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Supply Chain Digital Twins: A Comprehensive Review and Case Studies

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Abstract

In the domain of supply chains, digital twins (DT) are reshaping traditional business approaches by offering diverse solutions that foster collaborative environments and data-driven decision-making. We examine digital twin technology, which involves creating virtual replicas of objects or processes to simulate the behavior of their real counterparts. We research the effectiveness of these digital twins in specific cases to enhance their performance. When applied to products, machines, and entire business ecosystems, the digital twin model can unveil information from the past, optimize the present, and even predict future performance in different areas. Drawing parallels with real-world examples, such as the supply chain management practices of major retailers like Walmart, we demonstrate the impact of digital twins on operational efficiency and overall supply chain performance. However, we critically address the challenges inherent in this system, such as costs, data quality, and model complexity. Through our research, a comparative analysis between digital twins and traditional simulations is provided, highlighting the distinct advantages and disadvantages of each approach in decision-making processes. This comparison aims to offer insights into the unique capabilities and constraints of digital twins in capturing the dynamics of real-world systems compared to simulation-based models.

Keywords

Digital Twins, Supply Chain, Data, Decision Making

1. Introduction and Background

In the realm of advanced simulation and predictive analytics, a digital twin stands as a sophisticated representation of a tangible entity or system. A digital twin is a comprehensive simulation model that mirrors the intricacies of a real-world counterpart (anyLogistix n.d.). What sets it apart is its reliance on real-time data, seamlessly integrating information from sensors, IoT devices, and diverse sources. This results in a dynamic virtual replica that not only predicts the behavior of the original entity but also facilitates understanding, learning, and reasoning about its complex dynamics. By the efficiency of real-time data, digital twins become invaluable tools for industries seeking to optimize processes, enhance decision-making, and gain deeper insights into the performance of physical entities in the ever-evolving landscape of technological innovation. This digital replica allows analysts to comprehend the behavior of the supply chain, foresee abnormal situations, and strategize action plans. Its versatile applications include

understanding supply chain dynamics, identifying bottlenecks, testing design changes, monitoring risk, optimizing inventory, planning transportation, conducting cash-to-serve and cost-to-serve analyses, and forecasting and testing operations for the upcoming days and weeks (Gerlach 2021).

The paper delves into researching the efficacy of digital twins in supply chain management to optimize performance, and draws insights from real-world exemplars, notably examining major retailers such as Walmart. By showcasing tangible examples, the paper illuminates the tangible impact of digital twins in enhancing operational efficiency and overall supply chain performance.

1.1 Digital Twin in Supply Chain Management

Digital twin technology plays a pivotal role in various aspects of supply chain management. In the realm of Inventory Management, companies utilize digital twins to create virtual replicas of their inventory, gaining real-time insights into stock levels, locations, and conditions. This enables businesses to optimize stocking levels, reduce carrying costs, and prevent stockouts or overstocking issues. In the domain of Demand Planning and Forecasting, digital twins allow companies to simulate diverse demand scenarios based on historical data and customer behavior, leading to enhanced accuracy in forecasting and improved customer satisfaction (Sahilbhutada 2023). Moreover, digital twin technology extends its influence across the entire supply chain, enabling modeling and simulation of suppliers, manufacturing sites, distribution centers, and transportation networks. Through this, businesses can identify bottlenecks, optimize logistics routes, shorten delivery times, and enhance overall supply chain efficiency. In the realm of Risk Management, digital twin technology proves valuable in identifying and mitigating supply chain hazards, empowering businesses to establish contingency plans and ensure business continuity amidst unexpected disruptions, ranging from natural catastrophes to geopolitical crises.

A supply chain digital twin is characterized by its imperative to house a detailed simulation model, endowed with the capacity to meticulously analyze a spectrum of interactions within the supply chain landscape. This encompasses the nuanced examination of macro demand changes, enabling a holistic understanding of the overarching demand dynamics (Sahilbhutada 2023). Simultaneously, the digital twin extends its analytical prowess to the microcosm of facility-level dynamics, delving into the intricacies of operational processes, resource utilization, and workflow efficiency. Through this comprehensive simulation, the supply chain digital twin emerges as a powerful tool, offering a multifaceted perspective that spans from the broader market trends down to the granular details of individual facilities, thereby facilitating nuanced decision-making and optimization strategies throughout the supply chain.

Integrating a supply chain digital twin involves the creation of a virtual replication of the entire supply chain network, providing organizations with unparalleled insights into their operational intricacies. This groundbreaking technology utilizes real-time data to simulate and optimize logistics processes, enabling businesses to pinpoint bottlenecks, minimize inefficiencies, and elevate overall operational performance (Sharma et al. 2022). Spanning applications from inventory management to demand planning, a supply chain digital twin offers a holistic perspective, encompassing production, logistics, customer data, and financial metrics. The benefits of this approach are extensive, including enhanced decision-making, heightened efficiency, increased resilience, cost savings, and improved customer satisfaction.

Moreover, the implementation of digital twins extends across diverse supply chain facets, as evidenced by industry leaders like GE, Rolls-Royce, Pratt & Whitney, FedEx, and DHL (Owczarek 2023). By harnessing the capabilities of artificial intelligence and digital twins, businesses not only optimize their operations but also contribute to sustainability goals by identifying energy-efficient transportation routes and reducing environmental impact. However, the successful integration of supply chain digital twins requires clearly defined objectives and strategic resource allocation to navigate potential challenges and ensure alignment with evolving business needs.

2. Real-World Examples

In the dynamic landscape of manufacturing, the widespread adoption of digital twins has redefined how companies optimize their processes and assets. General Electric, for instance, has embraced digital twins as integral to their operations. By creating virtual replicas of physical assets like turbines, GE gains the ability to monitor performance

in real-time. This not only facilitates the early detection of potential issues but also enables predictive maintenance, ultimately maximizing operational efficiency. The intricate understanding provided by digital twins empowers manufacturing entities to fine-tune workflows, identify bottlenecks, and streamline their production lines with unprecedented precision.

In the healthcare sector, the integration of digital twins has ushered in a new era of personalized medicine. Institutions like the Cleveland Clinic are at the forefront of utilizing digital twins to create virtual representations of individual patients. These digital replicas enable healthcare professionals to tailor treatment plans based on specific patient characteristics, simulate complex surgical procedures for optimal outcomes, and continuously monitor key health parameters. The result is a paradigm shift towards more effective and personalized healthcare interventions.
Aerospace industries, including NASA, leverage digital twins for spacecraft and satellite systems. The complex and critical nature of aerospace missions demands precise simulation and prediction capabilities, and digital twins deliver just that. By creating virtual models of space-bound components, organizations can enhance mission planning, anticipate potential issues, and develop proactive maintenance strategies, ensuring the reliability and longevity of space-based assets.

In the realm of smart cities, the visionary use of digital twins has been exemplified by Singapore. The city-state has embraced this technology to create a comprehensive digital twin of its urban environment. This intricate model allows city planners to simulate and optimize various aspects, from traffic patterns and energy consumption to environmental impact. The result is a more sustainable, efficient, and livable urban ecosystem.
The energy sector, particularly oil and gas companies such as Shell, has harnessed digital twins to revolutionize their operations. Offshore platforms, with their complex and remote nature, benefit immensely from the ability to create digital replicas. Companies can simulate diverse scenarios, optimize production processes, and predict maintenance needs, ensuring the safe and efficient operation of offshore facilities.

Automotive manufacturers like BMW have seamlessly integrated digital twins into their production processes. By using virtual models to simulate manufacturing workflows, test different design iterations, and optimize production lines, these companies achieve a level of precision and efficiency that was previously unattainable. This not only accelerates the product development cycle but also ensures the production of high-quality vehicles with minimal resources.

In essence, the transformative impact of digital twins spans a multitude of industries, reshaping how businesses operate, innovate, and deliver value. The technology's ability to create virtual replicas for monitoring, simulation, and optimization has become a cornerstone for efficiency and innovation across the manufacturing, healthcare, aerospace, smart cities, energy, and automotive sectors (Gerlach et al. 2021).

In a strategic move to enhance its supply chain operations, the global retail giant Walmart has implemented a digital twin solution. This innovative system integrates real-time data from various sources, including sales figures, inventory levels, and weather forecasts, to simulate and analyze the entire supply chain network.

By leveraging the digital twin, Walmart achieves precise demand estimation, optimizes inventory levels, and improves the efficiency of logistics and distribution processes. The technology also facilitates simulations and scenario planning, allowing the identification of potential bottlenecks and the enhancement of the overall flow of goods within the supply chain. The outcome has been a notable increase in customer satisfaction, attributed to enhanced inventory management practices and a reduction in waste. This application of digital twin technology underscores Walmart's commitment to staying at the forefront of cutting-edge solutions for optimizing its extensive and complex supply chain (Sahilbhutada 2023).

3. Challenges

Digital twins offer great potential for optimizing supply chains. They can help companies to improve processes, reduce costs and increase efficiency. However, companies face several challenges when introducing them.

The central aspect is updating the company's existing IT infrastructure while at the same time refraining from a standardized modelling approach. Consideration must be given to which hardware and software components are an obstacle to the implementation of a DT, which can be converted and integrated and ultimately which need to be purchased (Attaran and Celik 2023). This is associated with high initial investments in IoT devices, servers, communication systems, but also in personnel - for the development and implementation of the project - but is necessary to enable an accurate representation of the physical supply chain. A functioning data architecture must also be created on the software side, which includes several applications from data storage and use to data visualization. ICP & SimWell have created such an individualized end-to-end data model with SAP, alteryx, anyLogistix and PowerBI to represent a DT of the supply chain (Sakoian et al. 2023). In addition, further ongoing expenses are incurred for the increased energy requirements, maintenance and updating of the DT as well as investments in further research (Sharma et al. 2022).

Other challenges mentioned in the literature are the data quality and digital security of DTs. It is crucial to ensure reliable data quality in an application of DTs based on information provided by thousands of IoT systems. Faced with demanding operating conditions and communication over extensive networks, organizations must develop mechanisms to detect and eliminate unreliable data and deal with inconsistencies in the information collected. Furthermore, this extensive amount of information makes DTs an attractive target for criminal intrusion, so ensuring security is of great importance, however, maintaining adequate data protection routines for networks of this scale can be a daunting prospect for many organizations (Moshood et al. 2021).

In practice, it can already be observed that companies are able to map a location as a DT, but not yet a holistic logistics system. This is partly because the data does not have a standardized format, there is no central database and there are concerns about data exchange between the participants within the network (Zarnitz and Straube., 2023). It is also a challenge for the developers of DTs to represent the growing complexity within a supply chain. This often means that they must simplify procedures in the underlying model during development. Furthermore, any technological change inevitably requires employees to adapt and get used to modern ways of working. This adaptation leads to challenges in management change and knowledge transfer. It is not enough to have the necessary resources and expertise to operate and manage DT. Rather, it is necessary to motivate them to change their attitude and way of working. This in turn requires a detailed understanding of the causes and motives for this change (Moshood et al. 2021).

4. Digital Twins vs. Traditional Simulations

Digital Twins are an advanced technology that has a lot of benefits. There are several ways that digital twins trump traditional simulations. Firstly, digital twins come up with results that are verifiable and reproducible (Binsfeld and Gerlach 2023). This means that the outcomes generated by digital twins can be easily validated and duplicated, enhancing the reliability of the information they provide. Moreover, digital twins exhibit a significant edge in predictive capabilities, particularly in anticipating operational failures well in advance. This predictive process allows for proactive intervention, mitigating risks and enhancing overall system reliability (Kamble et al. 2022). The concept of a "virtual supply chain mirror," as referenced in Kamble et al.'s paper, showcases another remarkable application of digital twins. Through real-time monitoring and analysis, digital twins serve as vigilant observers, promptly identifying abnormal behaviors within a supply chain. This capability provides companies with timely notifications, enabling them to address irregularities and streamline their supply chain operations more effectively.

In contrast, it's crucial to note that while digital twins offer groundbreaking benefits, they are not one-size-fits-all solutions. As highlighted in Falk et al.'s paper, "one digital twin solution might suit one company, but not another." This emphasizes the importance of customization and adaptability in implementing digital twin solutions to cater to the unique needs and intricacies of different organizations (Falk and Sandén 2021). Traditional simulations hold a more established position in certain domains, particularly in the realms of product life cycle and cybersecurity. These conventional simulation methods have a long history of use and refinement, offering a solid foundation for understanding and addressing various aspects of a product's life cycle, from design to decommissioning. Additionally, their role in cybersecurity, where the focus is on identifying vulnerabilities and enhancing digital defenses, underscores the continued relevance of traditional simulation approaches in certain contexts.

5. Conclusion

The integration of digital twin technology into supply chain management emerges as a transformative force, reshaping the landscape of operational efficiency and strategic decision-making. The paper has illuminated the multifaceted applications of digital twins, emphasizing their pivotal role in inventory management, demand planning, risk management, and overall supply chain optimization. By creating dynamic virtual replicas that mirror real-world entities, digital twins enable businesses to gain unparalleled insights, from macro-level demand dynamics to micro-level facility operations.

The discussion on challenges underscores the importance of recognizing that digital twins are not universally applicable solutions, as highlighted by the nuanced comparison with traditional simulations. Customization and adaptability are key considerations in implementing digital twin solutions, ensuring alignment with diverse organizational needs.

Real-world examples from industries such as manufacturing, healthcare, aerospace, smart cities, energy, and automotive showcase the broad spectrum of transformative impacts facilitated by digital twins. The case study of Walmart further emphasizes the tangible benefits, with the retail giant leveraging digital twins to optimize its extensive supply chain, enhance customer satisfaction, and stay ahead in the competitive retail landscape.

As businesses continue to navigate the complexities of modern supply chains, the strategic adoption of digital twins emerges as a cornerstone for success. The technology's ability to harness real-time data, simulate diverse scenarios, and offer comprehensive insights positions it as a catalyst for innovation and efficiency across various sectors. Moving forward, the successful integration of supply chain digital twins will depend on strategic planning, clear objectives, and the ongoing commitment to adaptability in the face of evolving industry landscapes and technological advancements.

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