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DIGITAL MODELING AND SIMULATION IN INDUSTRY

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Аннотация:

В статье рассматриваются современные методы цифрового моделирования и симуляции в промышленности, включая использование технологии «цифровых двойников». Показано, что цифровое моделирование играет ключевую роль в повышении эффективности, оптимизации производственных процессов и прогнозировании отказов оборудования. Особое внимание уделено интеграции цифровых моделей с промышленным интернетом вещей (IIoT), киберфизическими системами (CPS), а также применению искусственного интеллекта и облачных технологий. Определены основные вызовы внедрения — высокая стоимость, вопросы совместимости систем, кибербезопасность и дефицит квалифицированных кадров. Сделан вывод о том, что цифровое моделирование является фундаментом умного производства и трансформации промышленности в условиях индустрии .

Ключевые слова

цифровое моделирование, цифровой двойник, симуляция, киберфизические системы, индустрия 4.0, промышленный интернет вещей, умное производство.

Abstract:

The article examines modern methods of digital modeling and simulation in industry, with a special focus on the concept of “digital twins.” It is demonstrated that digital modeling plays a crucial role in improving efficiency, optimizing production processes, and predicting equipment failures. Particular attention is given to the integration of digital models with the Industrial Internet of Things (IIoT), cyber-physical systems (CPS), as well as the application of artificial intelligence and cloud technologies. The main challenges of implementation are identified, including high costs, interoperability issues, cybersecurity risks, and the shortage of skilled workforce. The study concludes that digital modeling represents

a cornerstone of smart manufacturing and industrial transformation within the framework of Industry 4.0.

Keywords

digital modeling, digital twin, simulation, cyber-physical systems, Industry 4.0, Industrial Internet of Things, smart manufacturing.

Introduction

The current state of affairs in the industry is characterized by a profound transformation driven by the impact of digital technologies. A pivotal aspect of this metamorphosis is the widespread adoption of digital modelling and simulation techniques.

These methods allow for the development of precise virtual representations of physical entities, processes, and manufacturing systems, which can be employed throughout the entire lifecycle of a product — from conception to operation and eventual decommissioning.

The utility of digital models becomes particularly evident in situations where swift decision-making is essential, and cost optimization is of paramount importance. A critical component of these models lies in the creation of «digital twins», which are synchronized virtual counterparts of real-world assets that can be closely monitored using sensor data and advanced analytical tools.

Digital twins enable real-time surveillance and analysis, offering invaluable insights into the performance of physical systems, thereby empowering more informed decision-making processes.

The introduction of digital twins opens up new horizons in monitoring the condition of equipment, predicting potential failures, optimizing production processes and increasing the level of automation. These technologies are inextricably linked to the development of cyber-physical systems (CPS), which integrate physical devices, software, and network components into an intelligent environment.

Digital modeling and simulation technologies are widely used in various industries such as mechanical engineering, energy, aircraft, logistics, and others. However, effective use of these technologies requires an integrated approach that includes integration with the Industrial Internet of Things (IIoT), specialized modeling programs (CAE, CFD), lifecycle management systems (PLM), and cloud computing.

In addition to these obstacles, there are lingering issues such as reconciling the disparate systems and harmonizing data standards. Information security concerns and the substantial expenses associated with implementation present additional challenges. Nonetheless, digital modeling and simulation are emerging as an indispensable component of the contemporary industry, paving the way for a future characterized by sustainable, intelligent, and adaptable manufacturing practices.

Methods and Technologies of Digital Modeling

Digital modeling and simulation have become essential components of modern industry, enabling the accurate reproduction of physical processes in a virtual environment. The digital twin, a dynamic digital model linked to a physical object through data collected from sensors and industrial internet of things (IIoT) devices, is a central technology in this area. As noted by Grieves and Vickers, the digital twin "connects the virtual and physical worlds" and allows for both monitoring of the current state of an object and prediction of its future behavior [1].

Key tools for digital modeling include computer-aided engineering (CAE) systems, which are used for engineering calculations and analysis of structure behavior under load.

- CFD modeling (Computational Fluid Dynamics) — simulates the behavior of liquids and gases, particularly important in thermal and aerodynamic applications;
- PLM platforms (Product Lifecycle Management) — support the digital model throughout all stages of the product life cycle, from design to disposal [2];
- Cloud computing and HPC (High-Performance Computing) — enable large-scale processing of simulation data in real time;
- AR/VR tools — used for immersive visualization and interaction with digital models.

From a technical perspective, the successful implementation of digital modeling requires a robust data transmission and processing architecture. According to Tao and colleagues, an effective digital twin should be embedded within the enterprise control loop and be highly integrated with the physical object [3].

It is of particular importance to integrate digital modeling into **cyber-physical production systems**. These systems combine physical and computational components into a unified network that can adapt to changes in the production environment.

Monostori emphasizes that cyber-physical systems are becoming the technological backbone of smart manufacturing. Simulation plays a crucial role in decision-making processes in these systems, as it allows for accurate predictions and automated control based on data analysis and forecasting [4].

Therefore, digital modeling goes beyond being a mere visualization tool. It is a critical component of modern engineering thinking that relies on data analysis, prediction, and automated control to enhance industrial competitiveness in today's digital economy.

Industrial Applications of Digital Modeling

Digital modeling has become an essential tool in the ongoing transformation of industrial systems. It is used in manufacturing, energy, aerospace, and other industries where it helps with predictive analytics, system optimization, and strategic decision-making. Through the use of advanced simulation tools and digital twins, businesses can virtualize complex production and operational processes with great accuracy.

In the manufacturing industry, digital twins allow for comprehensive modeling of production lines. This includes the behavior of machinery, material flow, and scheduling dynamics. Grieves and Vickers have observed that such virtual environments support continuous data-driven improvement of operations. This allows for real-time monitoring of performance and dynamic process reconfiguration in response to external disturbances [1]. These capabilities are essential for implementing just-in-time manufacturing and minimizing non-value-added activities throughout the value chain.

In the energy sector, digital modeling is particularly beneficial for system-level simulations. Tao et al. explain how digital twin-enabled virtual power plants can analyze real-time sensor data to optimize load distribution, maintenance schedules, and component degradation. This contributes to enhanced operational resilience and reduced life cycle costs [2].

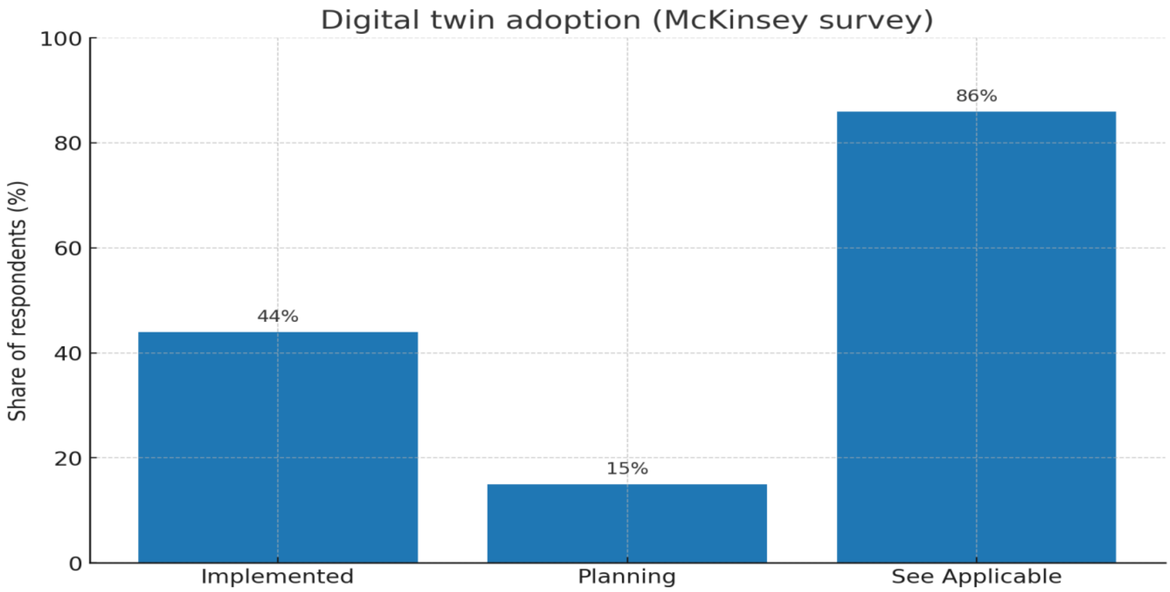
In industries with high reliability requirements, such as aerospace and automotive, simulation plays a crucial role in facilitating multiphysics modeling of components under extreme conditions. This reduces the need for physical prototyping, which can be time-consuming and costly.

The integration of virtual testing into the design process enables accelerated certification cycles, leading to more efficient and sustainable production. By limiting material waste, this approach also supports the lifecycle sustainability of products.

Additionally, Monostori emphasizes the strategic importance of cyber-physical production systems (CPPS). These systems integrate simulation modules into factories, allowing for the transition from deterministic, rule-based control to adaptive, feedback-driven models [3]. This shift enhances the ability to respond to market volatility, supply chain uncertainties, and customized demands.

In conclusion, the adoption of digital modeling techniques represents a paradigm shift towards intelligent manufacturing systems. These systems are characterized by the systematic integration of simulation, analysis, and cyber-physical feedback, enabling continuous optimization of industrial processes and strategic flexibility in complex, data-rich environments.

According to a McKinsey (2024) survey, 44% of respondents have already implemented a digital twin, 15% plan to do so, and 86% consider the technology applicable to their organization (Figure 1).



Challenges and Future Directions in Digital Modeling

Despite the transformative potential of digital modeling, its implementation in industrial settings is accompanied by several technical, organizational, and economic challenges. A key issue is the interoperability of digital systems. Ensuring smooth integration between simulation tools, sensor networks, and corporate information systems is a significant obstacle to widespread adoption [2]. Heterogeneous software standards and outdated infrastructure often impede data exchange and real-time synchronization.

Another significant challenge is the validation and accuracy of simulation models. Although digital twins can replicate complex behaviors, their predictive capabilities are highly dependent on the quality of the input data and the accuracy of the underlying physical models. As Grieves and Vickers point out, discrepancies between virtual and physical systems can lead to erroneous assumptions and suboptimal decisions if they are not properly calibrated [1].

Additionally, the economic costs of implementing digital modeling technologies, particularly for small and medium-sized enterprises, can be prohibitive. These costs include not only software and hardware expenses, but also the need for specialized staff to configure and maintain simulation environments. To address this issue, Monostori emphasizes the need for scalable solutions and mechanisms for transferring knowledge to democratize access to cyber-physical systems [3].

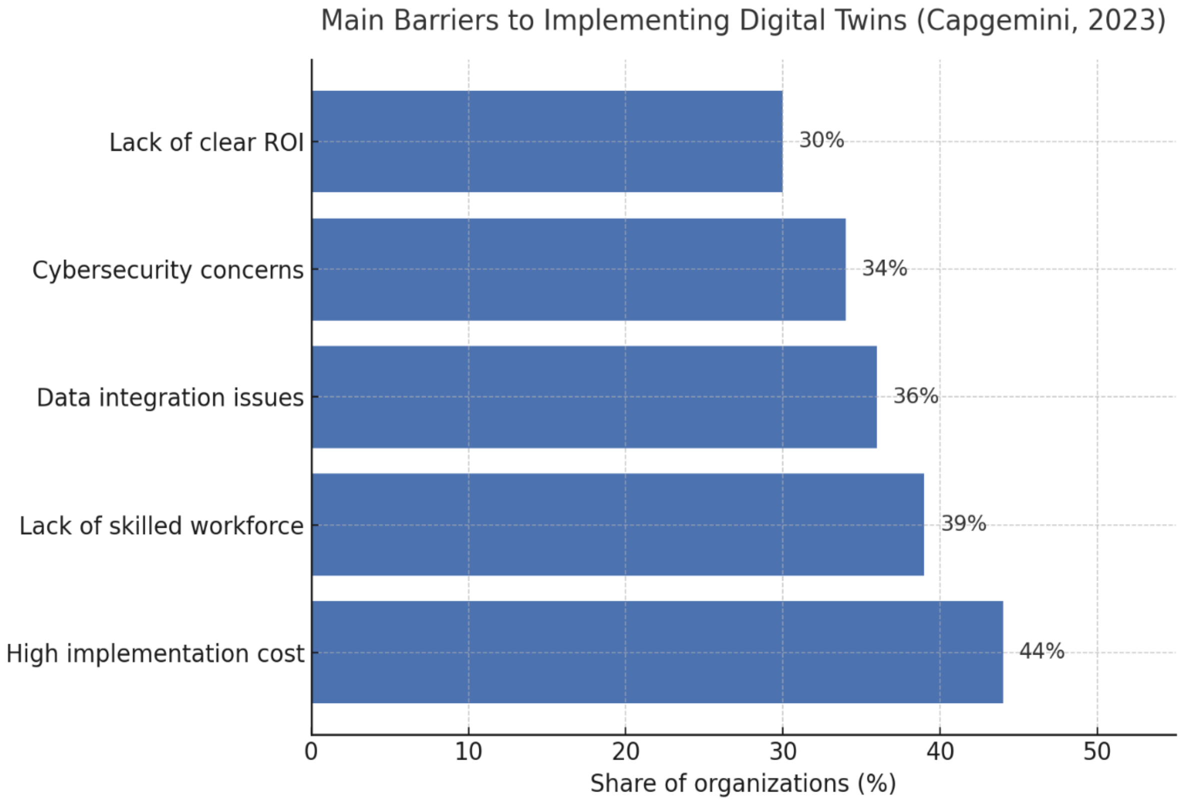
From a strategic perspective, the future of digital modeling is closely tied to advances in artificial intelligence and edge computing. Integration of machine learning algorithms with simulation tools enables autonomous model refinement and real-time anomaly detection. Moreover, the decentralization of processing through edge computing promises to reduce latency and enhance responsiveness in time-critical industrial applications.

While digital modeling stands as a cornerstone of Industry 4.0, its future success depends on addressing current limitations in interoperability, model accuracy, economic accessibility, and human capital development. Continued interdisciplinary research and collaborative innovation between academia and industry will be key to unlocking its full potential.

According to Capgemini Research Institute (2023), the most common barriers to implementing digital twins include high implementation cost (44%), lack of skilled workforce (39%), data integration issues (36%), cybersecurity concerns (34%), and lack of clear ROI (30%) (Figure 2).

Conclusion

Digital modeling and simulation are fundamental pillars in the digital transformation of modern industrial systems. They go beyond being auxiliary support tools and represent a paradigm shift towards data-driven and model-based engineering practices. These practices allow for high-fidelity virtual prototyping, real-time process optimization, and adaptive operational control in cyber-physical environments. The integration of digital twins enables bidirectional interaction between physical assets and their virtual representations, enabling predictive diagnostics and improved decision-making support.



Despite the numerous benefits of digital modeling technologies, their widespread adoption is contingent upon addressing several interdisciplinary challenges. These include interoperability between heterogeneous platforms, robustness of simulation models in terms of epistemology and scalability of technology adoption across different enterprise capacities. Aligning digital modeling infrastructure with enterprise resource planning systems, manufacturing execution systems and Internet of Things architectures remains a complex task requiring standardized protocols and reliable middleware solutions.

From a forward-thinking perspective, the integration of machine learning, edge analytics, and real-time simulation has the potential to drive the development of autonomous industrial systems. These systems will be able to dynamically respond to changing production conditions and continuously optimize themselves. This vision requires strategic convergence across industrial research fields, supported by collaboration between academia, industry, and public organizations. The trajectory of digital modeling will continue to shape the structure and operation of next-generation manufacturing systems. Its evolution represents a systemic reconfiguration of industry in response to the demands of efficiency, flexibility, and sustainability in today's complex global economy.

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