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ORIGINAL ARTICLE

The impact of digital twins on the evolution of intelligent manufacturing and Industry 4.0

Mohsen Attaran[1] · Sharmin Attaran[2] · Bilge Gokhan Celik[3]

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Abstract
As the adoption of Industry 4.0 advances and the manufacturing process becomes increasingly digital, the Digital Twin (DT) will prove invaluable for testing and simulating new parameters and design variants. DT solutions build a 3D digital replica of the physical object allowing the managers to develop better products, detect physical issues sooner, and predict outcomes more accurately. In the past few years, Digital Twins (DTs) dramatically reduced the cost of developing new manufacturing approaches, improved efficiency, reduced waste, and minimized batch-to-batch variability. This paper aims to highlight the evolution of DTs, review its enabling technologies, identify challenges and opportunities for implementing DT in Industry 4.0, and examine its range of applications in manufacturing, including smart logistics and supply chain management. The paper also highlights some real examples of the application of DT in manufacturing.

Keywords Digital twins · Digital twin · Digital twin technologies · Digital shadow · Digital model · Industry 4.0 · Digital twins challenges · Supply chain management · Smart logistics

1 Introduction

Consumer buying habits and supply chain disruptions created by the pandemic forced industries to re-evaluate their operations and incorporate robust digital platforms. For the past 15 years, consumers have increasingly embraced e-commerce and digital channels. This shift to e-commerce significantly accelerated during the pandemic (McKinsey and Company 2021). In addition, the buyers' habits changed to home ordering–a shift that industry experts forecast to be permanent. This consumer shift brought changes to supply chain disruptions—a dramatic need for increased agility and resilience in the consumer product manufacturing industries. As a result, manufacturers must incorporate robust digital platforms in a post-pandemic marketplace to maintain competitiveness, optimize their manufacturing value chain, and provide end-to-end supply chain visibility. This entails more than just optimizing current physical procedures. It requires combining digital technologies with physical goods, merging hardware and software elements. Collaboration between business and technology leaders is essential to develop organizations that are prepared for the future, fostering sustainable and lucrative client relationships.

According to a recent report, agility and flexibility were listed by 56 percent of the 3000 worldwide CEOs surveyed as their top strategic priorities (World Economic Forum 2021). They must incorporate toolsets such as cross-functional supply chain visibility and collaboration to stay competitive. They must also deploy advanced production planning to optimize plant schedules for on-time delivery, digitize and standardize best practices, and adapt to more frequent changes. According to another survey, manufacturing companies leveraging digital technologies to transform their operations have reduced costs by 5–30 percent, increased productivity by 5–40 percent, and achieved substantial agility

✉ Mohsen Attaran
mattaran@csub.edu

Sharmin Attaran
sattaran@bryant.edu

Bilge Gokhan Celik
bgcelik@rwu.edu

1 School of Business and Public Administration, California State University, Bakersfield, 9001 Stockdale Highway, Bakersfield, CA 93311-1099, USA

2 Bryant University, 1150 Douglas Pike, Smithfield, RI 02917, USA

3 School of Engineering Computing and Construction Management, Roger Williams University, One Old Ferry Road, Bristol, RI 02809, USA

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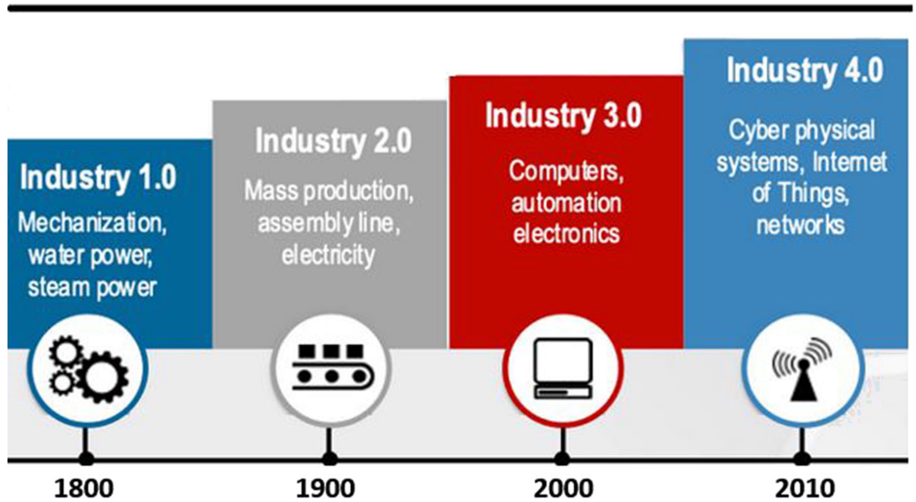

Fig. 1 Industrial evolution

and sustainability improvements (World Economic Forum 2020).

In today's world, numerous industries operate within unstable conditions and fluctuating global value chains. In addition to the widely recognized impacts of market globalization in the past decade, recent unforeseen events have added more complexity to business management and operational decision-making processes. Some notable examples of such disruptions are the post-COVID-19 pandemic, the war in Ukraine, and the effects of microchip and semiconductor shortages on various supply chains globally. As a result of these occurrences, making informed decisions to address challenges in operations and supply chains has become a more intricate managerial responsibility across several sectors. While supply chain disruptions have uncovered operational vulnerabilities, they have also presented transformative opportunities for manufacturing companies. In response to these circumstances, researchers focusing on operations and supply chain issues have devised innovative solutions grounded in supply chain coordination and data analytics science (Arpita et al. 2023; Kumar et al. 2023; Riahi et al. 2021). Furthermore, a prominent trend in empirical operations and supply chain research is related to the influence of advanced technologies on supply chains. Studies have been conducted to understand the impact of Industry 4.0 technologies on supply chain performance (Arji et al. 2023; Rad et al. 2022; Taddei et al. 2022). Meanwhile, innovative manufacturers quickly adapted during disruptions by implementing new advanced technologies, such as Digital Twins (DTs), at the core of true fourth industrial revolution innovation (World Economic Forum 2020). Industry 4.0 helped advance the usage of DTs and enabled progress and betterment in the industries that utilize DTs (Hinduja et al. 2020).

DT technology, with exceptional precision, is a critical component of an intelligent factory. The digital twin enables manufacturing companies to build better products, detect physical issues sooner, and predict outcomes more accurately. Until recently, limitations in digital technology capabilities, such as computing, storage, and bandwidth costs, hampered the broad applications of DT technology. However, significantly lower costs and more powerful computing capabilities have led to the exponential creation and use of a DT in the manufacturing industry (Mussomeli et al. 2016).

This article provides the main perspectives and definitions of DT in literature, emphasizing Industry 4.0 applications. Next, the paper reviews four enabling technologies of DTs and studies DTs applications and use cases in manufacturing, including smart logistics and supply chain management. Finally, we highlight the challenges and opportunities of this technology. A summary and a conclusion will follow. Finally, this article provides future research directions.

2 Background and definition

2.1 Industrial evolution

Smart manufacturing and Industry 4.0 are the foundation of modern industry. The First Industrial Revolution (Industry 1.0) was characterized by the transition from manual labor to mechanized production, driven by the invention of steam engines and the use of water and steam power. The Second Industrial Revolution saw the emergence of mass production and assembly lines. The Third Industrial Revolution marked the introduction of computerization and automation in manufacturing processes. Industry 4.0 differentiates itself by the interconnectedness and real-time data exchange between machines, systems, and humans, enabling highly flexible and efficient production processes (Fig. 1). This revolution focuses on harnessing data to optimize operations, predict equipment failures, and adapt to rapidly changing market demands.

Industry 4.0 aims to create a network that addresses the interoperability issues within and across all levels of an automated factory—improving the flexibility and agility of conventional manufacturing. Industry 4.0 is the advancement and integration of digital technologies, such as the Internet of Things (IoT), artificial intelligence (AI), machine learning, big data analytics, robotics, additive manufacturing, and DTs (Tao et al. 2018b; Scharl and Praktiknjo 2019). As Industry 4.0 continues to evolve; the above key trends and technologies are shaping the future of manufacturing and production, creating more efficient, flexible, and sustainable processes. These technologies enable increased automation, improved efficiency, and enhanced communication between machines, systems, and humans in the manufacturing and production sectors.

DT provides a digital replica of a physical entity. The basis of DT is the infrastructure and data. Its core is the algorithm and model, and its application is the software and service. By simulating real-world conditions and monitoring performance, digital twins can be used to optimize operations, predict equipment failures, and test new designs or production strategies without disrupting existing processes.

2.2 Origin and concept of DT

The concept of the DT dates back to 2003 when Professor Grieves of the University of Michigan introduced the idea in a total product lifecycle management course. It is also known as a digital mirror and digital mapping. Since then, many scholars have provided varied definitions of this technology and discussed various stages of digital twin development (Fuller et al. 2020; Stark and Damerau 2019; Kritzinger et al. 2018; Tao et al. 2018a). In general, the digital twin is defined as "virtual representations of physical objects across life cycle that can be understood, learned, and reasoned with real-time data, or "... a virtual representation of the physical configurations and the dynamic modeling of product, process, and resource changes during manufacturing..." (ISO/DIS 2020).

Even though DT got notability in the recent past, its existence is dated back to the 1960s. In 1970, NASA engineers used the first DT—a simulator, a twin of the command module, and a separate twin of the module's electrical system to remedy and save Apollo 13. NASA engineers completed the process in under two hours and saved the lives of the three astronauts on board (Uri 2020). Since then, NASA has been using DT solutions to develop next-generation vehicles and aircraft.

The application of DT has grown fast in recent years. According to Gartner, by 2021, half of the large industrial firms to use DTs in crucial business applications (Panetta 2016). DT's rapidly growing market suggests that demand will continue to escalate in the immediate future (Botín-Sanabria et al. 2022; Martínez-Olvera et al. 2022). A recent market analysis predicts that DT's market share will increase by $24.8 billion from 2020 to 2025. That growth will accelerate at a compound annual growth rate of 39.5 percent. The same study identified major market vendors, including General Electric, Honeywell, IBM, Microsoft, Oracle, etc. (Technavio 2022).

2.3 DT Vs. digital shadow and digital model

DT differs from Digital Shadow (DS) and Digital Model (DM). These three technologies are differentiated based on their data flow architectures and intended uses. Among the three, DT is the most capable one (Fig. 1). A DM is a virtual 3D representation of an object or a product that can be used for simulation and analysis. The digital model is a copy of the physical object with no automated data exchange between the physical world and the model. DS is based on scanned laser data, a virtual model representing the physical model only, with one-way data flow and no automated data exchange between the physical world and the model. DS is created for specific use at various times and can enhance the digital model by synchronizing it with the real world. It is mostly used after the design is completed in Industry 4.0, and it may not be a complete' representation of the entire system. DS can exist simultaneously and are produced using casting software or laser scans of physical objects (Wohlfeld et al. 2017; Bauernhansl et al. 2018; Riesener et al. 2019).

On the other hand, in a DT, both the virtual and physical entities communicate (Sepasgozar 2021) (Fig. 2). The DT is a complete virtual representation of the object or system where data flows from the system to the twin and from the twin to the system. To trigger actions on the manufacturing floor, a functioning DT allows for two-way data transmission where it receives data from the factory floor. It may also transmit data back to the factory floor. A wide range of manufacturing industries is using these three technologies. DM is helpful for industrial design and concept development. DS is a powerful technology for tracking production, and a DT is a beneficial tool for evaluating real-time manufacturing. These three technologies are powerful tools for continuously analyzing industrial processes, remote monitoring throughout manufacturing, and on-time decision-making. This results in faster production time, less waste, and more significant revenue.

2.4 DT Vs. previous simulation software

While DT shares similarities with other simulation software, such as fluid simulation software, mechanical calculation software, and computer-aided design (CAD) software, there

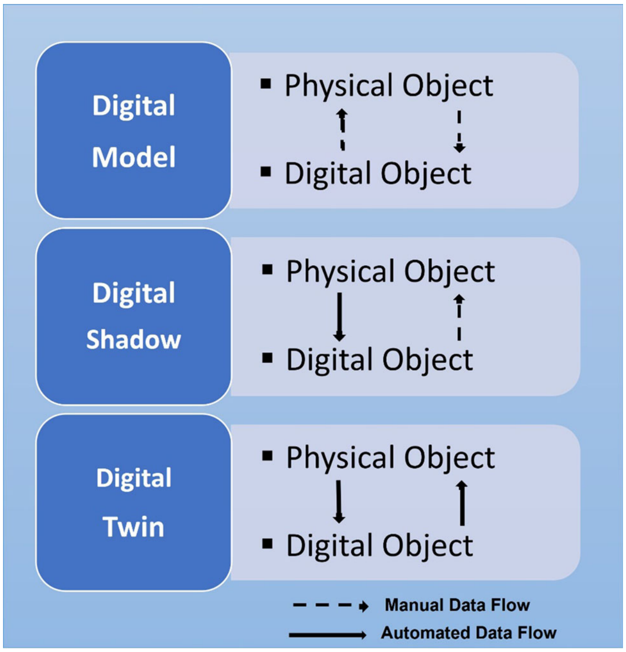

Fig. 2 Comparison of three models and their data flow

are several differences and advantages that set it apart. For example, while other simulation software typically relies on static data or predefined input parameters, DT technology incorporates real-time data from IoT devices, sensors, and other data sources to continuously update the virtual model. Additionally, whereas traditional simulation software mainly focuses on analyzing current or past performance, DT leverages advanced analytics, machine learning, and AI to predict and optimize future performance. Furthermore, DT technology spans an asset's entire lifecycle, from design and development to operation and maintenance, while other simulation software may be limited to a particular stage, such as design or analysis. Finally, while other simulation software may only focus on specific aspects or domains, DT solutions offer a comprehensive view of the asset, system, or process they are modeling.

3 Key enabling technologies

Industry 4.0 combines technologies such as Big Data, the Internet of Things (IoT), Cloud, and DT to create an efficient network for two-way data transmission between physical and digital objects. In addition, data digitization and analysis are used to improve and increase automation flexibility, manufacturing efficiency, and productivity ((Kenett et al. 2020).

DT brings IoT, cloud computing, artificial intelligence, advanced visualization tools, and other relevant technologies together to provide a unique, virtual representation of a physical object that monitors and simulates the object's physical state and behavior (Fig. 3). A digital twin differs from computer-aided design (CAD) and Internet of Things (IoT) solutions; it is much more than either. DT interacts with real-world physical production equipment, enhancing the digitalization capabilities of computer-aided design, or CAD. As a result, DT solutions can promise richer models with more realistic and holistic measurements of unpredictability.

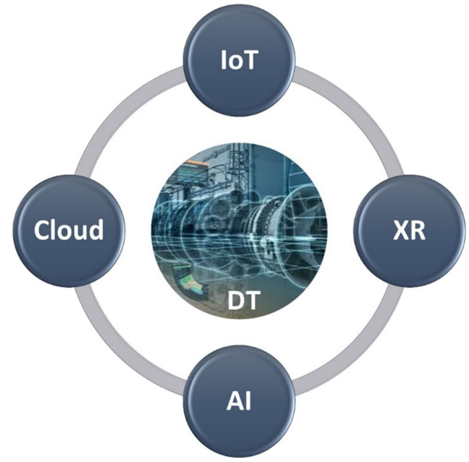

Fig. 3 Technologies of DT

The following section describes enabling technologies of DTs. These technologies constantly evolve, making creating and using DTs across various industries easier. Figure 3 depicts how different technologies of DT work together to link the physical and digital worlds.

1. *Internet of Things (IoT)*: IoT describes the network of physical objects, "things" embedded with sensors, and other technologies for connecting with other devices over the internet. (Attaran 2017). IoT is DT's primary technology in every application. It is predicted that by 2027, more than 90 percent of all IoT platforms will have DT capability and that DT will be a standard IoT feature (Researchandmarkets 2022). Industry 4.0 digitizes manufacturing by Combining IoT, AI, DT, and robotics. IoT continuously updates data and increases the volume of data usable in manufacturing environments. IoT helps create flexible and connected digital factories and facilitates communication between all system parts. The IoT sensors capture data that will be used to build the model and identify the current state of the process. DT uses data collected and transmitted by IoT to create a digital representation of a physical object. The digital version can then be analyzed, manipulated, and optimized for several manufacturing process developments, including predictive maintenance and fault detection, to name a few (Mandolla et al. 2019). Implementation of IoT with DT technology in Industry 4.0 provides better visibility of

the operations of the equipment, proper predictive maintenance, and better analysis of the behavior of a specific machine or a collection of devices (Oracle 2021).

2. *Cloud computing*: A vital benefit of the Industry 4.0 is real-time data collection by IoT sensors on all factory assets. This data collected continuously and transmitted can provide critical insights into factory performance. They can also get utilized in making production, inventory control, or forecasting decisions. Cloud computing offers hosted services and help manufacturers efficiently store and access data over the Internet (Attaran 2017). Cloud computing converts data generated by IoT from all systems into helpful information and can provide visualization and correlation analysis. In addition, advanced analytics could help the complicated manufacturing process. Cloud computing offers DTs continuous data collection, storage, data computing and analysis, reduced computation time, and easy and 24/7 access to data and information from any location (Shu et al. 2016). Additionally, Cloud computing provides DT with analytics techniques to produce insights. Cloud technologies empower DT to provide new functionality and facilitate real-time collaboration across the manufacturing space. Several companies, including Microsoft, offer cloud capabilities in their end-to-end solutions. Examples are Microsoft Azure Big Compute portfolio, Microsoft HoloLens, Microsoft Azure IoT, and Azure Cortana Intelligence. These cloud-based solutions offer complete capabilities, enabling manufacturers to deploy DTs quickly and realize the powerful results DTs can deliver (Microsoft 2018).
3. *Artificial intelligence (AI)*: Artificial intelligence (AI) and DTs technologies have grown in recent years and are critical enablers for Industry 4.0. AI mimics the basis of intelligence and seeks to calculate the impact of changes and an optimum range for parameters (Brune 2016). AI can assist DTs by providing an advanced analytical tool for analyzing obtained data and providing valuable insights. This stream of data and advanced analytics helps decode complicated manufacturing processes and systems, making predictions about outcomes and suggesting how to avoid potential problems (Lv and Xie 2021). Huang et al. (2021) provided a comprehensive review of over 300 manuscripts on AI-driven DT technologies of Industry 4.0. They discussed the advantages of AI-driven DTs in sustainable development and elaborated on the Practical challenges and development prospects of AI-driven DTs.
4. *Extended reality (XR)*: XR is a general term used to describe immersive technologies like Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). These technologies can merge the physical and virtual worlds and extend the reality we experience (Marr 2019). DT technology utilizes essential data to create a digital model of the physical objects and provide actionable insights within the product or process. It is equally important and helpful to visualize the data. VR technology, combined with DT solutions, allows manufacturers the ability to immerse themselves and fully understand data, providing necessary solutions. As an essential tool of Industry 4.0, IoT continuously collects data from these devices. DT solutions digitize and analyze these data. VR and AR provide connected workers with opportunities to visualize, spot areas of concern, reduce errors, and save time. VR and AR complement the benefits provided by DT and give a sense of reality to digital data (Geng et al. 2022).

4 DTs applications in supply chain management and smart logistics

The COVID-19 pandemic affected the manufacturing sector with unprecedented conditions, including social distancing and supply chain disruptions. According to a McKinsey report, these conditions greatly affected factories and warehouses, and the world suffered supply chain disruptions. Therefore, Supply chain cost reduction is considered critical. The disruptions demanded a move towards more innovative logistics management. Moreover, according to the same report, the supply chain landscape is filled with disruptions and risks—geopolitical situations are less stable than in the past decades, and climate crises are more frequent and intense, causing more supply chain interruptions. The COVID-19 pandemic is not the last global health crisis we face. Therefore, companies must embrace building dynamic and more resilient supply chains and more innovative logistics management (Alicke et al. 2021).

According to a recent report published in Fortune, COVID-19 changed supply chains forever. Many companies have been rethinking their supply chains and implementing changes to make them more resilient. Three major shifts are identified—changes significantly affecting business and consumers (Sanders 2023). The first one is reshoring—the process of bringing supply chains home to reduce reliance on one country or region and reduce the risk of disruptions. The second shift is investing in more technology. Poor technology resulted in companies not having proper visibility across the supply chains, making it difficult to anticipate shortages. Modern digital technologies such as AI, IoT, and DT are key to making this happen. The third shift is the movement toward the Just-in-Case model (and away from Just-in-Time), where companies carry more inventory, making it less likely to experience shortages (Sanders 2023).

Table 1 Potential DT use case in supply chain and smart logistics

Potential use cases	Benefits gained
Supply chain management	Help discover bottlenecks Optimize supply chain design changes and development Improve understanding of supply chain dynamics and behavior Improve testing of supply chain design changes and development Help optimize just-in-time or just-in-sequence production Help improve product inception, development, and distribution Help create contingency plans and figure out how much safety stock you might need Determining the future availability of resources to calculate the approximate timeframe of deliveries Help boost decision-making amid procurement chaos Help stress-test the supply chain before the problems manifest Recognize long-lead-time and impact on supply chain Improve monitoring of risk and testing contingencies Optimize transportation and inventory planning Improve forecasting and testing operations over the coming days and weeks Improve cash-to-serve and cost-to-serve analysis
Smart logistics	Solve logistics challenges, including packaging performance, fleet management, and route efficiency Help identify alternate transportation/logistics routes Optimize warehouse design and create a logistic network Optimizing transportation routes to help reduce carbon emissions Help logistics companies to optimize the transport load Helps air transport companies to enhance quality control

4.1 Supply chain management

Gartner believes that DT technology enables companies to successfully transition from a steady-state supply chain to an agile one that evolves and adapts to changes at an exponential pace. DT technology aims to make supply chains more efficient, effective, agile, and resilient. (Tichon 2021). Table 1 highlights potential use cases of DT solutions in supply chain management and smart logistics. The following sections review applications of DT solutions in supply chain and smart logistics.

4.1.1 Building a dynamic supply chain

A Supply Chain DT uses real-time data and snapshots to provide a detailed simulation model of an actual supply chain. Engineers can use the digital model to understand the behavior of a supply chain, test scenarios, model different nodes, modes, flows, and policies, uncover abnormalities and take corrective action. As a result, DT provides greater visibility across the supply chain, helps engineers identify patterns, discover opportunities for improvement, eliminate inefficiencies, and optimize current processes (Moshood et al. 2021). Many supply chain leaders have already embraced DT technology to stress test their supply chain design and to help them build a supply chain that can not only withstand setbacks but also bounce back quickly after disruptive events such as COVID-19. For example, DT solutions helped companies make informed decisions in a seemingly chaotic business environment during the COVID-19 pandemic (Tichon 2021).

4.1.2 Predictive maintenance

DT can be used to monitor the performance of machinery and predict when maintenance is needed, therefore helping avoid unexpected downtime and reducing the risk of supply chain disruptions (Tao et al. 2018b). DT solutions enable manufacturers to make smarter, faster, data-driven decisions when something goes wrong. DT solutions provide the digital representation of a supply chain where it surfaces all the hidden rocks in the company's supply chain. Companies can use it like a flight simulator and stress-test their supply chain before the problems manifest Xu et al. 2019).

4.1.3 Risk management

DT provides greater visibility across the supply chain, helps engineers identify patterns, discover opportunities for improvement, eliminate inefficiencies, and optimize current processes. Engineers can use DT solutions to simulate the entire supply chain and model different scenarios to assess the potential impact of disruptions, such as transportation delays or natural disasters. These disruptions can be costly and damage brand reputation. Mitigating potential risks in advance can reduce the impact of disruptions and maintain business continuity (Wainewright 2022).

4.1.4 Improved collaboration

In recent years, various studies have explored the numerous benefits of fostering coordination and collaboration within sustainable supply chains. These advantages include improved efficiency, reduced environmental impact, increased cost savings, enhanced innovation, and strengthened stakeholder relationships (Arpit et al. 2023; Totan et al. 2022). Collaboration and coordination can spur innovation as companies collectively identify new sustainable materials, technologies, and processes to improve their supply chains. This collaboration often leads to the developing of novel solutions that can be mutually beneficial.

DT offers different stakeholders in the supply chain, including suppliers, manufacturers, distributors, and retailers, a powerful tool for collaboration. The technology provides a shared platform for data sharing and communication and can help improve transparency, reduce miscommunication, and facilitate faster decision-making. Overall, the technology enhances collaboration and increases the efficiency and effectiveness of stakeholders' supply chain management (Tao et al. 2018a).

4.2 Logistics management

Factories can use DT solutions in many logistics and supply chain management areas. For example, DT can help improve the accuracy and efficiency of logistics and supply chain management, from inventory, material handling, transportation and shipping, fleet management, and route efficiency (Blomkvist et al. 2020). DT can help manufacturers anticipate disruptions, create contingency plans, figure out the optimum safety stock, identify optimum transportation/logistics routes, and help the organization build a more resilient supply chain.

4.2.1 Smart logistics

DT solutions can help manufacturers to move towards smarter supply chain and logistics management by optimizing just-in-time or just-in-sequence production and analyzing distribution routes (Blomkvist et al. 2020). Other vital phases of supply chain management, including product inception, product development, and product distribution, can also benefit from DT solutions (Moshood et al. 2021). The technology also helps logistics companies to test warehouse layouts to optimize operational performance. General Electric uses DT at its Nevada facility to improve supply chain and factory processes (Deloitte 2017). The use of DT solutions helps air transport companies to enhance quality control of the condition of the transport units and their overall safety in various scenarios and environmental conditions (Miskinis 2019). Finally, DT technology helps logistics companies to assess the exact cargo weight in real-time, optimize the transport load and thus avoid underperformance. For example, according to a recent test on the aircraft's weight load optimization, the DT solution found that the total load weight can be increased by 23% from standard weight limits imposed on flight operations (Miskinis 2019).

Logistics applications of DT technology are highlighted in a recent report by DHL. The report discusses various applications of the technology in logistics along the entire value chain, including managing container fleets, monitoring shipments, and designing logistics systems. Furthermore, the report recommends DT for individual assets, networks, and ecosystems such as warehouses. Finally, the report invites partners and customers to explore DT's potential in logistics (DHL 2019).

4.2.2 Reducing carbon emission

Another great benefit of a DT of the supply chain is optimizing transportation routes to help companies take action on reducing carbon emissions. Without DT solutions, companies had to slice their supply chain into segments and optimize within functional areas of manufacturing, distribution, sourcing, etc. As a result, they had limited visibility across the supply chain as a whole. DT of the supply chain provides an end-to-end view of the various elements and enables companies to optimize and stress-test their supply chain before the problems manifest. This supply chain optimization can be planning a new production facility, adjusting the daily vehicle route plan, or adjusting the product mix to optimize profitability or reduce carbon emissions. In addition, DT solutions can help companies find optimal outcomes by analyzing different parameters, including availability, margins, sustainability goals, etc. (Wainewright 2022). The distribution represents an obvious starting point when seeking to reduce emissions.

Several companies have used DT supply chain modeling to reduce carbon emissions through network optimization. As a result, these companies optimize their supply chains around their carbon footprint. For example, Nestle used DT technology, reconfigured its distribution networks in Mexico, North America, and China, and lowered costs and emissions. In another example, Microsoft used DT solutions to optimize its supply chain, save money and reduce emissions by moving certain components from air freight to ocean shipment. The saving from switching to sea freight was more than the cost of adding extra stock in inventory as a buffer. Moreover, the company optimized its supply chain and reduced its carbon footprint. Overall, Microsoft enjoyed 10% savings in cost and carbon footprint (Wainewright 2022).

5 DTs potential applications in different manufacturing process

Industry 4.0 and digital factories are creating new opportunities and possibilities for the manufacturing industry and are the future of manufacturing. Many of the technologies used in smart factories are constantly improving; therefore, manufacturers must plan and strategize technology adoption to stay competitive. Today, engineering and manufacturing predominantly use DT to provide accurate virtual representations of objects and simulations of operational processes (Ding et al. 2019; Park et al. 2020). DT applications in manufacturing automation and supply chain management, especially DT' role in product and process design, smart logistics management, predictive maintenance, asset visualization, and design customization, are reviewed in related publications (Chiara et al. 2019; Geng et al. 2022; Qiao et al. 2019; Warke et al. 2021; Qi and Tao, 2018). Likewise, other significant advantages of DT are the quick assessment and analysis of reconfiguration changes in production, performance prediction, and improved efficiency (Zhang et al. 2019b; Rodionov and Tatarnikova 2021). In addition, DT solutions can be utilized to address sustainability challenges (Martinez et al. 2021). Another study discussed how DT could be utilized to optimize assembly lines (Bilberg and Malik 2019).

The best aspect of DT technology is its range of applications. DT works on the factory floor to assist in monitoring and controlling physical assets with virtual objects (Tekinerdogan and Verdouw 2020). Industry 4.0 enabled technological advancements in sensing, monitoring, and decision-making tools, creating new opportunities and possibilities for the manufacturing industry. These advancements helped implement DT technology for the real-time monitoring and optimization of the process (Qiao et al. 2019; Qi and Tao 2018). As a result, the DT may enable manufacturing companies to solve product issues faster by detecting them sooner, designing and building better products, predict outcomes with higher accuracy (Deloitte University Press 2017). Table 2 highlights potential use cases and benefits of implementing DT in the Industry—the following sections review applications of DT solutions in different areas of the manufacturing process.

5.1 Product design and development

Product design is the lifeblood of any business since introducing new products or services can impact the organization. Good product design has strategic implications for the success of an organization. DT technology enables fundamental design and process changes by providing a virtual replica of a manufacturing asset. This digital model collects data and can be used to create, build, test, and validate predictive analytics and automation. The digital model also helps to provide brand consistency and evolution for products and processes until the end of a product's lifespan. Designers can use the virtual model generated by DTs to test different designs before investing in a solid prototype (Schleich et al. 2017). DT helps to reduce the number of prototypes, save time, and reduces costs. Finally, engineers can use data collected over time by DT solutions to improve customer expectations regarding product quality, customization, and ease of use (Tekinerdogan and Verdouw 2020).

5.2 Process design and optimization

DT helps manufacturers observe processes under multiple performance conditions and eliminate problems before they occur. The DT represents a replica of a manufacturing process in the physical world, what is happening on the factory floor, and its companion twin in the digital world. The digital model enables manufacturers to move from reactive to predictive and helps turn existing assets into tools that optimize processes, save money, and accelerate innovation (Schleich et al. 2017). The DT solutions enable a continuous analysis of incoming data over a period. The results may uncover unacceptable trends in the actual performance of the manufacturing process compared with an ideal range of tolerable performance.

5.3 Quality control and predictive maintenance

Maintenance is a high cost for any operation. The traditional approach to regular maintenance is costly, inefficient, and increases the risk of the breakage and wear of machine tools. Preventive maintenance improves plant efficiency. According to a recent report, predictive maintenance can reduce downtime by 50 percent and cost by 10–40 percent (McKinsey Report 2015). Predictive maintenance systems rely on IoT for real-time information about each asset. Based on the data, the system predicts the time for asset maintenance (Kang et al. 2021). Manufacturing plants have interconnected systems where changes in Load, process, and design at one location can affect the entire plant. DT-based predictive maintenance finds excellent use in such cases. DT solutions use data collected from assets around the plant and model individual equipment or manufacturing processes to predict the need for preventive repairs or maintenance (Tao et al. 2018b). This would prevent costly failure before a serious problem occurs. Smart maintenance management systems with DTs, IoT, AI, and ML can consider the effects of various systems on manufacturing to estimate, predict, detect, or diagnose and make better accurate predictions with time. This smart maintenance management system can also determine if better materials or processes can be utilized or help optimize cycle times, load levels, and tool calibration (Dinter et al. 2022).

Table 2 Potential use case and specific business values

Potential use cases	Benefits gained
Product design	Improve product design and engineering change Improve equipment performance Reduce the number of prototypes, save time, and reduce cost Improve customer expectations regarding quality Identify products that are ready for the upgrade Predict the end of life of the product
Process design	Reduce process variability Help turn existing assets into tools that optimize processes and accelerate innovation Help observe processes under different conditions and eliminate problems before they occur Help identify bottlenecks
Production planning & control	Reduce the overall cost of producing a new product Reduce time to market for a new product Improve Product tracking and monitoring Facilitate Energy consumption analysis
Facility and asset management	Assist in viewing what is happening on the factory floor Identify quality and safety problems, monitor machine capacity, and make necessary changes Give real-time status on machine performance
Innovative process	Gaining big-picture visibility Help reimagine innovation processes Help strategizes for many possible futures Share designs, information, and insights easily across ecosystems
Preventive maintenance	Facilitate maintenance repair operations Help with product tracking and monitoring Facilitate product failure analysis and prediction
Empowerment and collaboration	Makes information more readily accessible to workers Help with education and research Incentivizes curiosity and encourages innovation Allow multi-disciplinary teams to collaborate on projects seamlessly
Warranty and services	Help understand equipment configuration for more efficient service More accurately determine warranty and claim issues Help reduce overall warranty cost and improve customer experience Improve efficiency and cost to service product Help better manage recalls and warranty claims
Quality control	Improve overall quality and detect defects sooner Improve reliability and performance Determine when quality issues started Help improve diagnostics and preventive maintenance

Finally, DT can diagnose the fault in a smart manufacturing environment (Xu et al. 2019). The digital factories of tomorrow will find smart maintenance management systems inevitable to stay competitive.

5.4 Empowerment and cross-functional collaboration

Advances in big data, analytics, AR and VR, and mobile applications enable manufacturers to empower operators and decision-makers to make sense of operational data. DTs collect operational data transmitted by IoT over time to provide insights into product performance and end-user experience. In turn, engineering, production, sales, and marketing employees can share this information to make more informed decisions (Tao et al. 2018a). In addition, DTs transformation makes information more readily accessible to workers by connecting them to plant processes, real-time data, and one another. As a result, the solution incentivizes curiosity and encourages innovation. Finally, the technology provides everyone with the same information simultaneously, allowing multi-disciplinary teams to collaborate on projects seamlessly, thereby improving efficiency and agility in tandem.

5.5 Facility and asset management

Applications of DT have found use in complex industries, with large numbers of facilities to overview all equipment and find it promptly when needed. DT uses the IoT sensors embedded in all equipment that constantly transmit data to the DT system, revealing the current location of assets. DTs, in conjunction with virtual reality (VR) glasses, can assist facility and operations managers in viewing what is happening on the factory floor at any given time and identify which production adjustments are needed. Using DT technology, operations managers can identify quality and safety problems, monitor machine capacity, and make necessary changes (Zhang et al. 2019a). Siemens is a German industrial manufacturing company that uses DT solution to enable informed decision-making concerning a deployed fleet of gas turbines. DT relies on vast amounts of available data to integrate customers, supply chain, production, and maintenance to improve productivity and efficiency in customer operations and asset management. The technology captures turbine performance, repair, and overhaul capacity, and spares inventory from the real world. It feeds the information into its dynamic simulation model to enable informed decision-making concerning a deployed fleet of gas turbines. Engineers can run what-if analyses and quickly identify bottlenecks and the state of the system's operation (Anylogic 2022).

5.6 Production planning and control

Manufacturers can use digital tools to optimize production scheduling, accommodate real-time operational planning cycles, and improve flexibility when re-planning critical orders (Tao et al. 2018b). DT solutions may optimize the production schedule to deliver business-critical orders, on time and in full, at the lowest possible cost. The technology also offers advanced planning and scheduling capabilities allowing for optimizing the production schedule around business drivers like material, equipment, and labor availability. Finally, DT solutions are vital for aligning people, equipment, and operational processes for efficient and compliant work execution and continuous improvement (Rosen et al. 2015). Black and Decker utilizes DT technology in some of its business operations to create digital replicas of entire assembly lines of its factories to improve operations and increase the efficiency of its production (Ikimi 2020).

5.7 Training and education

Education and training are vital for the manufacturing industry for several reasons, including improved safety, increased efficiency, adapting to new technology, cost saving, etc. Education and training improve employee knowledge and skills and reduces the likelihood of accidents and injuries. Trained workers are more efficient in their tasks and can use new technology efficiently, enhancing productivity and quality. DT can be used to educate and train employees about equipment and the manufacturing process. DT provides a virtual digital environment that can be used to train employees to ensure they are up to date with the latest technologies and can use them efficiently. In conjunction with VR, DT can be used for safety and emergency training scenarios, including off-site safety training (Kaarlela et al. 2020). Educated workers are more likely to understand how to optimize the manufacturing process and are less likely to make mistakes, leading to improved quality and productivity.

6 DTs use cases in manufacturing

Advancements in Industry 4.0 and the availability of technical resources have enabled many large manufacturing companies to utilize the benefits of DTs in multiple domains. Below are a few examples of manufacturing companies leveraging DT technology to improve operations and stay competitive in a rapidly changing industry.

6.1 Automotive industry

Intense competition among auto manufacturers for introducing advanced and innovative cars encourages them to invest in advanced information and communications technologies. This time around, it is technologies like DTs. Automobile manufacturers use interactive automobile dashboards on websites to improve customer engagement by allowing customers to customize vehicles conveniently. The information obtained monitors consumer behavior and helps manufacturers to modify or change existing models (Grand View Research, 2022). DT solutions are implemented on various aspects of intelligent vehicles to explore their potential, opportunities, and challenges (Bhatti et al. 2021). DT solutions have great potential in the electric vehicles (EV) industry (Ibrahim et al. 2022). DT can be used for the prediction of the energy consumption of EVs (Zhang et al. 2021; Han et al. 2022). Using IoT sensors installed in the EV, DT exchange data with the IoT provides information for testing every aspect of the vehicles, including road testing and vehicle maintenance, and help automakers ensure unexpected damage and injuries are prevented. The manufacturer uses the data gathered to digitally record the car's working condition. The information gathered help detects potential problems at an early stage before they evolve to avoid possible repairs.

There are several examples of applications of DT solutions in the auto industry. For example, Tesla uses the DT of engines or car parts for simulation and data analysis to improve testing accuracy for predicting components' current and future performance. Real-time Tesla Motors mechanical issues are being fixed by downloading over-the-air software updates (Longo et al. 2019). Maserati is using DT technologies to accelerate product design. DT helps the automaker reduce the number of expensive, real-world prototypes required and the need to launch physical wind tunnel tests and test drives. As a result, the company reduced vehicle development time by 30 percent (Bhatti et al. 2021). Mercedes-Benz uses DT solutions and simulates the entire production process from the first design stages to the final assembly to optimize the production of their vehicles. Likewise, Ford uses DT technology to optimize their vehicles' design and performance, reducing maintenance costs and downtime (Bhatti et al. 2021).

6.2 Aviation industry

The aerospace industry widely uses DT solutions for tracking, weight monitoring, aircraft maintenance, defect detection, measurement of flight time, and an accurate stipulation of weather conditions (Xiong and Wang 2022). In a recent survey, 75 percent of air force executives favored DT technology and believed that DT technology would help overcome many challenges in the aerospace industry. Most of these executives successfully use DT solutions for existing and new products, while others use the solutions for temporary aircraft testing. It is estimated that DT of an aircraft would allow for increased accurate tracking by 147 percent. (Miskinis 2019). Another recent study reviewed the application of DTs and Blockchain to optimize the aircraft manufacturing industry and provide a comprehensive and predictive. DT solutions enable engineers to operate effectively, reducing testing costs and maintaining and repairing aircraft when they aren't within physical proximity (Mandolla et al. 2019). DT solutions create a virtual model that emulates the real-time functioning of a spacecraft. The simulation of real-time data can help to optimize the designing and planning of the spaceship, save up costs in research and development, and play an essential role in the safety of the spacecraft (Hinduja et al. 2020). Moreover, DT technology will allow aircraft engineers to be more productive in executing new model tests providing more pleasant and safe travel for commercial travelers. Finally, DT's solution creates a virtual model that emulates the real-time functioning of a spacecraft. DT of an aircraft or a rocket ship would allow for tracking aircraft worldwide with high accuracy. In a recent survey, three-fourth of air force executives favored DT solutions for their industry (Miskinis 2019).

General Electric (GE) created a DT to monitor and improve the maintenance of an aircraft engine blade of the most powerful engine that flies on the long-range Boeing 777 aircraft. DT solutions can help GE better predict how a blade will degrade over time and perform maintenance before a problem occurs (GE Research 2022). Boeing uses DTs solutions in its commercial and military airplanes to improve the safety of the parts and systems and has achieved a 40 percent improvement in the quality (Woodrow 2018). Northrop Grumman uses DT solutions for the assembly line for the F-35 fighters to improve manufacturing efficiency and reduce cost (Tao et al. 2019). Royal NLR, an aircraft manufacturing company, uses DT solutions for composite components and human–machine interactions. The objective is to optimize production and make it more efficient and greener. DT technology gives the company new understandings during the production of composite parts and helps engineers optimize the production processes (Baalbergen 2021). Finally, AmVac, the most prominent industry leader in agriculture, utilizes DT solutions to increase the effectiveness of the aircraft they actively use to monitor commercial crop fields. As a result, the company managed to constantly monitor the machine's overall health, reduce maintenance costs and improve the durability of the aircraft part (Miskinis 2019).

6.3 Steel industry

DTs can effectively test the designs and compositions of the end products where a virtual copy of the real-world project is subjected to a wide range of conditions to confirm the durability and sustainability of the output (Hinduja et al. 2020). Similarly, a DT of the product can be simulated to test the rusting problem in different weather conditions with varying alloy compositions to arrive at the most suitable product. Moreover, DTs can be used to test the benefits of utilizing certain metals in steel alloys for kitchenware, making it more appealing to customers. DT simulations can provide a perfect solution for experimenting with multiple ratios of carbon in steel to arrive at suitable products. In addition to understanding the strength of the materials, DTs can also assist in determining the optimal number of materials to be used (Hinduja et al. 2020).

7 DTs drivers and challenges

COVID-19 exacerbated the shortage of skilled workers in the manufacturing industry. Manufacturers combat that problem by using digital tools to endure that institutional knowledge can be retained. Digitalizing work processes enable manufacturers to connect workers to instructions and efficiently collect data. A manufacturer may use DT solutions as a part of their digitization strategy to ensure execution follows scheduled product, work process, and quality specifications.

7.1 Opportunities and drivers

An essential key factor driving DT growth is industry 4.0 and IoT. Industry 4.0 introduces innovative production methodologies where DT technology is at the center that embraces automation, real-time data exchange, and smart manufacturing processes (Technavio 2022). Moreover, industry leaders and manufacturers invest heavily in developing DT technology. Similarly, growth in DT's enabler technologies of AI, IoT, and IIoT has facilitated the applications of DT in the manufacturing industry. In addition, decreasing costs of technologies that enhance IoT and DT solutions contribute to the current application acceleration. Therefore, the technology is predicted to expand to more use cases and applications. The incredible potential of 5G in terms of speed, latency, and accuracy is another driver for DT technology's acceleration. In addition, 5G technology facilitates DT solutions in providing an emulated replica of the physical asset that allows for continuous testing, prototyping, and optimization of the physical asset. Finally, cloud-based Digital Twin platforms, offered by Google Cloud and Microsoft Azure, provide easy accessibility and customized solutions. For example, the supply chain Digital Twin platform launched by Google Cloud in January 2022 provides the manufacturing industry with visibility of operations occurring in their supply chains (Grand View Research 2021).

7.2 Challenges to implementation

As discussed in this article, DT technology has many advantages; however, the technology currently faces shared challenges in parallel with AI and IoT technology. Those include data standardization, data management, and data security, as well as barriers to its implementation and legacy system transformation (Technovio 2022). DT solutions use data from different sources, including IoT sensors, CAD models, historical data, and real-time data stored in other systems and various formats. Integrating all of this data into a single model can be a complex and challenging process. Any data inaccuracies can compromise the effectiveness of the DT solutions. Ensuring the accuracy and completeness of the data can be challenging. Moreover, scaling the DT technology to accommodate large amounts of data and complex models can be difficult and pose a significant challenge (Technovio 2022). Other challenges in the literature include the need to update old IT infrastructure, connectivity, privacy and security of sensitive data, and the lack of a standardized modeling approach (Fuller et al. 2020). Moreover, managing and running a DT system needs personnel with the necessary skills, including data integration, modeling, simulation, and data analysis knowledge. Training existing employees or finding qualified personnel can be a challenge. Furthermore, the significant challenges likely to hamper DT technology applications include the high deployment cost and complex architecture. Implementing DT solutions requires substantial investment in technology platforms (sensors, software), infrastructure development, maintenance, and security solutions. Finally, the DT infrastructure maintenance is costly and requires significant investment in operations. The high cost of implementing and maintaining a DT system can be a significant challenge for small and medium-sized businesses. The high fixed cost and the complex infrastructure of DT are expected to slow down the deployment of the DT technology (Technavio 2022).

7.3 Security threats

DTs must be treated as critical systems where security issues regarding the availability, integrity, and confidentiality of data and resources must be considered. The risks and threats that target the components of DT, from IoT, AI, and data communication, need to be analyzed, and potential countermeasures to be taken to alleviate the security threats. Several articles investigated the risks and threats that could target the digital twin's physical and digital components (Alcaraz and Lopez 2022; Hearn and Rix 2019; Humayed et al. 2017; Lu et al. 2015; Riahi et al. 2013). These threats, potential limitations, and unintended consequences are listed below:

- Data integrity and confidentiality.
- Unauthorized access to the digital twin software or source code.
- Data communications and transmission between IoT and the cloud.
- The physical security of the IoT and DT devices.

8 Summary and conclusions

Industry 4.0 aims to transform manufacturing using the latest technologies of IoT with AI, ML, and robotics to digitize manufacturing. In the post-pandemic, there was also increased interest in Industry 4.0 for exploiting the enormous amounts of industrial data being routinely collected and stored. As a result, industry 4.0 utilized advanced information and communications technology, including IoT and DT solutions, to gain much-needed agility. DTs are among the rising technologies of Industry 4.0, and their implementation may bring many benefits to industrial processes, including predicting supply chain disruptions and anticipating consumer demand. Overall, DT technology has the potential to transform manufacturing by improving efficiency, increasing quality, and reducing costs.

DT helps companies establish more dynamic, mature supply chain models to identify potential risks early on, so they can take action before a risk becomes a catastrophe. Organizations use DT solutions to optimize transportation routes and model how different raw materials and suppliers will impact their carbon footprint. DTs played a central role in providing effective monitoring, diagnostic, and prescriptive analytic capabilities and helped manufacturers transform operations for business agility and competitiveness. DT solutions helped companies make informed decisions in a seemingly chaotic business environment during the COVID-19 pandemic.

In summary, DT solutions play a crucial role in Industry 4.0 by driving efficiency, innovation, and sustainability across various aspects of industrial operations. More specifically, DT solutions help guide companies' supply chains to be more resilient.

8.1 Future research direction

In the future, DT solutions will expand to encompass a broader range of use cases and industries. However, while the adoption of DT technology has been steadily increasing in recent years, a review of existing literature reveals that its development is still in the early stages. Furthermore, most available publications focus on theoretical concepts and frameworks rather than providing concrete case studies demonstrating DTs' practical application and benefits.

As the technology matures, it will be crucial for researchers to conduct in-depth case studies in various industrial environments to assess the potential advantages and real-world impact of DT solutions. By investigating diverse sectors, such as manufacturing, healthcare, energy, transportation, and agriculture, these case studies can offer valuable insights into each industry's unique challenges and requirements, enabling the development of tailored DT implementations.

Moreover, these case studies will facilitate the identification of best practices and successful strategies for implementing DTs, fostering cross-industry collaboration and learning. Additionally, they will help uncover any limitations or challenges in the technology that need to be addressed for wider adoption and more effective use.

As more concrete evidence of the benefits of DTs emerges, we can expect increased investment in research and development and a greater focus on integrating DTs into existing workflows and processes. Ultimately, the continued growth and advancement of DT technology will enable organizations to optimize their operations, enhance decision-making, and drive innovation across a broad spectrum of industries.

Data availability This manuscript has no associated data.

Declarations

Conflict of interest The authors declare no conflict of interest.

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