Siemens' Industrial Internet of Things and Digital Twin Pioneers New Pathways for Digital Transformation in Manufacturing

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Abstract: With the advent of the Industry 4.0 era, the Industrial Internet of Things and digital twins have become the core drivers for intelligent transformation in manufacturing. This paper examines Siemens, a global manufacturing giant, to explore how its strategic approach of 'virtual-physical convergence' enabled a successful transition from a traditional electrical and automation hardware manufacturer to a digital industrial technology service provider. The study employs case study methodology, literature analysis, and inductive-deductive reasoning to conduct a comparative analysis of recent global and Chinese industrial Internet of Things data alongside digital twin technologies.Research reveals that Siemens has achieved closed-loop management across the entire product lifecycle-from design and production planning to after-sales service-by deeply integrating the data acquisition capabilities of the Industrial Internet of Things with the simulation and predictive capabilities of digital twins through open platforms such as MindSphere and Xcelerator. This convergence not only enhances productivity and energy efficiency but also drives innovation in manufacturing business models, shifting from single-product sales to outcome-oriented service trade centred on 'products plus services'. This paper summarises Siemens' technological approach of 'first testing in the virtual realm, then optimising in reality,' along with its economic value in reducing costs and accelerating innovation. It provides support and practical pathways for China's manufacturing sector to upgrade its industrial chain and reconstruct global value chains within the context of the digital economy.

Keywords: Industrial Internet of Things; Digital Twin; Siemens; Digital Transformation

1. Introduction

1.1 Research Background and Significance

As a core technological enabler for the current transition into Industry 4.0, the Industrial Internet of Things (IIoT) empowers enterprises to overcome data silos, achieve real-time awareness of production processes, advance product lifecycle management, and forecast future production resource allocation. Particularly within Siemens, a high-tech manufacturing enterprise, its global implementation of IIoT and digital twin technologies provides exemplary reference cases and novel pathways for manufacturing digital transformation.

Firstly, digital twin technology constitutes a real-time mapping of the three-dimensional physical world within a virtual environment. Through integrated data and simulation models, it supports future decision optimisation. Its core value lies in achieving real-time control over the operational status of physical entities, risk assessment, and predictive analysis through digital integration, positioning it as one of the key enabling technologies within modern intelligent manufacturing systems. Secondly, diverse research on digital twin technology indicates that its integration with the Industrial Internet of Things significantly enhances enterprises' capabilities for intelligent control of production processes and optimisation of future decision-making.

1.2 Literature Review

As core intelligent manufacturing technologies for the new era and stage, the Industrial Internet of Things and digital twins are driving the transformation of manufacturing from automation towards intelligence. These represent the three driving forces of the Third Industrial Revolution: exponential growth in information technology, widespread adoption of digital networking, and integrated intelligent innovation (Zhou Ji, 2015)[1]. Through data-driven approaches and the convergence of virtual and physical realms, these technologies collectively form the neural centre and digital framework of future factories. This not only reshapes production and operational models but also provides entirely new pathways for comprehensive optimisation across enterprise value chains.

As the cornerstone of intelligent manufacturing, domestic scholars widely recognise the Industrial Internet of Things (IIoT) architecture as the digital foundation enabling factories to achieve perception, analysis, and optimisation. Its value manifests in real-time monitoring, intelligent analysis, and closed-loop control of production processes, ultimately optimising efficiency, reducing energy consumption, and minimising downtime (Liu Qiang et al., 2020)[2]. International research on IIoT has transcended mere device connectivity, focusing instead on multi-dimensional platform solutions encompassing entire production systems. By integrating edge data collection and computation, these solutions achieve data coverage from shop floor operations to enterprise management, providing critical support for predictive maintenance, energy optimisation, and adaptive production adjustments (Siemens AG, 2022)[3].

Digital twins constitute dynamic digital representations of physical entities or processes throughout their lifecycles. Within enterprise operations, they enable comprehensive, real-time monitoring of entire manufacturing processes, addressing enterprises' data-related challenges (Lin Guoyi et al., 2024)[4]. Unlike traditional static 3D models, digital twins constitute dynamic systems integrating data-driven and model-driven approaches, emphasising ‘virtual-physical synchronisation’ and ‘bidirectional interaction’ (Grieves, M. 2014)[5]. This technology creates novel industrial IoT solutions, combining AI and data analytics to endow networks with advanced cognitive capabilities (Liu Miao et al., 2024)[6]. Within manufacturing, its application spans the entire lifecycle, encompassing product design, production planning, virtual commissioning, equipment health management, and after-sales services (Zhang Yingfeng et al., 2017)[7]. Current academic research on digital twins primarily focuses on constructing technical frameworks, encompassing multidimensional model fusion, data integration and driving mechanisms, alongside leveraging embedded sensing technologies and high-performance simulation to support advanced applications such as real-time control and predictive maintenance (Negri et al., 2017)[8]. A synthesis of domestic and international research indicates that a mature digital twin system can serve as a bridge connecting industrial IoT data with business value, transforming fragmented data into actionable decision insights.

Siemens' native digital factory in Nanjing, China, stands as a global benchmark for implementing the ‘virtual-physical convergence’ concept. From its inception, the facility established a comprehensive digital twin model encompassing layout, production lines, processes, and logistics. Through a series of simulations, debugging, and optimisations conducted in the virtual environment, potential issues were successfully mitigated. This approach significantly reduced the factory's planning and construction cycle while ensuring efficient and stable operation upon commissioning. This fully demonstrates the core value of digital twins in both product lifecycle management and factory lifecycle management-testing for errors in the virtual realm before optimising in reality (Stark R et al, 2019)[9]. At the operational level, Siemens leverages its industrial internet of things platform to collect vast amounts of equipment sensor data in real time, followed by cloud-based analysis and intelligent edge responses (Siemens AG, 2022)[3]. This platform enables predictive maintenance by analysing equipment operational data, allowing models to issue early warnings of potential failures and minimise unplanned downtime (Lee J et al, 2018)[10]. Furthermore, the platform facilitates granular management and optimisation of entire factory energy consumption. By analysing energy flow data, it identifies energy-saving opportunities, enabling sustainable green manufacturing (Zhou Keliang, 2015)[11].

Today, the convergence of the Industrial Internet of Things (IIoT) and digital twins represents an unmistakable trend in technological advancement. The IIoT extensively collects real-time data from the physical world, supplying fresh insights to digital twins. These twins construct and operate high-fidelity models to analyse, simulate, and predict data, ultimately generating optimised decisions. These decisions are then fed back to the physical world via the

IIoT, completing the closed-loop process of 'perception-analysis-decision-execution' (Qi Qinglin, 2021)[12]. This deep integration provides factory management with a unified data-driven view, enabling collaborative decision-making across production line operations, process optimisation, and maintenance on a single platform. This facilitates the realisation of adaptive, automated smart factories (Tao Fei et al., 2019)[13]. Figure 1 and figure 2 illustrates that the scale of the industrial Internet of Things (IIoT) both nationally and within China has exhibited an upward trajectory since 2020. Following its integration with digital twin technology by 2025, this scale is projected to experience explosive growth.

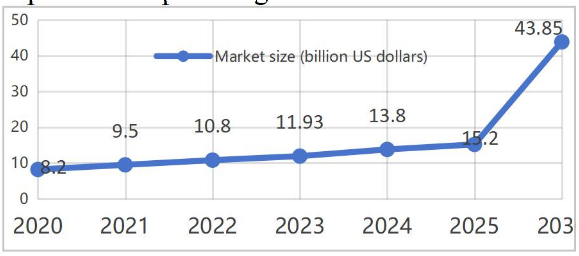

Figure 1. Global Industrial Internet of Things Market Size Trends (2020–2030)

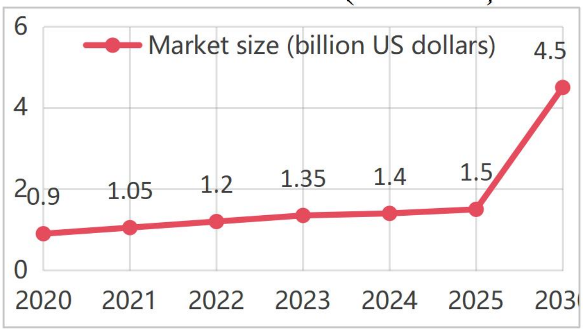

Figure 2. Market Size Trends for China's Industrial Internet of Things (2020–2030)

1.3 Research Content, Methodology and Framework

1.3.1 Research content

This study focuses explicitly on Siemens' native factory, using Siemens AG as a case study to conduct an in-depth analysis of how its industrial internet of things and digital twin technologies enable strategic digital transformation within the context of the digital economy and global trade. By examining the company's transformation strategy, new pathways for digital transformation are derived, thereby generating broad economic impacts. The research systematically maps Siemens' technological framework and business architecture for IIoT and digital twins, emphasising how its core platforms and software portfolio integrate data and models to form digital twin solutions spanning the entire product lifecycle. This aims to clarify the intrinsic logic underpinning its technological implementation. It further examines how Siemens' digital transformation drives its own industrial chain evolution, analysing the successful transition of a traditional hardware manufacturer into a digital business service provider. The study investigates whether internal organisational business models and roles within the global industrial ecosystem have shifted during this transformation. Finally, it assesses the impact of this transformation on global trade within the digital economy and identifies lessons learned. We will examine how the cross-border flow of digital products, digital services, and industrial data itself fosters new trade forms, assess the potential for widespread application of this pathway, and analyse emerging issues such as data governance and international regulations [14].

1.3.2 Research methodology

This study employs three research methods:

1) Case Study Method

Siemens is selected as a representative case for in-depth analysis, owing to its global leadership in the digital industrial Internet of Things and comprehensive practical framework. The research will synthesise primary and secondary sources to trace the evolution and implementation outcomes of Siemens' digital transformation strategy.

2) Literature Review Method

Theoretical literature will be collected, reviewing and synthesising academic works on the digital economy, global value chain theory, and the transformation of manufacturing towards service-oriented models to establish the theoretical foundation for this study. Cutting-edge reports and papers on the Industrial Internet of Things and digital twins will be examined to ensure an appropriate and accurate understanding of technical concepts and development trends. This will clarify the theoretical entry points for this research and enhance the academic depth of the analysis.

3) Inductive-Deductive Method

Building upon the case study and literature review, this approach identifies characteristic features, success factors, and fundamental patterns within Siemens' practical implementation. Employing relevant economic theories, it applies logical deduction to elevate the case study to a generalisable discussion. This process enhances the study's broader implications for China's manufacturing sector and the global digital trade transformation landscape, achieving a cyclical progression from the concrete to the abstract and back to the concrete. This methodology fulfils the research's objective of delivering practical significance.

2. Core Concepts and Theoretical Framework

2.1 New Characteristics of the Digital Economy and Trade

The digital economy differs fundamentally from the mere digitisation of traditional economic activities. It is underpinned by data resources, facilitated by modern information networks, and driven by the effective application of information and communication technologies. This ultimately catalyses profound transformations in economic structures, enhancing the operational efficiency of economic activities. Within this new paradigm, the overall form, objects, and rules of global trade will undergo significant changes, diverging markedly from the industrial economy era.

Firstly, data is being comprehensively utilised. Traditional production factors such as land, labour, capital, and technology are being redefined and empowered by the data factor. Within manufacturing, industrial data sourced from product sensors, supply chain segments, and customer feedback has become a potent tool for enterprises to optimise decision-making and enhance efficiency. The non-rivalrous, replicable, and highly permeable nature of this data enables its infinite reuse and cross-sector integration, giving rise to new production functions. For Siemens, the core mission of its Industrial Internet of Things lies in capturing, organising, analysing, and activating data streams from factories and products worldwide. By calculating future value from cost stages, the flow and allocation efficiency of data elements directly determine a company's core competitiveness within the digital economy.

Secondly, platform competitiveness has become increasingly pronounced. Today's digital economy transcends competition between individual products or enterprises. Industrial IoT platforms serve as hubs connecting devices, software, developers, and customers. By integrating data interfaces, providing development tools, and sharing infrastructure, they attract broader user communities, fostering network effects and closed-loop data ecosystems. Siemens has not only pioneered its own industrial IoT platform but also established an open digital twin application ecosystem. This platform-based competition is reshaping industrial division of labour globally, compelling enterprises to prioritise their role within this environment: whether as rule-makers, value-providers, or specialised participants.

Most critically, global value chains are undergoing digital, agile, and regional restructuring, with service trade and digital product commerce rapidly ascending. For manufacturers, this necessitates shifting from selling physical products to hybrid models combining products and services, or outcome-oriented services. Siemens exemplifies this transition from selling machine tools as physical goods to a business model centred on purchasing machining capabilities. Leveraging its IoT and digital twin technologies, it positions services as separately priced, high-value-added commodities. This demonstrates how extensive digital technology adoption reduces barriers to service trade.

2.2 The Technological and Economic Implications of Industrial IoT and Digital Twins

2.2.1 Industrial IoT: from physical interconnection to data-intelligent interoperability networks

The essence of the Industrial Internet of Things lies in forming an intelligent value network capable of perception, analysis, and control. This is achieved through real-time collection of data from observed objects and processes using various devices and technologies, including information sensors, radio-frequency identification (RFID), global positioning systems (GPS), infrared sensors, and laser scanners. Its technical framework primarily comprises the perception layer and the network layer. Sensors in the perception layer are typically deployed on equipment and products to gather real-time status data from the physical world. The network layer manages data transmission and communication connectivity. It combines wired and wireless networks to enable IoT data collection across diverse scenarios, utilising technologies like 5G, TSN, and industrial Ethernet to ensure secure, reliable, and real-time data transfer. Its economic significance lies in reshaping industrial economic models. Firstly, it reconfigures cost structures by reducing unplanned downtime through predictive maintenance. Secondly, it enhances yield rates via process optimisation, directly lowering variable production costs and the uncertainty costs associated with maintenance. Secondly, it unlocks network effects by connecting vast numbers of devices and users, creating a two-way network effect. Finally, it empowers new service-oriented business models, enabling value migration. The advancement of industrial IoT makes real-time monitoring of product operation status, pay-per-use models, and the sale of operational maintenance guarantees feasible. This extends corporate revenue streams from one-off hardware sales to sustainable service offerings, achieving a fundamental value shift from product manufacturer to service provider.

2.2.2 Digital Twins: the value creation engine of virtual-physical mapping and closed-loop optimisation

Digital twins represent the dynamic, full-lifecycle mapping of physical entities within virtual spaces. Leveraging historical and real-time data alongside algorithmic models, they simulate, predict, and control the state and behaviour of physical assets. Siemens factories exemplify this transformation through the development of full-lifecycle digital twins for products and digital workshops. Its technical essence lies in integrating physical entities, virtual models, and bidirectional data connections with service systems. It connects virtual and real-world bidirectional data flows, utilising data support from the Industrial Internet of Things to simulate outcomes that guide the physical world. Depending on the application level, digital twins can be categorised as descriptive, predictive, or prescriptive. Its economic implications are multifaceted. Firstly, it reduces trial-and-error costs by enabling simulation testing and performance optimisation prior to physical manufacturing, thereby mitigating substantial expenditures on future prototype development and testing. Secondly, it accelerates innovation cycles: developers can employ digital twin technology for virtual product process design and capacity simulation, achieving first-time-right outcomes that enhance return on investment and expedite product market launch.

3. Siemens' Industrial Internet of Things and Digital Twin Strategy and Practice

3.1 Evolution of Siemens' Digital Strategy

3.1.1 Foundations in automation

By the late 20th century, Siemens was universally recognised as the world's leading supplier of electrification, automation, and drive technologies. Its products-programmable logic controllers, industrial computers, drive systems, and more-formed the ‘skeleton’ and ‘muscle’ of modern factory automation. At that stage, digitalisation remained confined to the electronic integration of individual products, with value primarily manifested in enhanced production line automation. However, during this period, these digital systems were predominantly closed-loop, with data flow confined to the control layer. They failed to achieve cross-tier, end-to-end connectivity across the entire value chain. Nevertheless, Siemens undeniably pioneered automation, accumulating vast industrial field knowledge and deep understanding of physical manufacturing processes. This foundation laid the groundwork for its subsequent evolution into an industrial IoT company, distinguishing it from purely digital IT firms.

3.1.2 The digital factory vision and the rise of the software division

By the early 21st century, as product complexity escalated and global production networks emerged, Siemens astutely recognised that hardware alone could no longer satisfy customer demands for operational efficiency, flexibility, and product innovation. Consequently, its strategic focus gradually pivoted towards an integrated hardware-software approach. In 2007, Siemens acquired UGS, a software development company, for US$3.5 billion. This move granted Siemens core digital software capabilities spanning the entire product lifecycle from design to manufacturing. Subsequently, Siemens formally introduced the core concept of digital twin-driven innovation-creating within a virtual world. This represented not only a significant breakthrough in product efficiency but also the realisation of applying digital technologies to product design and manufacturing.

3.1.3 Establishing a digital enterprise responding to industry 4.0

Entering 2010, Siemens' digital transformation accelerated with Germany's introduction of Industry 4.0. Acquisitions of LMS, Camstar, and

Mentor Graphics addressed gaps in simulation analysis, production operations management, and electronic system design. By integrating its disparate hardware and software assets, Siemens articulated a coherent digital transformation strategy, emphasising the digital twin as the bridge between virtual and physical realms. In 2016, responding to the global wave of industrial IoT platforms, Siemens launched MindSphere-an open, cloud-based IoT operating system. This marked its strategic shift towards platformisation and digitally-driven services.

3.1.4 Focusing on platformisation, delivering services and sustainability

From the 2020s onwards, Siemens' digital strategy has matured, characterised by openness, agility, and ecosystem building-qualities capable of addressing all transformations within the industrial world and embracing new paradigms of sustainable development. In 2020, Siemens introduced the Xcelerator strategic business framework, consolidating all its software, services, and application development platforms into a unified, open portfolio. This aims to lower the threshold for customer adoption of digital transformation while delivering flexible solutions. In 2023, Siemens announced its future focus on three core domains: Digital Industries, Smart Infrastructure, and Mobility. It actively collaborates with giants like Amazon Web Services and Microsoft, gathering third-party developers to jointly build a new industrial ecosystem. Its strategic transformation emphasises establishing digital twin technology as the key enabler for this new industrial ecosystem and sustainable development, committing to creating a comprehensive digital twin system spanning from components to enterprise level.Figure 3 illustrates the developmental stages of Siemens' transformations across different eras, enabling us to observe the technological composition of each phase at a glance.

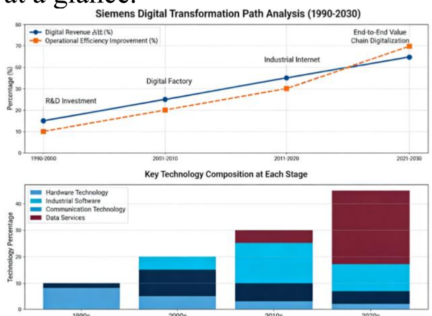

Figure 3. Siemens Digital Transformation Path Analysis(1990-2030)

3.2 Case Studies of Typical Application Scenarios

As both an advocate and practitioner of industrial IoT and digital twin technologies, Siemens exemplifies the core value of digital twins across different stages of a product's lifecycle through the following three scenarios. Together, they outline a blueprint for the future industrial world where virtual and physical realms converge.

3.2.1 Product design optimisation

When developing complex systems such as gas turbines and high-speed trains, where physical prototyping and testing incur substantial costs, Siemens employs simulation and design software from its Xcelerator suite to create high-fidelity physical simulation digital twins. By integrating historical operational data from the industrial internet of things, boundary conditions and load spectra are refined to more accurately reflect real-world scenarios. Within the virtual space, the digital twin conducts countless hypothetical analyses, rapidly generating diverse design proposals. It predicts multiple metrics-including fatigue life and operational efficiency-to pinpoint the optimal design before physical prototyping commences.

3.2.2 Production process control

When confronting the demands of personalised production involving multiple varieties and small components, Siemens employs digital twins to create one-to-one virtual models of physical factories. This enables rapid reconfiguration of production lines, ensuring product quality while maximising the efficiency of both equipment and personnel. Prior to new product deployment, the entire production process undergoes simulation, validation, and optimisation within the digital twin. This ensures error-free procedures and disseminates optimal production parameters to each physical device. Finally, systems such as industrial IoT sensors throughout the facility continuously feed data back to the digital twin, creating a closed-loop ‘perception-analysis-optimisation’ system.

3.2.3 Predictive maintenance and services

Unexpected downtime of critical production equipment often inflicts substantial losses on customers. Siemens equips its sold products with sensors, delivering data-driven predictive maintenance that significantly reduces costs associated with traditional scheduled maintenance and reactive repairs. First, sensors on the equipment transmit operational data-such as vibration, temperature, and current-to the cloud via the MindSphere platform. Machine learning models on the platform analyse real-time data from the equipment's digital twin to identify anomalies, predict equipment lifespan, and issue early warnings before failures occur. Upon receiving alerts, service engineers can provide remote diagnostics to customers, pre-plan spare parts, and schedule on-site maintenance appointments, thereby achieving zero unplanned downtime.

These three scenarios clearly demonstrate how Siemens transforms industrial IoT and digital twins from concepts into tangible productivity and competitive advantage. Together, they demonstrate how the IIoT enables universal data interconnectivity and perception, while digital twins facilitate deep simulation and predictive analysis. This ultimately achieves precise execution and optimisation in the physical world. Such integration not only resolves specific engineering and operational challenges but fundamentally transforms business models and value creation methods. It revolutionises global service delivery formats, laying a robust microfoundation for the subsequent digital economy and trade.

4. Conclusions and Future Outlook

Technological convergence serves as the core engine of transformation. Siemens' success lies in effectively integrating the ‘perception’ capabilities of the Industrial Internet of Things with the ‘cognitive’ capabilities of digital twins. The IIoT dismantles data silos, furnishing digital twins with real-time, high-fidelity data support; conversely, digital twins transform fragmented data into actionable decision insights through simulation and model analysis. This bidirectional interaction mechanism enables the closed-loop process of ‘perception-analysis-decision-execution,’ forming the foundational logic for intelligent manufacturing. The Value Reshaping of Full Lifecycle Management Digital transformation transcends isolated stages, permeating the entire product lifecycle. Siemens has fundamentally altered traditional manufacturing's cost structure and risk management by employing digital twins for virtual validation during R&D, virtual commissioning to optimise production lines during manufacturing, and predictive maintenance to prevent downtime during operations. This ‘virtual-physical synchronisation’ significantly reduces physical trial-and-error costs while shortening time-to-market. The Leap Towards Service-Oriented and Platform-Based Business Models Siemens' transformation reveals a new paradigm for manufacturing within the digital economy: corporate competitiveness no longer hinges solely on hardware performance, but increasingly on data mining and the construction of platform ecosystems. Through platforms like MindSphere, Siemens has transformed machine tool processing capabilities and equipment maintenance into tradable service commodities. This shift from selling products to selling services (servitisation) has enhanced its irreplaceability within global value chains.

Whilst Siemens' approach sets an industry benchmark, the future development of Industrial Internet of Things (IIoT) and digital twins presents fresh opportunities and challenges:

Building Open, Symbiotic Industrial Ecosystems Future competition will be ecosystem-centric. As Siemens advances its Xcelerator strategy, the IIoT will further dissolve corporate boundaries, evolving towards open architectures. Manufacturing enterprises will increasingly need to collaborate with cloud computing giants (such as Amazon and Microsoft), third-party developers, and cross-industry partners to jointly build standardised, interconnected industrial internet platforms, thereby maximising the value of network effects.

Deep Integration of Sustainable Development and Green Manufacturing Against the backdrop of carbon neutrality, digital twins will extend beyond efficiency gains to play a greater role in refined energy consumption management and carbon footprint tracking. Through real-time analysis and simulation of energy flow data, enterprises can identify critical energy-saving points, achieving a win-win for economic and environmental benefits. This represents an essential challenge for future digital transformation in manufacturing.

Data Governance and the Reconstruction of Cross-Border Trade Rules As the service orientation of manufacturing deepens, the cross-border flow of industrial big data will become the norm. Future research must further address issues such as international trade rules for digital products and services, data security, and privacy protection. How to promote the efficient allocation and global flow of data elements while safeguarding national and corporate data security will be a significant challenge in the digital economy era.

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