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ДИГИТАЛНИ БЛИЗНАЦИ В КОНТЕКСТА НА ИНДУСТРИЯ 4.0: СЪЩНОСТ, ХАРАКТЕРИСТИКИ И ПЕРСПЕКТИВИ

DIGITAL TWINS IN THE CONTEXT OF INDUSTRY 4.0: ESSENCE, CHARACTERISTICS, AND PROSPECTS

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Abstract: In the context of accelerated digitalization and the development of Industry 4.0, digital twins are becoming a crucial tool for transforming industrial enterprises. This study aims to analyze the core of digital twins by identifying their main features and exploring their potential applications in manufacturing settings. The article reviews existing scientific definitions and traces the evolution of the concept, focusing on the relationship between physical and virtual systems in real time. Key characteristics include integration with the Internet of Things, simulation and forecasting abilities, and support for management decision-making. The primary areas where digital twins are applied in industry are examined, such as optimizing production processes and enabling predictive maintenance. Lastly, the study discusses prospects and challenges for implementing digital twins, considering technological, organizational, and economic factors. The findings contribute to a better understanding of the role of digital twins in modern industrial transformation.
Keywords: digital twins; Industry 4.0; artificial intelligence; Internet of Things.
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INTRODUCTION

Rapid advances in digital technology and increasing global competitiveness are dramatically transforming the industrial landscape. In this context, the Industry 4.0 paradigm has emerged as a groundbreaking framework that integrates cyber-physical systems, the Internet of Things (IoT), artificial intelligence (AI), and big data analytics within manufacturing. This convergence simplifies the shift from traditional production methods to intelligent, interconnected, data-driven industrial ecosystems that depend heavily on real-time information sharing and autonomous decision-making.

Among the technologies enabling Industry 4.0, digital twins have attracted growing academic and practical interest for their ability to connect the physical and virtual worlds. A digital twin is broadly defined as a dynamic digital replica of a physical asset, process, or system, continually updated with real-time data and capable of simulating, predicting, and optimizing its real-world counterpart.

By establishing a two-way data flow between physical entities and their virtual counterparts, digital twins improve visibility, boost operational efficiency, and support advanced decision-making throughout the product lifecycle. Although there is an increasing body of literature on digital twins, the concept remains open to various interpretations owing to its multidisciplinary nature and rapid technological development. Current research mainly concentrates on technical architectures, data integration, and engineering applications, with less emphasis on systematic conceptualization of digital twins and

their broader implications for industrial management and organizational change. This scattered focus highlights the need for a comprehensive synthesis that consolidates existing research and clarifies the defining features of digital twins within the Industry 4. 0 paradigm.

Addressing this gap, the current study aims to explore the core of digital twins by critically evaluating and organizing their fundamental characteristics and detailing their potential uses in industrial organizations. The study seeks to contribute to the literature by developing a structured conceptual framework that encompasses technological, functional, and managerial perspectives. Additionally, it outlines key potentials and limitations associated with digital twin deployment, laying the foundation for future empirical research and practical implementation.

LITERATURE REVIEW

The concept of the digital twin originated in the early 2000s and is strongly related to the development of product lifecycle management (PLM). Michael Grieves was the first to introduce the concept of the digital twin, which he defined as a virtual version of a physical asset linked by data flows (Grieves, 2014). Later, this concept was refined in collaboration with John Vickers, highlighting the integration of physical and virtual systems throughout a product's lifecycle (Grieves & Vickers, 2017). A digital twin is a set of virtual information constructs that fully describe a physical object and allow for real-time interaction between physical and digital worlds (Grieves, 2014), (Grieves & Vickers, 2017).

Glaessgen and Stargel offer further theoretical development by defining the digital twin as a multiphysics and multiscale simulation model capable of replicating the lifecycle of complex systems, especially in aeronautical applications (Glaessgen & Stargel, 2014).

A significant contribution to clarifying the concept of digital twins is made by Kritzinger et al., who differentiate between digital models, digital shadows, and digital twins, emphasizing that only the latter involves automated, bidirectional data exchange (Kritzinger, et al., 2018). This distinction has become essential in later research.

Furthermore, Tao et al. introduce a five-dimensional model of digital twins that includes physical entities, virtual models, data, services, and relationships (Tao, 2019). This method has been widely adopted in smart manufacturing and Industry 4.0, significantly strengthening the field's theoretical foundation.

In recent years, research on digital twins has expanded significantly, focusing on enhanced architectures, intelligent systems, and integration with emerging technologies. For example, Zheng, Lu, and Kiritsis develop the concept of cognitive digital twins, which combine semantic information and artificial intelligence to boost decision-making capabilities in manufacturing systems (Zheng, et al., 2022).

Similarly, Zhou et al. explore the origins and fundamentals of digital twins, emphasizing their evolution from simulation-based models to dynamic, data-driven systems that support real-time decision-making (Zhou, et al., 2022).

More recent review studies have highlighted the importance of digital twins in enabling intelligent, interconnected systems. For instance, Wang et al. give a detailed assessment of digital twin architectures, supporting technologies, and security problems, emphasizing their importance in the upcoming Internet of Digital Twins (IoDT) (Wang, et al., 2023).

Furthermore, current conceptual research emphasizes the philosophical and systemic foundations of digital twins, describing them as integrated frameworks that facilitate the convergence of data, models, and decision-making processes within complex systems (Rosen, et al., 2015), (Wagg, et al., 2025).

Recent research has also highlighted application-focused perspectives. For instance, knowledge-driven and AI-enabled digital twin systems are being used to optimize industrial processes, enhance predictive maintenance, and boost operational efficiency (Su, et al., 2024).

Furthermore, comprehensive edited volumes like Crespi, Drobot, and Minerva summarize the evolution, technology, and future potential of digital twins across various industries, highlighting their strategic role in digital transformation. (Crespi, et al., 2023).

METHODOLOGY

This study employs a qualitative research design, grounded in a structured, integrative literature review, to explore the core features and outlook of digital twins within the Industry 4.0 framework.

Given the conceptual nature of the research and the absence of a universally accepted definition, a theory-building approach is used to synthesize and organize current knowledge. The empirical foundation of the study consists of peer-reviewed academic publications retrieved from major scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and IEEE Xplore.

The literature review used a combination of terms, including "digital twin," "Industry 4.0," "smart manufacturing," and "cyber-physical systems." The inclusion criteria targeted both highly cited foundational works and recent publications from 2022 to 2026 to ensure both theoretical depth and relevance.

The collected materials were analyzed using qualitative content analysis, focusing on the definitions, structural components, and functional aspects of digital twins, as well as their applications in industrial settings.

A comparative method was employed to identify similarities and differences across studies and to distinguish digital twins from related concepts such as digital models and digital shadows.

Based on this review, a conceptual synthesis was developed to organize the defining features of digital twins and position them within the broader ecosystem of Industry 4.0 technologies. This approach facilitates the identification of key trends, challenges, and research gaps, thus providing a foundation for future empirical studies.

DISCUSSION

The current study's findings show that digital twins are shifting from a mainly technological concept to a strategic tool for driving industrial change within the Industry 4.0 framework. Recent legislative documents, market research, and scientific publications strongly support this shift, highlighting the technology's rapid growth and increasing importance for industrial ecosystems.

One of the key trends is the rapid adoption of digital twin technology in the market. According to a report by Research and Markets (2024), the global digital twin market is projected to grow from USD 11.5 billion in 2023 to approximately USD 119.3 billion by 2029, driven by increased access to real-time data, IoT expansion, and advancements in connectivity technologies. Similarly, Markets & Markets (2025) forecast that the global market will reach about USD 150 billion by 2030, with an annual growth rate exceeding 45%, emphasizing the strategic importance of digital twins for businesses (Research and Markets, 2024), (Markets and Markets, 2025).

At the European level, digital twin development is closely linked to the twin transition — digital and green transformation — as emphasized in the European Research Area policy agenda (European Commission, 2021). This link is strengthened by flagship initiatives like Destination Earth (DestinE), which aims to create a highly accurate digital replica of the world to support environmental monitoring and policymaking (European Commission, 2025). At the same time, the European Digital Twin of the Ocean project demonstrates how digital twins can be used in large-scale, data-rich environments, enabling real-time analysis and predictive simulations for sustainable resource management (European Commission, 2022).

Recent reports indicate that digital twins are being rapidly adopted across industrial sectors, including predictive maintenance, process optimization, and lifecycle management. The manufacturing sector is the primary focus of digital twins, which enable real-time monitoring and modeling of production processes leading to increased efficiency and reduced downtime (Virtue Market Research, 2024). Additionally, combining digital twins with artificial intelligence and machine learning is seen as a key driver of future growth, enabling more advanced, autonomous, and adaptable systems.

Another significant development is the rapid growth of the European digital twin industry, driven by sustainability standards and regulatory requirements. According to Markets & Markets, the European market is expected to grow from USD 7.08 billion in 2025 to USD 49.32 billion by 2030, primarily due to demand for energy efficiency, emissions monitoring, and compliance with environmental laws (Markets and Markets, 2026). Complementary analyses also indicate that Europe will remain a leading

region, thanks to investments in smart infrastructure, digital innovation hubs, and industrial modernization (Global Market Insights, 2024).

Beyond technological and economic factors, recent academic research has identified several significant obstacles to the widespread adoption of digital twins. Jørgensen and Ma highlight issues such as interoperability, data governance, cybersecurity, and the lack of shared frameworks among businesses (Jørgensen & Ma, 2025). High implementation costs and a shortage of skilled personnel are often mentioned as challenges, particularly for small and medium-sized enterprises.

Looking ahead, the future development of digital twins is expected to follow several key directions:

1. Integration with emerging technologies, especially AI, edge computing, and 5G/6G networks, which facilitate real-time, autonomous decision-making systems;

2. Expansion toward Industry 5.0, focusing more on human-centered, sustainable, and resilient manufacturing processes;

3. Development of large-scale digital ecosystems, including digital twins of cities, infrastructure, and entire environmental systems;

4. Adoption of international standards, such as ISO frameworks, and legislative efforts to promote standardization and interoperability;

5. Greater accessibility for SMEs, supported by cloud-based solutions and European initiatives like the Digital Europe Programme (European Commission, 2025).

In this context, digital twins are expected to play a key role not only in optimizing industrial operations but also in supporting wider societal goals such as sustainability, resilience, and data-driven governance. Their development toward smarter, more connected, and scalable systems will further strengthen their position as a fundamental part of future industrial and digital ecosystems

CONCLUSION

This paper offers a comprehensive conceptual synthesis of digital twins within the Industry 4.0 context, enhancing existing scholarly discussion by clarifying their core principles, outlining their main characteristics, and describing their evolving role in industrial transformation. By integrating foundational and recent research, the study addresses the field's fragmentation and provides a structured understanding that connects technological, functional, and managerial perspectives.

The findings confirm that digital twins are no longer restricted to their original engineering and simulation uses but are increasingly employed as strategic tools to boost operational efficiency, enable predictive functions, and support data-driven decision-making across industrial organizations. Their ability to create a dynamic, bidirectional link between physical and virtual systems makes them an essential part of intelligent manufacturing and a key driver of the broader Industry 4.0 ecosystem.

Meanwhile, the study highlights that developing and implementing digital twins is shaped by a complex interaction of technological advances, market trends, and policy initiatives, especially within the European context of twin digital and green transitions. Despite their significant potential, widespread adoption faces challenges such as interoperability, data governance, standardization, and the need for skilled human resources.

Looking forward, digital twins are expected to become more autonomous, scalable, and integrated with technologies like artificial intelligence, edge computing, and next-generation connectivity infrastructure. Their significance is also likely to expand beyond industrial settings, aiding in the development of large-scale digital ecosystems and supporting sustainability objectives.

Finally, this research enhances the conceptual clarity of digital twins and identifies key areas for future investigation. There is a particular need for more empirical studies focusing on organizational, economic, and managerial factors, as well as the development of implementation frameworks tailored to different types of enterprises, especially small and medium-sized businesses. These efforts will be crucial to fully harness the revolutionary potential of digital twins in the next stage of industrial and digital evolution.

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