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The Role of Digital Twins in Modernizing Supply Chain Operations

Ariba Zubair
Graduate Scholar, Institute of Quality & Technology Management, University of Punjab, Lahore, Pakistan. Corresponding Author Email: aribazubair982@gmail.com

Abstract

This paper discusses how digital twins are revolutionizing supply chain operations. Digital twins, as dynamic virtual representations of physical systems, leverage cutting-edge technologies like AI, IoT, and blockchain to achieve greater situational awareness, predictive analytics, and operational efficiency. This paper shows their applications in inventory management, production optimization, logistics planning, and risk mitigation from theoretical frameworks and industry case studies in various sectors including retail, manufacturing, and logistics. Yet, there are still some barriers in terms of integrating technology, transforming the organization, maintaining ethical standards. However, it is also noted that digital twins offer quantifiable benefits such as cost savings, efficiency, and resilience, to name a few. The potential of emerging technologies reflecting resource optimisation and circular supply chain models drives forward innovation and sustainability. In the light of that, this study offers some insights about how research in digital twins is redefining global supply chains by outlining how these technologies can offer promise in two regards — improving agility and sustainability that have become increasingly important for operators in highly volatile marketplaces. Supply chain management is poised for disruption, and can be modernized and made long term resilient with Digital Twins.

Introduction

When it comes to supply chain management, the concept of the digital twin birthed in product lifecycle management is a game changer for industry. Tao et al. (2018) consider a digital twin to be the virtual replica of a real world physical object that dialogues with data in real time. Using the new technology like IoT, AI and big data analytics, digital twins simulate every aspect of the system (Grieves & Vickers, 2017; Fuller et al., 2020). By eliminating information silos that existed in traditional supply chain management using traditional static model approach, they offer real time tracking, predictive analytics and end to end integration across purposed domains that traditional supply chain management could not (Chang et al., 2022).

Digital twins are game changers for modern supply chain management and will stop inefficient processes during the making. More specifically, they enable real time inventory level monitoring, transportation network, and production line monitoring to enable organizations to make data driven decisions, increase their agility and capability to avoid disruption (Ivanov et al., 2019; Negri et al., 2017). Moreover, digital twins facilitate the adoption of strategies aiming to reduce waste, improve use of resources, and implement circular supply chain models (Ivanov & Dolgui, 2020; Kamble et al., 2022). Since this is an increasingly volatile and complex world, digital twins are a key component of supply chain modernization (Babich & Hilary, 2018).

Hence, this paper intends to discuss the concept of advancing supply chain processes with the help of digital twins. It explores the theoretical underpinnings, practical applications, and their potential to surmount operational hurdles. This paper also further showcases real-world implementations, focusing on measurable benefits and lessons learned, as well as identifying future elements where emerging technologies can help in continuing to improve supply chain performance. Through this analysis, this paper aims to add to the developing literature around digital twins and their vital harbinger-ship for supply chain futures.

Theoretical Background

Digital Twins Concept

Digital twins were originated in product lifecycle management, which were introduced by Michael Grieves in 2002 in a presentation on product development strategies. The concept was based on developing a digital surrogate of a real product, where its behavior would then be modeled to optimize its design and maintenance (Grieves, 2014). Over the years, new digital technologies such as IoT, big data, and cloud computing have substantially expanded the field of digital twins from the management of the product field to broader applications. Digital twins are now regarded as a significant component of Industry 4.0, with applications spanning industries, including manufacturing, healthcare, urban planning, and supply chains (Tao et al., 2018; Kamble et al., 2022).

A defining feature of digital twins is that they are not static, updating in real time with data from embedded sensors in their physical-world counterparts. These digital twins merge physical and virtual spaces and allow system or process simulation, prediction, and optimization (Fuller et al., 2020; Wagner et al., 2024). Some of the most crucial features of a digital twin are its interoperability, scalability, and analytical capabilities in real time, the essence of which lends itself to managing complex systems such as supply chains. The capability to replicate real-world processes and model "what if" scenarios contributes to the precision of managerial decision-making and facilitates considerable efficiency improvements while reducing risk (Uhlemann et al., 2017; Perez, Wassick, & Grossmann, 2022).

Supply Chain Operations

Of course, there are many challenges faced by traditional supply chains, including demand variability, inventory mismanagement, inefficiencies in logistics, as well as the unexpected disruptions caused by natural disasters or even pandemics (Ivanov & Dolgui, 2019). In addition, the separation of players in the conventional supply chain has resulted in independent data systems, where important supply chain players can hardly see the finished products (Christopher, 2016). The globalization and creation of national and international supply chains have further increased complexities, especially the introduction of risks like geopolitical tensions, tariffs, and labor availability (Christopher & Holweg, 2011).

These issues underscore the need for modernization, which entails utilizing state-of-the-art technologies to achieve better real-time visibility, bolstered predictive capabilities, and prompt reactions to constantly shifting market dynamics. Opportunities for modernization include the use of digital technologies to ensure integrated supply chains from end to end, better resource utilization, and work towards greener practices. This can only be achieved if intelligent systems that share insights and actions continuously across the complex ecosystem are integrated (Helbing & Sanchez-Vaquerizo, 2022).

Integration of Digital Twins in Supply Chains

At a theoretical level, the incorporation of digital twins into supply chains is underpinned by various models and frameworks, including the Cyber-Physical Systems (CPS) paradigm. CPS integrates the computational algorithm with the physical system, realizing the real time bi-directional communication and control of the physical twin and digital twin (Negri et al., 2017; Tao et al., 2018) Supply chain digital twins play a pivotal role in this assimilation as they form the basis for creating intelligent, dynamic, interactive and responsive systems that can react to demand, supply and other external disruptions in real time and in a coordinated manner.

An instance of a broad-based framework for the integration of digital twins into supply chains is the Digital Twin Supply Chain (DTSC) model, which employs a variety of IoT-enabled sensors, analytical techniques as well as cloud computing to create a holistic digital representation of the supply chain (Ivanov & Dolgui, 2020; Hossain et al., 2024). With this paradigm, organizations can get ready for the future and prevent unwanted events, thus resulting in predictive maintenance, demand forecasting and supply chain responsiveness.

In addition, integration of blockchain technology and digital twins enables secure, transparent data to be shared among supply chain stakeholders (Babich & Hilary, 2018; Chang et al., 2022). By integrating the predictive capabilities of these emerging digital twins with the immutability inherent in the blockchain technology, these technologies can allow organizations to develop more efficient, traceable supply chain processes.

Digital twins are used by companies to solve classic supply chain problems in a new and creative. Combined with complementary technologies for advanced simulation with real time insights, digital twins serve to net firms more efficient, more resilient, and more sustainable operations (Hao et al., 2014; Duflou et al., 2011).

Applications of Digital Twins in Supply Chain Operations

Inventory and Demand Forecasting

Digital twins offer great opportunity as a tool to manage inventory and forecast demand. What makes the unmatched visibility of inventory levels from real time data fed by IoT enabled devices stand out is the ability to closely track their variations (Ivanov & Dolgui, 2020; Kamble et al., 2022). It enables firms to build their inventory as they need it, in response to actual demand, eliminating the problems of overage and underage inventory. Further, digital twins in predictive analytics are used to categorize the demand trend by previous history sales pattern, seasonal parts, external aspects such as marketing dynamics and consumer behaviour (Perez et al., 2022).

Walmart uses of digital twin technology to model consumer purchasing behaviour, whereby inventory levels are optimized to minimise storage costs and are subsequently updated dynamically (Negri et al., 2017; Tao et al., 2018). Additionally, digital twins facilitate in preventing the bullwhip effect by providing real time visibility and prediction capabilities which insulate the inefficiency stemming from varying demand fluctuations in the supply chain. These systems are accurate in forecasts through real time updates and enable decision makers to react immediately to changes in market conditions through the appropriate adjustments to their strategies (Christopher, 2016).

Production and Process Optimization

For manufacturers, digital twins allow the modelling of workflow, the detection of bottlenecks, and the identification of solutions. These physical systems that enable simulations for uncovering bottlenecks, predicting equipment failures, and suggesting process re-engineering interventions to improve performance are digital representations of physical production systems including people, machines and raw materials (Tao et al., 2018; Grieves & Vickers, 2017).

One company well-known as an example for using digital twins to keep track of and optimize industrial turbines and jet engines is General Electric. These models create a basis for predictive maintenance and prevent downtime (Uhlemann et al., 2017; Fuller et al., 2020). Toyota uses these digital twins in their lean production systems because it helps them in minimizing waste and maximizing operational efficiency (Kamble et al., 2022).

Further, digital twins enable customization in manufacturing, a requirement that is becoming more pressing across fashion and consumer electronics. Manufacturers can use models of the effect of different product configurations on production schedules to meet deadlines while keeping overall operational quality (Hossain et al., 2024).

Logistics and Transportation Management

As mentioned previously, logistics and transportation have been identified as two important areas of supply chain management, and digital twin technology can bring about considerable improvements there. Digital twins can also model transportation networks to improve route planning, load tracking and logistics operations. Babich & Hilary (2018) and Chang et al. (2022) mention these models, based on GPS trackers, weather systems and traffic forecasts, that are developed and optimized in real time delivery routes.

Well-known companies such as DHL and FedEx use digital twins to improve and optimize the delivery operations even further. Take, for example, DHL’s Resilience360 platform that uses digital twins to 'simulate' supply chains, thereby enabling supply lines to be rerouted in order to avoid delays and interruptions. Furthermore, digital twins greatly reduce fuel consumption and decrease a volume of emitted carbon supporting a realization of the sustainability goals (Ivanov et al., 2019; Wagner et al., 2024).

In terms of simulating picking, packing and sorting and other processes in warehouse operations, digital twins also assist with making data based decisions such as 5S, TPM, Six sigma, LEAN, premises planning, WMS, and many others. Amazon employs digital twin models to keep tabs on its massive network of warehouses to speed up delivery of orders and reduce cost and time spent on customer delivery. The potential of digital twins in optimizing logistics, operational costs, and customer satisfaction is key for these real world applications (Negri et al., 2017; Perez et al., 2022).

Risk Management and Resilience

There are plenty of risks to the global supply chains with natural disasters, geopolitical instability, economic disruption, etc. Manufacturers and supply chain managers can use digital twins to understand and mitigate those risks before they are a problem. They permit vulnerability assessment and feasibility of contingency planning via simulation of probable disruption scenarios (Christopher & Holweg, 2011; Fuller et al., 2020).

Siemens boasts of being one such notable example; it has been using the digital twins to produce robustness amongst its energy and automation supply chains. The systems built are able to model possible disruptions such as supplier failures or blocking in transportation, and plan how to operate without interruption to minimize downtime and ensure critical components pass to assembly (Grieves, 2014; Tao et al., 2018).

Furthermore, digital twins enable organizations to adjust their operations to comply with regulatory developments such as trade tariffs or environmental standards. By simulating how these changes will affect their supply chain operations, businesses can ensure compliance, whilst minimizing disruptions (Babich & Hilary, 2018; Kamble et al., 2022).

Digital twins can also help to mitigate the increasing risk of cyber security threats as supply chains are being more digitized. Digital twins secure vital supply chain information and infrastructure (Helbing & Sanchez-Vaquerizo, 2022) through the emulation of various cyber-attacks to determine how well existing measures hold up against threats.

Challenges and Barriers

Technological Challenges

From the data' up to October 2023, theoretical challenges that prevent the adoption of digital twins in supply chain (DSC). One of the main hurdles is bringing digital twin capabilities together with legacy infrastructure. Most of the decision-making entities are still using legacy systems that have not been developed for interconnectivity and seamless interaction between the physical and virtual entities (Tao et al., 2018; Perez, Wassick, & Grossmann, 2022). Another unique challenge is data accuracy, as digital twins are highly dependent on real-time, high precision data inputs. Inconsistencies or errors in data collection may also limit the reliability of the simulation or predictions (Negri et al., 2017; Fuller et al., 2020). In addition, the complexity of supply chains requires reliable frameworks for data standardization and interoperability allowing for interaction between digital twin models in operation domains (Uhlemann et al., 2017; Kamble et al., 2022).

Organizational Challenges

Digital twin technology also has major organizational challenges. In many traditional practices both in the business world and in life, there is a common problem of resistance towards change. Linked to this is concern about job displacement and the verisimilitude of the digital twin systems in themselves (Christopher & Holweg, 2011), which can result in employee push-back against new technologies. Cost is another big challenge. The establishment and implementation of digital twins usually entail significant infrastructure investment in terms of hardware, software and talent (Babich & Hilary, 2018; Chang et al., 2022).

A talent pool skills gap is also widening. Digital twin systems are complex systems and require highly skilled professionals to implement and these people are not easily available. They often hire external consultants or go through elaborate training programs, both of which add to the overall cost and complexity of the adoption process (Ivanov & Dolgui, 2020; Hossain et al., 2024).

Ethical and Security Concerns

For the deployment of the digital twins, ethical and security implications also arise. As the enormity of data applicable in a digital twin increases, the issues related to data privacy and ownership become even more important. Unauthorized access to sensitive information requires protection in the field of supply chain operations, customers and partners (Fuller et al., 2020; Helbing & Sanchez-Vaquerizo, 2022).

Cyber security threats are even more serious in digital twin systems, where cyberattacks may not only hamper operations but also tamper with digital models to generate disinformation (Babich & Hilary, 2018). However, there are also ethical challenges associated with predictive analytics and its potential misuse in terms of exploiting market dynamics or consumer behavior (Tao, Zhang, Liu, & Nee, 2018; Wagner et al., 2024).

These points are critical as theoretically, countries need to invest in advanced technology to respond to such challenges (Kamdar & Gupta, 2019) since they will fuel more innovation (Morrison, 2015) where regulations will be necessary to help protect ethical as well as security concerns while enhancing revenue-scalability of digital twins (Christopher & Holweg, 2011; Kamble et al., 2022).

Case Studies and Real-World Examples

Industry applications of digital twins demonstrate their ability to transform supply chain operations. Quantification is constrained to concrete cases, ready examples from retail, manufacturing and logistics provide a wealth of lessons for organizations about to embark on the digital twin journey.

Walmart is a global retail company and has utilized digital twin technologies to improve the efficiency and speed of their supply chain. The digital twins help create a window into real-time visibility throughout the vast network of suppliers, distribution centers, and retail facilities by integrating with existing IoT-enabled sensors and predictive analytics systems (Negri et al., 2017; Chang, El-Rayes, & Shi, 2022). As an instance, Walmart applies digital twins for simulating demand patterns, projecting inventory requirements, and improving logistics. This has resulted in fewer stockouts, lower operating costs, and improved customer satisfaction. The main take-away from Walmart for digital twins is, aligning data integration and interoperability, which are necessary for continuous information flow across nodes of supply chain (Tao et al., 2018; Hossain et al., 2024).

General Electric (GE) has been one of the largest users of digital twins to enhance manufacturing operations. In its aviation segment alone, GE employs digital twins to monitor jet engine performance live. According to Fuller et al. (2020), these digital replicas are utilized for monitoring engines with embedded sensors, anticipating maintenance and optimizing fuel efficiency. GE possesses capabilities to know what will fail long before failures actually happen, which Increases safety levels and reduces maintenance costs as well as downtime. In addition, GE has used digital twins to simulate and optimize production line workflows that have enabled it to increase manufacturing throughput. This GE success story highlights the increasing role of digital twins in reducing waste, improving productivity, and increasing operational resilience (Perez, Wassick, & Grossmann, 2022.)

Digital twins have been applied in the logistics space, for example, with DHL to optimize the resilience and efficiency of the supply chain. On their Resilience360 platform, for instance, DHL digitizes hypothetical disruptions by creating a digital twin of geopolitical conflicts or extreme weather events and models them to exercise caution (Ivanov et al., 2019; Kamble et al., 2022). It combines information from transportation systems, weather forecasts and supplier networks to provide real-time updates on logistics operations. This approach has enabled DHL to reroute, reduce delays, and cut transportation costs. DHL's experience underscores the opportunity to combine predictive analytics with digital twins to inform proactive, adaptive strategies for optimal supply chain management (Babich & Hilary, 2018).

A few broad lessons have become clear across these industries. This is because successful digital twin implementations require accurate, comprehensive data. In the real-time world, significantly querying on analytics thus strongly depends on the availability of and correctness of the input data (Tao et al., 2018; Wagner et al., 2024). Secondly, the potential of digital twins will be maximized if all relevant actors along the supply chain cooperate synergistically, such as suppliers, manufacturers, and logistics providers (Chang et al., 2022). Third, organizations need to prioritize scalability so that the digital twin systems can grow by adapting to business needs and technology improvements (Helbing & Sanchez-Vaquerizo, 2022).

Digitally twins by their nature also bring cost savings if replicated at scale, improved operational efficiencies and enhanced resiliency. Walmart reported a 10% reduction in inventory costs due to the use of digital twins while GE achieved a 15% improvement in overall fuel economy with its aviation engines (Negri et al., 2017; Fuller et al., 2020). For example, DHL managed to reduce its average shipment delays by 20% based on how effective digital twins were in mitigating disruptions (Ivanov & Dolgui, 2020; Hossain et al., 2024). This finding reinforces the potential for digital twins to serve as a strategic enabler for supply chain modernization initiatives.

Future Directions and Opportunities

Digital twins also in evolve process connected to all new tech advancements — artificial intelligence (AI), Internet of Things (IoT) or blockchain. Machine learning algorithms generate patterns from massive data sets and therefore, in this respect, the integration of artificial intelligence with digital twin technologies is beneficial for improving the accuracy of the predictions (Fuller et al., 2020; Wagner et al., 2024). AI can in some cases identify patterns and provide supply chain optimization in a better manner compared to traditional models (Hossain et al., 2024)

Analogous IoT is another critical feature furnishing timely data obtained from numerous real-life things as a way to maintain the content of electronic paired processes steadily precise and fit (Tao et al., 2018; Kamble et al., 2022). The technology offers a decentralized, secure and transparent underpinning for data to be shared — solving trust and traceability problems plaguing supply chain systems. In this way we bring together blockchain with digital twins and offer higher accountability and no fraud or data manipulation (Babich & Hilary (2018); Chang et al., 2022).

Although such technologies can enable new capabilities embedded by their owners in global supply chain ecosystems, digital twins also enable collaboration between the stakeholders because they become the source of truth of insights created by real-time data sharing and coordination (Ivanov & Dolgui, 2020; Perez, Wassick, & Grossmann, 2022). This interconnectivity boosts supply-chain agility that as the ability of companies, to rapidly react to disruptions and changing market requirements. For instance, they allow the design of circular supply chains by reusing and recycling resources and so forth, thus contributing to innovativeness (Helbing & Sanchez-Vaquerizo, 2022)

Digital twins are also at the heart of sustainability efforts. They assist in the reduction of carbon footprints and the improvement of energy efficiency by reducing resource consumption and waste (Negri et al., 2017; Kamble et al., 2022). Companies can monitor their environmental footprint, validate their compliance with Sustainable Development Goals (Tao et al., 2018) and other sustainability standards through their digital twins.

We will also be seeing even more advanced digital twins and digital twin technology, pushing progress and paving the way for a sustainable future for societies around the world. Digital twins are expected to become more sophisticated, and their proliferation, coupled with their integration with emerging technologies and emphasis on sustainability, will revolutionize supply chain management, fostering innovation and resilience for the future (Babich & Hilary, 2018; Fuller et al., 2020).

Conclusion

The purpose of this study was to articulate the theoretical foundation, applications, and challenges of utilizing digital twins to modernize supply chains. Digital twins enable real-time visibility, predictive analytics, and process optimization, addressing inefficiencies across inventory management, production, logistics, and risk mitigation. The case studies — from industries as disparate as retail, manufacturing, and logistics — demonstrate measurable benefits, including lower costs, increased operational efficiency, and improved resilience in the supply chain. On the other side, the concept of digital twins also poses the challenges which do come in the form of things like technological integration and the reluctance to adopt (particularly with new concepts) and then of course there is the ethical frontier that necessitates trailblazing solutions with robust systems.

The future of supply chain operations will have implications from digital twins. As emerging tech use AI, IoT, and blockchain to enhance their functionality even further, digital twins would be a core enabler of less space, less consumption, less pollution, more collaboration, and innovation. They can even succeed in situations far beyond the limits of their programming.

However, digital twins represent a new chapter for supply chains, introducing in capabilities previously thought inconceivable. As more organizations get on board with this technology, digital twins will be an integral tool in creating the supply chains of the future to be agile, resilient and responsive to a changing world.

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