THE ROLE OF DIGITAL TWINS IN VERTICAL E-BUSINESS APPLICATIONS

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Abstract: *This paper presents a review of digital twins (DT) application in e-business, with a focus on vertical applications in healthcare, agriculture, and smart cities. Digital twins serve as advanced digital replicas that enhance decision-making and operational efficiencies. The main value of this review is identification of different DT application in e-business, gaps in current research and potential research directions, highlighting the importance of DTs in transforming e-business practices across various domains. In healthcare, they provide realistic simulations for medical training and optimize hospital operations. Agriculture benefits from DTs through enhanced modeling and simulation of complex biological systems, driving the digitization and sustainable practices in the sector. Smart cities utilize DTs for urban planning and infrastructure management, leveraging large-scale data and cloud computing. Despite the promising advancements, gaps exist such as the integration of human factors in healthcare, the comprehensive adoption in agriculture, and the interdisciplinary approach needed in smart cities.*

Keywords: *digital twin, healthcare, smart cities, agriculture, vertical applications*

1. INTRODUCTION

Digital twins (DTs) are accurate digital replicas that integrate real-time data to enhance the efficiency and effectiveness of physical systems across industries like energy and telecommunication (Jafari et al., 2023), aerospace, automotive (Li et al., 2017), healthcare (Xames & Topcu, 2024), agriculture and urban planning and smart cities (Qi et al., 2021). Supported by IoT, AI, machine learning, and big data analytics, these models simulate and analyze physical properties and operations (Qi et al., 2021; Tao et al., 2019). They continuously update from sensor data, ensuring accurate real-time representation and operational diagnostics. While digital twins offer significant advantages, they also pose challenges related to data security, scalability, and ethical considerations, necessitating ongoing research to address these issues and expand their applications (Purcell & Neubauer, 2023).

DTs have rapidly evolved as a pivotal technology in various sectors, propelling e-business into a new era of digital integration. In healthcare, DTs are crucial for simulating both physical spaces and biological entities, significantly enhancing medical training and operational efficiency (Chen et al., 2024; Hassani et al., 2022; Xames & Topcu, 2024). In the agricultural sector, DTs facilitate complex simulations of biological systems, supporting sustainable practices and advancing digitization efforts (Liu et al., 2023; Purcell & Neubauer, 2023; Slob et al., 2023). Similarly, in urban development, DTs contribute to the optimization of city planning and infrastructure management through sophisticated data integration and simulation capabilities (Botín-Sanabria et al., 2022; Jafari et al., 2023; Lehtola et al., 2022).

While the application of DTs is advancing, several critical gaps remain underexplored. In healthcare, the integration of human factors and the transition from theoretical models to practical applications lag behind technological capabilities (Xames & Topcu, 2024). Agriculture's full potential for DTs is hindered by a lack of comprehensive adoption strategies and specific models for varied agricultural practices (Purcell & Neubauer, 2023). In the realm of smart cities, there is a need for more interdisciplinary approaches that combine technological, sociological, and environmental insights to fully leverage DT capabilities (Botín-Sanabria et al., 2022).

This paper aims to bridge these gaps by presenting an in-depth review of current DT applications and identifying unexplored areas that could benefit from further research. By analyzing existing literature and applications, the paper highlights the transformative potential of DTs in e-business and proposes pathways for their fuller integration and utilization across the highlighted sectors.

The rest of the paper is organized as follows: Section 2 shows the theoretical framework behind this research explaining DT as a concept, different architectures and underlying technologies. The third section describes specific applications in healthcare, agriculture, and smart cities, each subsection identifying current implementations, benefits, and gaps. The conclusion synthesizes these findings, proposing future research directions and practical applications.

2. THEORETICAL FRAMEWORK

Digital twin (DT) technology is a key driver in the advancement of Industry 4.0, seamlessly merging cyber and physical spaces (Tao et al., 2019). As a growing field, digital twins have increasingly been used in studies focusing on lifecycle management and predictive analytics across various sectors (Botín-Sanabria et al., 2022). This technology provides comprehensive insights into system operations, interactions between system components, and the anticipated behaviors of their physical counterparts, offering practical benefits for users and stakeholders (Tao et al., 2019). While DTs are seen as innovative, they are essentially an evolution of existing technologies such as 3D modeling, system simulation, and digital prototyping, which includes geometric, functional, and behavioral aspects (Qi et al., 2021).

The origin of the Digital Twin concept can be traced back to a 2002 presentation at the University of Michigan, by dr Grieves titled “Conceptual Ideal for PLM” (Grieves & Vickers, 2016). This slide, although simple, contained all the fundamental components of a DT, including the physical space, virtual space, a connection for data transfer from physical to virtual space, a conduit for information flow from virtual to real space, and various virtual sub-spaces. All five components are critical for DT, and require full integration of data flow in both directions (physical-virtual and virtual-physical) (Fuller et al., 2020). The physical component forms the foundation for constructing the virtual counterpart. This virtual element facilitates the simulation, decision-making, and control processes of the physical component (Grieves & Vickers, 2016; Tao et al., 2019). Central to DTs is data, which is essential as it serves as the basis for generating new knowledge (Tao et al., 2019).

Digital twin is not a singular technology. It is a term encompassing various technologies working together to create a digital replica of the physical product, or a process. Technologies enabling DTs include, but are not limited to (Fuller et al., 2020) (Table 1):

Table 1: DT enabling technologies

Domain	Technology layer	Enabling technology
A - Application Domain	Model Architecture and Visualization Software and APIs Data collection and Pre-processing	3D modeling Business process modeling Computer Simulation Virtual and extended reality Internet of Things Cloud computing and infrastructure
B - Middleware Domain	Storage Technology Data Processing	Cloud computing and infrastructure Blockchain Big data analytics Artificial intelligence Machine learning
C - Networking Domain	Communication Technology Wireless Communication	Cloud computing and infrastructure Internet of Things Mobile technologies, 5G
D - Object Domain	Hardware Platform Sensor Technology	Cloud computing and infrastructure Internet of things

The Application Domain of enabling technologies for DTs facilitates the creation, visualization, and data handling of detailed virtual models that enhance the interaction and management of their physical counterparts. The Middleware Domain provides storage and processing of data collected within the A domain, ensuring the transfer between B and C domains. The Networking Domain enables consistent communication between the domains and layers and wireless communication for data transmission. The last domain ensures the correct hardware is in place to conduct the DT analysis (Fuller et al., 2020).

3. DIGITAL TWINS IN VERTICAL APPLICATIONS

Vertical applications, as mentioned in the IEEE Technology Predictions Report for 2024 (Abedi et al., 2024), refer to specialized digital solutions designed to meet the unique needs of specific industries or sectors. These applications focus on addressing the particular challenges and requirements of various sectors, enhancing efficiency, productivity, and innovation within those industries. Vertical applications refer to industry verticals, segments of an industry that focuses on a particular niche or market (*What Is an Industry Vertical?* **|** *Enigma*, n.d.). When talking about vertical applications, we are mostly focusing on following industry verticals (Abedi et al., 2024; *ATIS' Next G Alliance Maps the Future of 6G Vertical Applications – ATIS*, n.d.; ATIS, 2023): Agriculture; Automotive; Education, Gaming and Entertainment; eHealth; Industrial; Mining; Public Safety and Smart Cities.

While DT as a concept has been applied in various industries and domains such as energy and telecommunication, aerospace, automotive, healthcare, agriculture and urban planning and smart cities, this paper will focus on healthcare, agriculture and smart cities. These industry verticals have been identified as key beneficiaries of advancements in state-of-the-art predictions, what-if analysis and oversight, that DT technology brings (Abedi et al., 2024).

3.1. DT in Healthcare

One of the main areas of DT application is medicine and healthcare. DTs have emerged as a transformative technology in healthcare, revolutionizing various aspects from clinical applications to operational management (Sun et al., n.d.). The integration of DTs enhances diagnostic accuracy, treatment personalization (Hassani et al., 2022), and healthcare facility operations, promising significant advancements in patient care and system efficiencies. Figure 1 shows how DT technology transforms healthcare services.

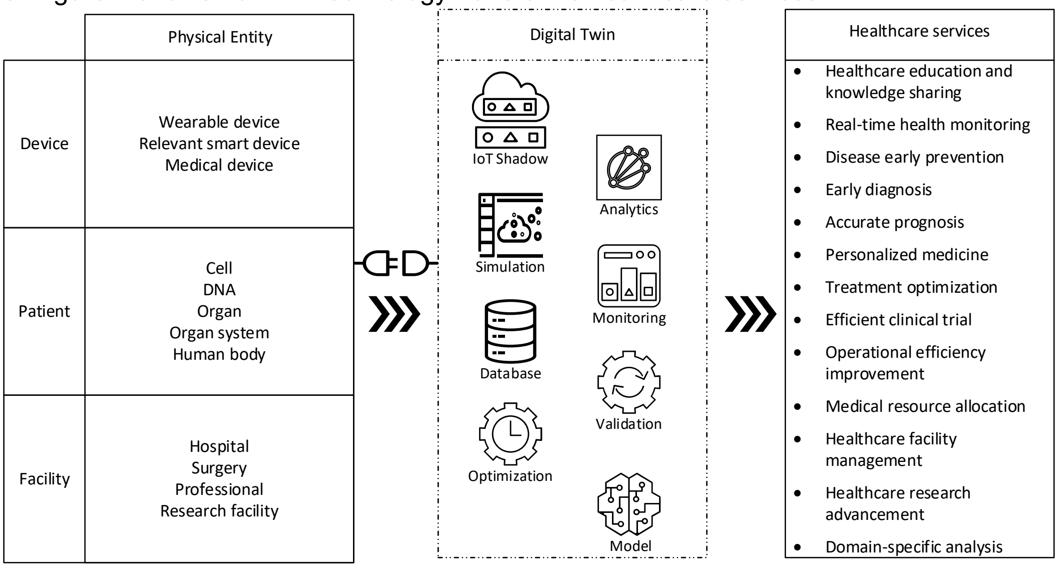

Figure 1 Digital twin in Healthcare (Hassani et al., 2022)

In clinical applications, DTs have demonstrated substantial benefits across several domains. Specifically, In cardiovascular healthcare, DT technology facilitates precise heart modeling, supporting both diagnosis and interventional procedures(Sun et al., n.d.). Similarly, (Coorey et al., 2022) highlight the deployment of DTs in cardiovascular disease management, stressing their potential in improving outcomes through sophisticated simulation models that anticipate patient-specific reactions to treatments.

Beyond cardiology, DTs extend their utility to areas like surgery, where they provide detailed pre-surgical planning and simulations, and pharmacy, where they model metabolic responses to drugs, allowing for personalized medicine (Sun et al., n.d.). These applications underscore DTs' capacity to adapt treatments to individual patient needs, significantly reducing risks and enhancing therapeutic efficacy.

However, the path to integrating DTs in healthcare is full of challenges. Data integration, real-time processing capabilities, and ethical concerns about data privacy present an unsolved hindrance (Hassani et al., 2022). Moreover, the interdisciplinary nature of DT development necessitates a collaborative approach involving various stakeholders to realize its full potential (Coorey et al., 2022). Another major gap highlighted by (Xames & Topcu, 2024) is the lack of implementation research. While many studies propose theoretical models and conceptual frameworks for DTs in healthcare, there is a need for more empirical studies that move beyond conceptualization to evaluate the effectiveness, usability, and impact of DTs in live healthcare environments.

3.2. DT in Agriculture

The agriculture industry can benefit immensely by integrating DT. Some of the areas of enhancement are precision, sustainability, and operational efficiency. Sophisticated modeling of crop and livestock systems, enabled by DT technology, facilitates real-time monitoring and predictive analytics, leading to more informed decision-making (Ghazvini & Sharef, 2023; Purcell et al., 2023; Purcell & Neubauer, 2023). In crop management, DTs specifically aid in precise nutrient management and disease control. For example,(Ghazvini & Sharef, 2023) describe a DT model for rice that uses regression algorithms to accurately predict nutrient concentrations and compositions, thereby optimizing fertilization practices and reducing environmental impact by preventing fertilizer overuse.

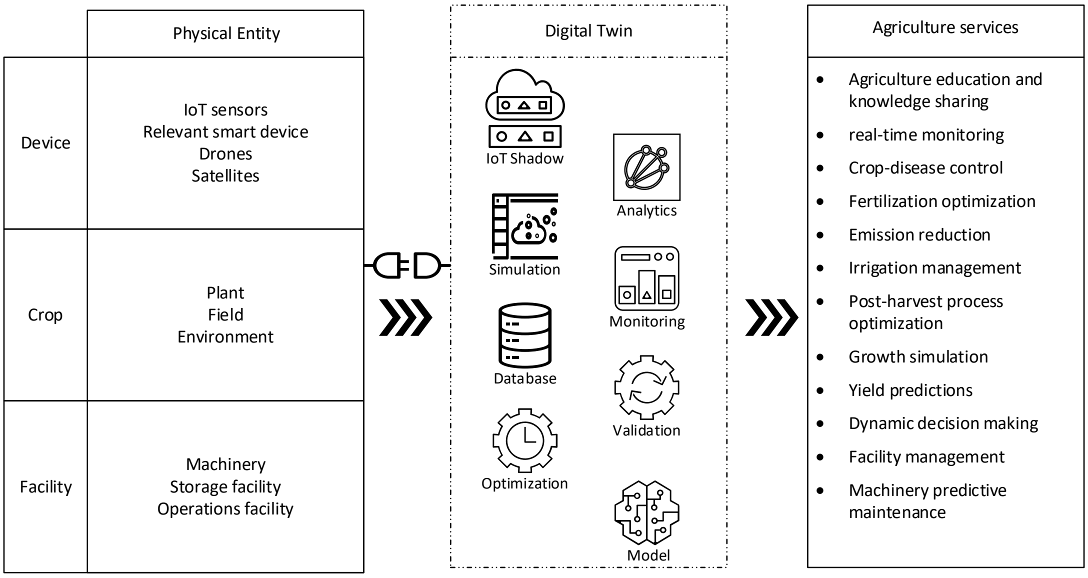

Figure 2 Digital Twin in Agriculture

Expanding the application of DTs, (Purcell & Neubauer, 2023) showcase how these technologies enhance livestock monitoring, crop input optimization, and emissions reduction (Fig 2). Similarly,(Nasirahmadi & Hensel, 2022) emphasize DTs' contributions to soil and irrigation management, as well as post-harvest processes, which collectively improve water use, crop productivity, and food quality. In the specific arena of greenhouse horticulture, (Ariesen-Verschuur et al., 2022; Slob et al., 2023) explore DTs' capabilities in growth simulation and yield prediction, integrated with greenhouse control systems for better-automated management. These studies highlight the critical role of DTs in addressing global challenges like food security and climate change, advocating for continued technological advancement and a multidisciplinary approach to ensure DTs' sustainable development in agriculture.

3.3. DT in Smart Cities

Digital Twins are reshaping urban landscapes by offering sophisticated solutions for city management, planning, and governance. DTs are utilized in urban management by creating dynamic, virtual replicas of cities that integrate real-time data from IoT devices, sensors, and other digital sources (Botín-Sanabria et al., 2022). This technology supports city planners in simulating and analyzing urban scenarios, enhancing decision-making, and improving public services, with systems like GIS and BIM providing high-fidelity content that accurately reflects the urban environment (Deng et al., 2021; Lehtola et al., 2022). DTs contribute to sustainable urban planning by optimizing resource use and infrastructure development, supporting public safety through efficient emergency response systems, and fostering greater public participation in planning processes, making them more inclusive and transparent (White et al., 2021).

Furthermore, DTs are vital in managing energy systems within smart cities, enhancing the efficiency of smart grids and transportation systems through capabilities like real-time monitoring, system management, fault detection, and predictive maintenance (Jafari et al., 2023). Practical implementations, such as Dublin’s Docklands digital twin model, showcase DTs' ability to simulate new building developments, green spaces, and flood scenarios, enabling effective community engagement and feedback integration into urban planning and policy-making (White et al., 2021). This hands-on application highlights DTs’ potential to transform urban landscapes into smarter, more responsive, and sustainable environments.

Having this in mind, (fig 3) shows how city can be transformed into a smart city utilizing devices, citizens and DT technology.

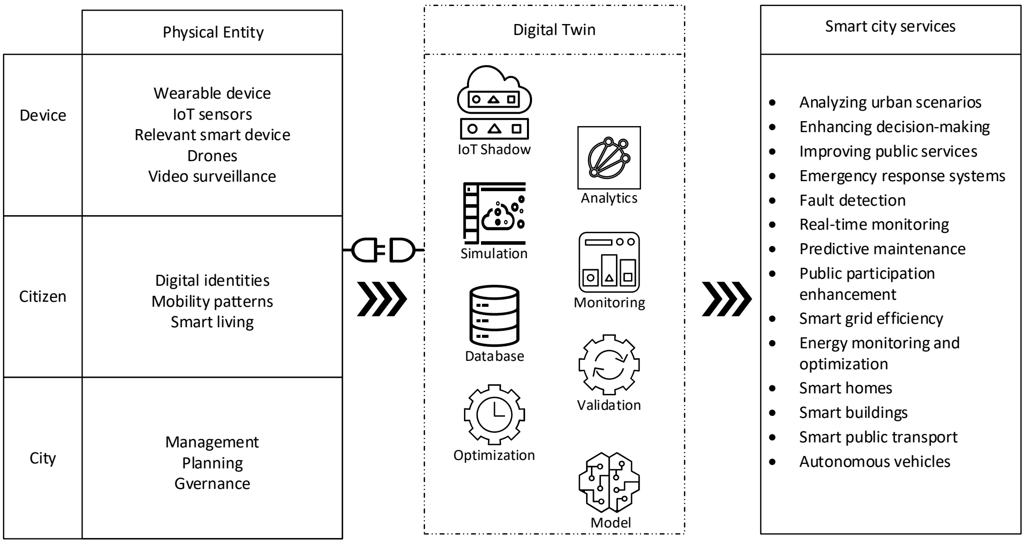

Figure 3 Digital Twin in Smart Cities

4. DISCUSSION AND CONCLUSION

Digital Twins in vertical applications like healthcare, agriculture, and smart cities offer transformative potentials but also face significant challenges and limitations that must be addressed to realize their full benefits.

In healthcare, the future of DTs lies in enhancing precision in health monitoring and predictive healthcare (Hassani et al., 2022), potentially leading to earlier interventions and better health outcomes. However, challenges such as the integration of advanced technologies into clinical settings, data privacy concerns (Venkatesh et al., 2024), and the need for substantial infrastructural changes pose barriers to adoption. (Venkatesh et al., 2024) emphasize that advancing drug discovery and personalized medicine through DTs will require overcoming socioeconomic and regulatory challenges to ensure equitable access and effective implementation.

In agriculture, DTs promise to revolutionize farming practices through improved data integration and IoT technology (Nasirahmadi & Hensel, 2022). Yet, the adoption faces technological challenges such as managing data from diverse sources and ensuring real-time data processing capabilities. Socioeconomic barriers, accessibility, affordability, and the need for training reflect the multifaceted challenges in this sector. Environmental considerations are also crucial, as DT implementations must not exacerbate existing ecological issues or fail to adapt to climate change impacts. Ethical and social considerations, including data security and potential job displacement due to automation, are paramount for ensuring that DT adoption is secure and socially beneficial.

For smart cities, DTs hold the promise of making urban areas more efficient, sustainable, and responsive to citizen needs. However, similar to healthcare and agriculture, challenges such as data integration, cybersecurity, and maintaining the continuity and reliability of digital models are significant. These issues require ongoing research and interdisciplinary efforts to develop robust and secure DT frameworks capable of handling urban complexities (Botín-Sanabria et al., 2022).

Overall, while DTs present a forward-looking approach to managing complex systems across various domains, their successful integration hinges on overcoming these diverse challenges. The future of DTs will depend on continuous technological innovations, policy support, and ethical considerations, ensuring that these powerful tools enhance rather than complicate the sectors they are meant to transform.

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