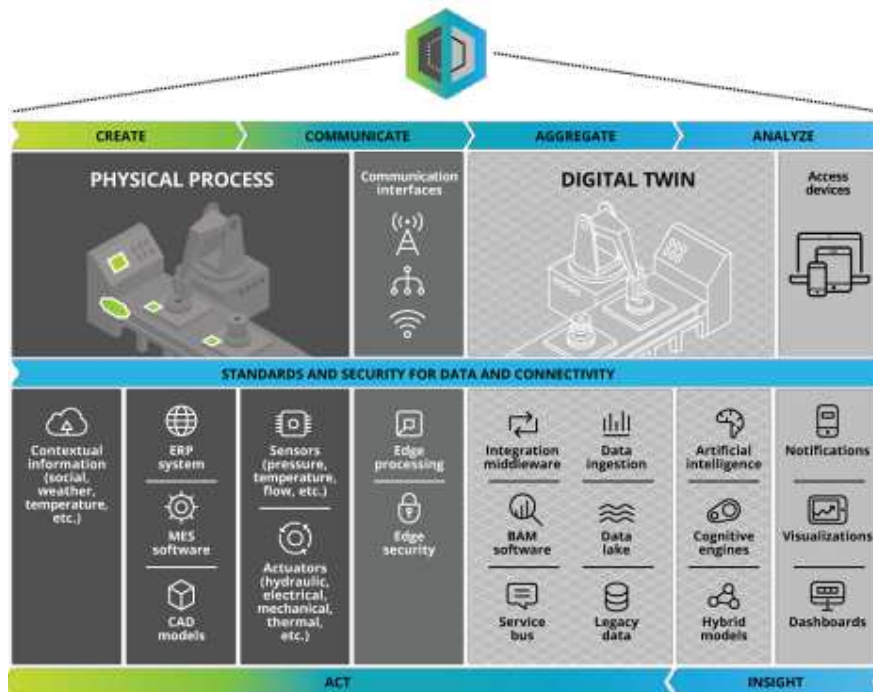


Figure 4 The digital twin conceptual architecture [6].

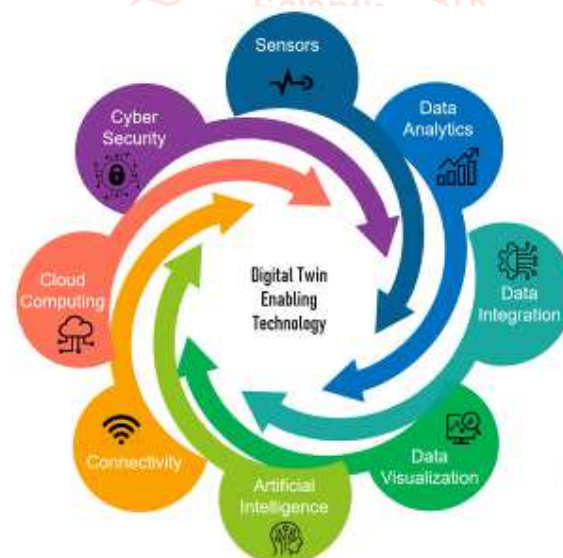


Figure 5 DT enabling technology [7].

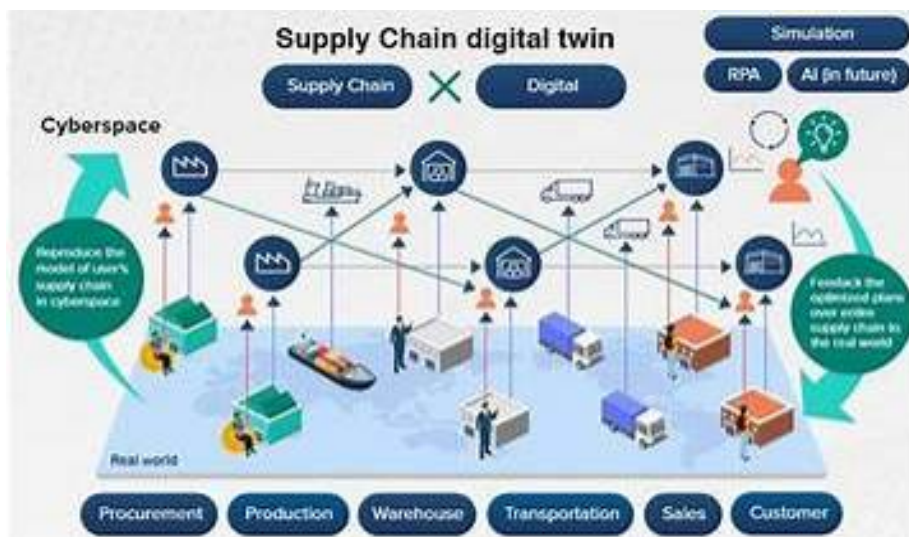


Figure 6 Digital twins in supply chain [9].



**Figure 7** Some applications of DTs in supply chain [10].



**Figure 8** A supply chain worker in a warehouse [12].