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DIGITAL TWIN IN THE MANAGEMENT AND TECHNOLOGY OF ENTERPRISE TRANSPORT SERVICES IN LOGISTICS

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Abstract: This article explores the use of digital twin technology in logistics management and transportation services. It reviews current research, theoretical foundations, and highlights real-world implementations, particularly examples from Slovakian companies. The benefits of digital twins, such as improved efficiency, real-time optimization, and enhanced decision-making capabilities, are demonstrated through practical case studies. The article concludes that digital twins contribute significantly to modern logistics innovation and competitiveness.
Keywords: digital twin, optimization, logistics

Introduction

Digital Twin (DT) technology refers to the creation of a virtual replica of a physical entity - such as a product, process, or system - that is continuously synchronized with the real-world counterpart via data streams. The concept originated in the aerospace industry: NASA pioneered early "living models" of spacecraft during the Apollo program, an ancestor of today's digital twins. In the manufacturing domain, Grieves (2014) formally introduced the digital twin concept as a tool for virtual replication of factory systems to drive manufacturing excellence [1]. In essence, a DT is more than a static simulation; it is a dynamic, data-driven model that evolves in real time alongside the physical object, enabling monitoring, analysis, and control as if in a mirror world [2].

In recent years, advances in sensors, Internet of Things (IoT) connectivity, and data analytics have pushed DTs to the forefront of Industry 4.0 strategies in many sectors. Logistics and transportation operations, in particular, have much to gain from DT technology. By bridging the physical and digital realms, DTs enable companies to gain unprecedented visibility into supply chain and transportation processes, identify inefficiencies, and test improvements virtually before implementing changes on the ground. Research shows that the adoption of DT solutions in logistics leads to significantly improved decision making and efficiency, giving companies a competitive edge in dynamic market environments [3]. Accordingly, industry adoption of DT has accelerated: a recent review found a surge in publications on DT applications in the supply chain since 2017, reflecting both growing academic interest and practical deployment [4]. From DHL's experiments with warehouse digital twins [5] to Mars, Inc.'s creation of a twin of its manufacturing supply chain to improve production and inventory planning [6], major global companies have begun deploying digital twins to optimize logistics. The remainder of this paper provides a detailed examination of the state of the art of digital twin applications for logistics and transportation within companies, the theoretical foundations of DTs, and a practical case study of Volkswagen Slovakia's implementation.

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State of the Art Review

Digital twin technology has rapidly evolved from its manufacturing roots into a transformative tool for logistics management and supply chain optimization. State-of-the-art applications of DTs in logistics span a wide range of use cases, including real-time supply chain monitoring, predictive analytics for transportation, and optimization of warehouse operations. A digital twin in a logistics context is essentially a live digital model of the end-to-end logistics network or specific operations (e.g., a warehouse or a fleet of delivery vehicles) that is continuously fed with data from the physical operations. This live mirroring enables several capabilities that characterize the state of the art today: real-time visibility, scenario simulation, and data-driven decision support.

One key trend in current applications is using digital twins to achieve end-to-end supply chain visibility and responsiveness. For example, confectionery and food giant Mars has integrated a digital twin of its supply chain using IoT sensors and cloud analytics, providing a unified real-time view of production and distribution from factories to customers [6]. This twin allows Mars to simulate production adjustments, optimize machine maintenance schedules, and even account for external factors (like climate or supply disruptions) by running "what-if" scenarios digitally before acting in the real world. Likewise, studies report that digital twins are increasingly employed to model complex global supply networks for risk management. A notable case is the use of a digital supply chain twin to stress-test resilience under disruptions – during the COVID-19 pandemic, researchers built a twin of a German retail food supply chain to analyze the impact of lockdowns and demand surges, identifying bottlenecks and testing mitigation strategies in the virtual model [7]. This exemplifies how state-of-the-art DTs serve as powerful tools for scenario planning and enhancing supply chain resilience in the face of uncertainties.

Another active area is the application of DTs in intralogistics and warehouse management. Here, digital twins of warehouses or factories (including material handling equipment, inventory, and workflows) enable optimization of internal logistics flows. Leading logistics providers and technology firms have piloted such twins to improve throughput and resource utilization. For instance, DHL's innovation arm has explored digital twin models of distribution centers to identify bottlenecks in order picking and to test layout changes virtually to boost efficiency [5]. Modern warehouse twins often integrate real-time locating systems (RTLS) and telematics data from forklifts and autonomous guided vehicles, yielding a live 3D model of operations. This model can continuously measure performance (e.g. travel distances, idle times) and feed AI algorithms to optimize task scheduling and routing. Indeed, the integration of AI with DTs represents the cutting edge: companies like Siemens and Linde Material Handling are embedding DTs into AI platforms (such as NVIDIA Omniverse) to achieve real-time coordination between human-operated forklifts and autonomous robots, using the twin to simulate optimal routing and avoid congestion in the warehouse . These developments illustrate that current state-of-the-art DT deployments in logistics are leveraging not only IoT data but also advanced analytics (machine learning and simulation) to drive intelligent optimizations in transport and material flow systems.

In automotive logistics, several manufacturers now rely on digital twins for production logistics and supply chain synchronization. BMW, Volkswagen, and others have digital twin initiatives to model parts flows and production schedules, creating a virtual copy of the production logistics pipeline to fine-tune operations. For example, an automotive OEM used a supply chain twin to dynamically adjust production plans based on real-time supplier status and logistics constraints, resulting in more resilient performance during supply fluctuations [4]. In addition, process mining and DT techniques are being combined (as seen in Celonis' work with VW) to create real-time digital process models that highlight inefficiencies in complex

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automotive supply chains, much like getting an "X-ray" of the entire logistics process to pinpoint delays or suboptimal inventory levels [4][6].

Theoretical Background

At its core, a digital twin is based on the integration of several theoretical and technological components: modeling & simulation, sensor data fusion, and bi-directional information flows between physical and virtual systems. Grieves' early formulation of the DT concept emphasized that a true digital twin consists of three parts: (1) the physical entity in real space, (2) the virtual entity (its digital counterpart) in virtual space, and (3) the data links that connect the two and enable synchronization [1][2]. It is this continuous data loop-often via IoT sensors on the physical side, and APIs or data streams that update the digital side-that distinguishes a digital twin from a traditional static model. The physical and virtual twins inform each other: the status of the physical object updates the digital model in real time, and insights or control signals derived from the digital twin can be applied back to the physical object (e.g., an optimization or a control command), closing the loop. This cyber-physical integration conceptually links DTs to cyber-physical systems (CPS) theory, where computational (cyber) elements monitor and control physical processes, often in real time. Indeed, a digital twin can be seen as a specific CPS implementation with a high-fidelity simulation model at its core, enabling not only real-time control, but also prediction and "what-if" experimentation [3].

A critical theoretical distinction in the DT literature is between a Digital Model, a Digital Shadow, and a Digital Twin, as described by Kritzinger et al. (2018) [7]. A Digital Model is any digital representation of an existing system, but without automatic data exchange with the physical original; updates must be done manually. A Digital Shadow involves a one-way data flow - changes to the physical object automatically update the digital model (via sensors), but there is no feedback from the digital to the physical. A digital twin, on the other hand, involves bi-directional data flow: the twin not only receives real-time data from the physical object, but can also send back information (or control signals via actuators) to influence the physical system. This bi-directional connectivity allows the twin to continuously adapt to reality and actively optimize or control the physical process. Modern DT implementations strive for this full twin paradigm, although some practical systems may initially operate as digital shadows (for monitoring) before closing the loop for automatic control.

From an architectural perspective, an influential framework is the five-dimensional digital twin model proposed by Tao et al. (2019) [2]. This framework defines five key components of any digital twin system: (i) the physical entity (the equipment, vehicle, warehouse, etc. that will be twinned), (ii) the Virtual Entity (the models and simulations that represent this physical asset), (iii) the Data (the live data streams and historical databases that feed the twin), (iv) the Connection (the IoT infrastructure, networks, and interfaces that ensure real-time data flow between physical and virtual parts), and (v) the Services (the analytical or control functions enabled by the twin, such as diagnostics, predictions, optimizations, decision support). In a logistics environment, for example, the physical entities might be delivery trucks, forklifts, or packages; the virtual entities might be discrete-event simulation models or 3D representations of the warehouse and transportation routes; the data might come from sensors such as GPS trackers, RFID scans, or ERP systems; the connectivity might be provided by wireless networks and cloud platforms; and the services might include optimal route calculation for vehicles, predictive maintenance scheduling for equipment, or real-time congestion alerts in a distribution center. By structuring a DT in this way, organizations ensure that all the necessary elements are in place to create a functioning twin. The bidirectional data loop resides in the connection dimension, enabling continuous synchronization between the live system and its replica [2].

Another theoretical underpinning of DTs is their reliance on high-fidelity modeling and simulation techniques. The virtual entity of a DT often uses physics-based models or data-driven models (or a hybrid of both) to emulate the behavior of the physical system. In transportation and logistics, discrete event simulation and agent-based modeling are common approaches to represent processes such as order fulfillment or vehicle movement. What distinguishes a DT is that these models are not run in isolation, but are continuously calibrated with real data. For example, the travel time of a truck on a route in a supply chain twin can be updated in real time using telematics data, improving the accuracy of the twin's predictions for downstream deliveries. This dynamic calibration means that the twin's simulations can more reliably predict outcomes and support decision-making with current ground truth. In addition, with the rise of machine learning, some digital twins incorporate predictive algorithms (e.g., neural networks) that learn from historical and real-time data to predict future states (e.g., predicting a delay or machine failure) [3]. Such capabilities take DTs beyond reflecting the current state to predicting future states - a key reason why digital twins are valuable in logistics, where anticipating problems (such as a bottleneck or vehicle breakdown) can save costs and time.

It is also important to note the role of standards and integration in the theoretical background. Logistics systems include heterogeneous components (vehicles, IT systems, machines from different manufacturers). Effective DT implementations require interoperable data formats and possibly standards (such as OPC UA for industrial data or GS1 standards for supply chain data) to integrate data into a virtual environment. The concept of a "single source of truth" digital thread often accompanies discussions of digital twins, meaning that data from different sources is unified in the twin. Recent research also talks about national or large-scale digital twins for logistics that would integrate data across organizations for systemic efficiency [3]. While the fully integrated, cross-enterprise supply chain twin is still an aspiration, the architecture and enabling technologies (cloud computing, big data platforms, standardized APIs) to support such efforts are rapidly evolving.

In summary, the theoretical foundation of digital twin technology in logistics is based on the principles of real-time simulation, cyber-physical integration, and data-driven modeling. A true digital twin is characterized by continuous synchronization and interaction between the physical logistics system and its virtual counterpart. Enabled by IoT sensors, connectivity, and advanced analytics, the twin evolves simultaneously with its physical twin, allowing companies to monitor current operations in great detail, predict future behavior, and optimize processes in silico. The next section illustrates these concepts in practice by examining how Volkswagen Slovakia applied a digital twin to its internal logistics and transportation operations, highlighting the practical benefits achieved.

Practical example: Volkswagen Slovakia's Logistics Digital Twin

Assembly line at Volkswagen Slovakia's Bratislava plant. The plant's internal logistics, including the movement of vehicle bodies, parts, and material handling equipment (forklifts and AGVs), is managed and optimized using a digital twin of the manufacturing and warehousing processes.

Volkswagen's production plant in Bratislava, Slovakia-one of the largest and most complex in the VW Group, producing multiple brands under one roof-provides a compelling real-world example of digital twin technology applied to logistics management. Faced with high production volumes (over 300,000 cars per year) and a complex network of parts moving through stamping, body shop, paint and assembly operations, the plant's logistics managers sought to increase efficiency and reduce costs through innovation and digitization. The solution was implemented in partnership with technology provider Asseco CEIT and involved the deployment of a state-of-the-art indoor Real Time Location System (RTLS) and a Digital Twin platform to create an "identical twin of the real company in digital form" [8]. In essence, Volkswagen Slovakia built a digital twin of its intralogistics - the internal transport flows and warehouse operations - to gain granular visibility into movements and optimize the use of resources such as forklifts, storage space and routes within the plant.

System Implementation: The digital twin project at VW Slovakia combined hardware and software to bridge the physical and virtual worlds. On the physical side, hundreds of moving assets (forklifts, AGVs, tractors, etc.) in the production halls were equipped with ultra-wideband (UWB) RTLS tags. A network of 66 UWB receivers was installed across 10,000 m² of factory floor space [8], enabling precise real-time tracking of each vehicle's location (with ~50 cm accuracy and sub-second refresh rates). This high-resolution location data was fed into the digital twin software platform - a system known as Twiserion Digital Manager with a visualization interface called ELLA [8]. The virtual model of the twin consisted of a mapped layout of the shop floor and warehouse zones, where each tagged vehicle and load could be visualized moving in real time. In addition, the system ingested other operational data (e.g., forklift idle time, distance traveled, loaded vs. unloaded status) to provide a rich picture of logistics operations. In essence, managers could look at a screen at any given moment and see a live "mirror world" of their factory logistics: which forklifts are where, doing what, and where inventory is located. This is the live monitoring capability of the twin.

But the Volkswagen Slovakia digital twin went beyond passive tracking. The platform included analytics and optimization capabilities to improve logistics performance. For example, the twin continuously calculated traffic density at various aisle intersections and identified emerging bottlenecks in material flow [8]. By analyzing patterns in the RTLS data, the system could suggest route optimizations to drivers-a form of dynamic navigation guidance to avoid congested routes within the plant. The twin also enabled scenario simulation: before implementing a process change (such as rearranging a warehouse area or introducing a new delivery schedule), the logistics team could simulate it within the digital twin to predict the impact without disrupting actual operations [8]. This ability to test "what-if" scenarios in the virtual model helped avoid negative side effects and refine solutions prior to real-world implementation. In short, the digital twin served as both a real-time operational tool and a decision-support simulator.

Results and Conclusions

The deployment of the digital twin and RTLS at the Volkswagen Slovakia plant resulted in significant measurable improvements in logistics KPIs. According to the case study reported by the project team, the twin-driven optimizations resulted in a 20% increase in forklift fleet productivity and a more balanced workload across the fleet [8]. The "forklift OEE" (Overall Equipment Effectiveness for the internal transport fleet) improved by about 20%, meaning that forklifts spent more time productively moving material and less time waiting or running empty. This was achieved through better routing (reducing empty trips) and improved task scheduling using the insights from the twin. In addition, by analyzing the heat maps of forklift movement, the team discovered underutilized storage locations and subsequently rearranged the warehouse layout. Without building new space, they effectively increased usable warehouse space by 20% simply by using space more efficiently, guided by the twin's data [8]. Another concrete result was a 10% reduction in the total distance traveled by the forklift fleet, thanks to the optimized routing and congestion avoidance provided by the twin's navigation system [8]. This not only saves energy and time, but also reduces wear and tear on the vehicles.

Crucially, the digital twin contributed to safety and agility. Real-time visibility of each vehicle's position enabled improved traffic management on the factory floor, helping to prevent accidents by alerting drivers and managers to potential collisions or unsafe approaches. And when disruptions occurred - for example, when a section of the plant was temporarily closed or a rush of urgent orders needed to be handled - the logistics twin enabled rapid rescheduling. Managers could simulate new scheduling or routing in the twin and immediately implement the best alternative with confidence in the outcome. The Plant Logistics Manager at Volkswagen Slovakia praised the system, noting that the live visualization of the internal fleet in the Twin "has brought us increased safety in the workplace" and that the solution "ensures optimal material delivery with respect to current traffic, whether at intersections or along logistics routes" [8]. This underscores that beyond the hard metrics, the Twin has introduced a new level of transparency and responsiveness to operations.

It is also worth noting that the Volkswagen Slovakia case exemplifies the integration of DT with existing enterprise systems. The RTLS and Twin have been linked to the plant's production planning and warehouse management systems, so that logistical decisions (such as staging parts or dispatching forklifts) can be aligned with production needs in real time. The success of this project, which initially focused on the stamping plant's warehouse and forklifts, has led to consideration of extending the approach to other shops and processes within Volkswagen's facilities. In fact, Volkswagen and its partners see the Bratislava implementation as a template for the "smart factory" logistics of the future, where every material movement is visible and can be optimized through a digital twin. The case demonstrates how a traditionally opaque aspect of manufacturing (intralogistics) can be digitized and managed with the same rigor as the production line itself.

In summary, Volkswagen Slovakia's use of a logistics digital twin resulted in more efficient use of material handling equipment, increased warehouse utilization, reduced transit times, and improved safety. The practical lessons learned from this example reinforce the theoretical promise of DT technology: by providing a synchronized virtual counterpart to a complex physical system, hidden inefficiencies become visible and data-driven improvements become achievable. This case also highlights the importance of reliable data collection (in this case, via UWB RTLS) and user-friendly visualization tools to the success of a digital twin project. As more companies adopt digital twins in logistics, Volkswagen Slovakia's example serves as a benchmark for the potential benefits and a blueprint for implementation.

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