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Matchmaking The Success of Digital Twins: Aligning Capabilities, Conditions, and Key Drivers Across the Industrial Value Chain

Uliana Schmück ITEM - Innovation Management uliana.schmueck@unisg.ch
Kilian Schmück Institute of Technology Management kilian@schmueck.ch

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Digital twins are transforming industrial value chains, yet their full business potential remains underexplored beyond technological implementation. This study shifts the focus from technology adoption to value creation, examining the intrinsic characteristics that drive digital twin impact, the environmental conditions enabling their deployment, and the key business value drivers across the product and production lifecycle.Using an inductive, qualitative research approach, we analyze 54 expert interviews across manufacturing, technology, and platform-based ecosystems. Our findings reveal three core digital twin characteristics, five critical environmental enablers, and four dominant business value drivers—innovation, efficiency, effectiveness, and exploitation—each shaping distinct value areas within industrial operations.This study contributes to the literature by reframing digital twins as strategic assets rather than operational tools, highlighting their role in multi-stakeholder industrial ecosystems. It provides a structured framework for digital twin adoption, offering actionable insights for organizations seeking scalable, interoperable, and economically viable solutions. By bridging theoretical insights with managerial relevance, our research strengthens the foundation for digital twin-driven business transformation and long-term value generation in industrial environments.

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Keywords: digital twin; value creation; ecosystem; production; operations; industrial metaverse

1 Introduction

The increasing complexity of industrial value chains, coupled with the rapid digitization of manufacturing and logistics, has positioned digital twins as a crucial enabler of operational efficiency, resilience, sustainability, and flexibility (Lu et al., 2020). Despite significant advancements in digital twin technologies, critical challenges persist regarding their scalability, interoperability, and economic viability. Many industrial applications fail to exploit digital twin's full potential due to fragmented data ecosystems, a lack of harmonized integration frameworks, and difficulties in sharing digital twins across multiple stakeholders (Psarommatis & May, 2023b). While the technical feasibility of digital twins has been widely demonstrated, the question remains: "*Which intrinsic capabilities of digital twins unlock business value in the industrial context, what conditions must be met for their effective deployment, and what are the key value drivers enabling their impact?*"

This paper addresses this research gap by investigating how digital twins serve as multilateral digital assets within the Industrial Metaverse, unlocking value creation across product, production, and supply chain activities. Building upon prior research on digital twin ecosystems (Ivanov, 2023; Kritzinger et al., 2018; Psarommatis & May, 2023a; Van Dyck et al., 2023; Wang et al., 2021), this study extends the discourse toward the role of digital twins in enabling a seamless, interoperable, and transaction-driven industrial landscape. The study introduces a structured framework that links digital twin value creation to key environmental conditions and lifecycle integration strategies, outlining how firms can strategically implement digital twins to achieve economic impact.

This research makes several contributions to the understanding of digital twin business value in industrial settings. First, it develops an integrative perspective on digital twins as assets that harmonize multisource lifecycle data across product-centric and production-centric systems. This perspective highlights how digital twins break down data silos and bridge real-time data gaps, creating a unified, trustworthy data infrastructure applicable across design, manufacturing, and operational activities. Second, it identifies four dominant value areas—Virtual Synthesizing, Virtual Commissioning, Virtual Sensing, and Virtual Exploitation—in which digital twins drive measurable business benefits. Each of these areas links digital twin capabilities to one predominant value driver: innovation, efficiency, effectiveness, or exploitation. The findings indicate that digital twins' business value is contingent upon matching their intrinsic capabilities with specific environmental conditions, providing firms with a structured approach for optimizing digital twin deployment. Finally, this study contributes to the emerging discourse on the Industrial Metaverse by positioning digital twins as a transaction-based infrastructure for industrial ecosystems. The analysis reveals that beyond technical implementation challenges, the adoption of digital twins as industrial assets requires significant organizational and cultural adaptation. This highlights the need for a holistic industry ecosystem approach that supports efficient digital twin transactions, infrastructure development, and governance models.

Prior research has laid a strong theoretical foundation for understanding digital twin architectures, classifications, and technological enablers (Ivanov, 2023; Kritzinger et al., 2018; Tao et al., 2019). However, many existing studies focus predominantly on engineering aspects, overlooking the economic, organizational, and strategic implications of digital twins (Kusiak, 2023; Psarommatis & May, 2023a). While digital twins are often implemented at the operational level, their full value materializes only when they are embedded within an overarching business strategy.

From a managerial perspective, this research provides a decision-making framework for firms seeking to implement scalable, interoperable, and economically viable digital twin solutions.

Understanding the environmental requirements for digital twin adoption—including data standardization, transaction facilitation, and governance models—enables firms to transition from isolated digital twin use cases toward fully integrated industrial ecosystems. By framing digital twins as enablers of lifecycle-spanning value creation, this study delivers practical insights for executives, engineers, and policymakers, guiding them toward strategic investments in digital twin infrastructure.

The remainder of this paper is structured as follows. First, the theoretical background, reviewing existing research on digital twin typologies, enablers, and business applications. Second, the methodological approach is presented, detailing how insights were derived from qualitative empirical research and framework development. Third, the findings section introduces four distinct value areas for digital twin implementation and outlines their corresponding value drivers. Fourth, the discussion section explores the implications of digital twin adoption, providing also managerial recommendations, suggesting future research directions, and identifying key challenges for industrial adoption.

By addressing the strategic, technological, and managerial dimensions of digital twin adoption, this study contributes to the ongoing academic discourse on digital twin ecosystems while delivering actionable insights for industry leaders navigating the transformation of the industrial value chain.

2 Theoretical Background

2.1 The Digital Twin Concept

The concept of the digital twin represents a transformative approach to integrating the physical and digital realms. Initially formalized by Grieves in 2003 and later refined by NASA, a digital twin is defined as a comprehensive digital representation of a physical entity that maintains dynamic, real-time synchronization between the two (Grieves & Vickers, 2017; Tao et al., 2019). The digital twin encompasses three core components: the physical asset, its virtual counterpart, and the continuous exchange of data linking them (Kritzinger et al., 2018). In the production environment, digital twins enable monitoring, simulation, optimization, and decision-making across the entire lifecycle of products and processes (Jones et al., 2020; Liu et al., 2021).

Types of Digital Twins. digital twins in manufacturing and production are broadly classified into three categories: product, process, and operation twins. Product digital twins focus on managing the lifecycle of individual products, encompassing design, production, and maintenance stages (Bao et al., 2019). Product Twins are divided into Component Twins, representing individual parts; Asset Twins, combining multiple components into complete machines or systems; and System Twins, focusing on groups of assets working together (Uhlenkamp et al., 2022). Process Twins provide an overarching view of entire manufacturing workflows, enabling rapid adaptation to dynamic production environments. Operational digital twins provide insights into shop-floor activities, ensuring the synchronization of processes and improving operational efficiency (Ivanov, 2024; Liu et al., 2021). Together, these types offer an integrated view of the physical and digital realms, bridging the gaps between design, manufacturing, and operations (Tao et al., 2019).

Characteristics of Digital Twins. The defining characteristics of digital twins are their dynamic, real-time synchronization, high fidelity, and interoperability. Real-time synchronization allows digital twins to accurately mirror the current state and performance of their physical counterparts, thereby enabling predictive and prescriptive analytics (Jones et al., 2020; Liu et al., 2021). High fidelity ensures that digital twins replicate physical entities at both macro and micro levels, capturing operational, geometrical, and environmental details (Tao et al., 2019). Interoperability is a critical feature that allows digital twins to integrate diverse data sources and systems, ranging from IoT devices and cloud platforms to advanced simulation tools (Ivanov, 2024). Furthermore, digital twins leverage advanced technologies such as AI and machine learning to forecast disruptions, optimize processes, and generate actionable insights (Dhar et al., 2022).

Enablers of Digital Twins. The realization of digital twins depends on a robust ecosystem of enabling technologies. Internet of Things (IoT) devices form the foundation of digital twins by collecting real-time data from sensors embedded in physical systems (Liu et al., 2021; Tao et al., 2019). Cloud and edge computing technologies facilitate the storage, processing, and computational requirements of large-scale simulations and analytics (Ivanov, 2024). Artificial intelligence and big data analytics empower digital twins to derive meaningful insights from complex datasets, enabling decision-making processes that are both data-driven and dynamic (Dhar et al., 2022; Liu et al., 2021; Qi et al., 2021; Tao et al., 2019). Additionally, immersive technologies such as virtual and augmented reality enhance the usability of digital twins by providing operators and engineers with interactive and intuitive interfaces for simulation, monitoring, and control (Berti & Finco, 2022; Chandrashekhar et al., 2023).

2.2 Digital Twin Value Creation in Production Environments

digital twins have established themselves as transformative technologies that bridge the physical and virtual worlds, enabling dynamic interactions that foster real-time monitoring, predictive analytics, and operational optimization. By creating a continuous flow of information, digital twins empower manufacturers to respond proactively to disruptions, optimize processes, and drive innovation across the product lifecycle (Ivanov, 2024; Liu et al., 2021; Tao et al., 2019). Within smart manufacturing, digital twins support advanced capabilities such as real-time production monitoring and predictive maintenance, which enhance operational stability, reduce downtime, and improve overall efficiency (Liu et al., 2021; Lu et al., 2022). This alignment with intelligent manufacturing frameworks highlights their role in streamlining workflows and addressing complex industrial challenges.

Applications of digital twins extend across various stages of production and supply chain systems. In manufacturing, they enhance productivity and resource efficiency by simulating production scenarios before implementation, thus reducing bottlenecks and minimizing waste (Guo & Mantravadi, 2024). Moreover, their ability to perform early defect detection through predictive analytics supports quality assurance frameworks like zero-defect manufacturing (Psarommatis & May, 2023a). By leveraging standardized performance metrics and adaptability frameworks, digital twins enable manufacturers to evaluate and continuously optimize system performance (Psarommatis & May, 2023b). In supply chain management, they enhance visibility and resilience, offering real-time insights that allow firms to anticipate disruptions, adjust inventory strategies, and improve demand forecasting, particularly during crises such as the COVID-19 pandemic (Guo & Mantravadi, 2024; Ivanov, 2024). Their integration into lean supply chains further supports justin-time practices, logistics optimization, and agility in response to market fluctuations (Bao et al., 2019; Ivanov, 2024).

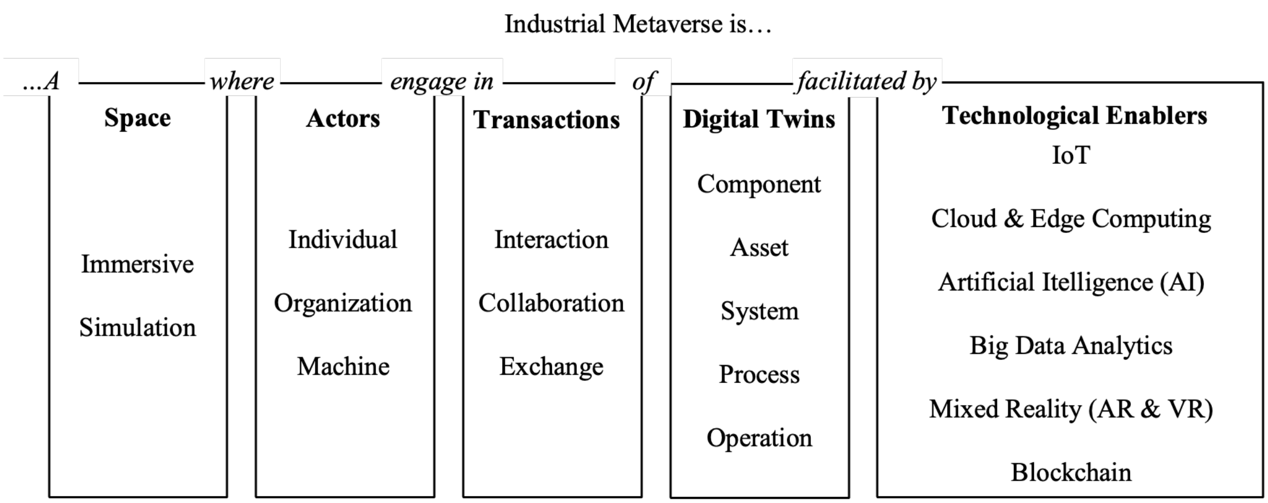
digital twins also play a central role in the evolution of industrial paradigms. In Industry 4.0, digital twins are the foundation of cyber-physical integration, enabling autonomous decision-making, data-driven operations, and enhanced connectivity (Ivanov, 2024; Lu et al., 2020). As industries shift toward Industry 5.0, digital twins evolve into human-centric systems that prioritize sustainability, collaboration, and ergonomics (Berti & Finco, 2022; Lu et al., 2022). These technologies facilitate adaptive, worker-friendly environments while fostering collaboration between human operators and autonomous systems, aligning with societal goals of inclusivity and resilience (Lu et al., 2022; Romero & Stahre, 2021). Modular digital twin systems are increasingly being deployed to provide sustainability insights, such as energy optimization and lifecycle impact analysis, advancing the transition toward green manufacturing practices (Werner et al., 2024).

Beyond operational efficiency, digital twins are enablers of economic value and innovation. By offering platforms for real-time experimentation and iterative development, they facilitate rapid prototyping and continuous improvement, reducing time-to-market and driving product and process innovation (Holopainen et al., 2024; Tao et al., 2018). Additionally, their integration into business ecosystems fosters collaborative innovation, enabling shared value creation between manufacturers, suppliers, and end-users (Holopainen et al., 2024). digital twins are also transforming business models by enabling service-oriented approaches, such as performance-based contracts and predictive analytics services, which create new revenue streams and enhance competitiveness (Khan, 2024). Recent advancements in semantic technologies, such as knowledge graphs, further enhance the cognitive capabilities of digital twins, allowing them to integrate complex datasets and support intelligent decision-making (Zheng et al., 2022). These technological foundations not only enhance operational efficiencies but also reduce costs, improve resource allocation, and support the transition to innovative, service-based economic models (Khan, 2024).

2.3 Digital Twins in The Industrial Metaverse

We define the Industrial Metaverse as an immersive digital space where industrial actors interact through the exchange and operation of digital twins, enabled by a range of advanced technologies. As illustrated in Figure 1, our conceptualization consists of five interrelated elements: space, actors, transactions, digital twins, and technological enablers. At the core of this ecosystem are Digital Twins, which serve as the primary assets, carriers of industrial knowledge, and enablers of value creation in the Industrial Metaverse.

Figure 1: Conceptual Elements of Industrial Metaverse



Seamless, Immersive Simulation Environment for Digital Twins. The space in the Industrial Metaverse is an immersive, simulation-driven environment that connects the physical and digital worlds. It provides the foundational infrastructure for digital twins, allowing them to replicate real-world physics, optimize industrial operations, and automate processes (Mourtzis, 2020; Tsujimoto et al., 2018). This space enables digital twins to function within arbitrary scenarios, industrial workflows, and experimental environments, supporting real-time simulations, training, and predictive modeling (Martínez-Gutiérrez et al., 2024). Unlike conventional industrial simulations, the Metaverse is seamless, meaning different digital twins and simulations can interact without technological barriers, creating a continuously connected industrial landscape (Schöbel & Leimeister, 2023). Accordingly, this environment is essential for multi-enterprise collaboration, cross-organizational simulations, and AI-driven optimizations (Lim et al., 2020). As such, the Industrial Metaverse does not merely host digital twins—it expands their functional reach, enabling real-time process control, lifecycle analysis, and automated decision-making.

Industrial Actors Shaping the Digital Twin Ecosystem. The Actors in the Industrial Metaverse include individuals, machines, and organizations that create, manage, and utilize digital twins. These actors interact within and beyond enterprise boundaries, assuming different roles such as as data providers, asset owners, service integrators, and decision-makers (Schöbel & Leimeister, 2023; Tsujimoto et al., 2018). They act on both the supply and demand side of the ecosystem, exchanging digital twin data and insights to optimize processes, improve performance, and co-develop (Martínez-Gutiérrez et al., 2024). The emergence of Interconnected digital twins (IDTs) allows industrial actors to integrate real-time monitoring and predictive analytics across value chains, fostering a shared intelligence network that improves efficiency and resilience (Van Dyck et al., 2023). The ability of digital twins to dynamically adapt based on interactions with other twins, simulations, and external data sources strengthens industrial adaptability and decision-making precision (Riasanow et al., 2021). This evolution marks a shift toward decentralized industrial ecosystems, where digital twins play an active role in orchestrating production, logistics, and operational management—a transformation enabled by the Metaverse's collaborative digital infrastructure (Gawer & Cusumano, 2014).

Digital Twin-Based Transactions. Transactions within the Industrial Metaverse center around the exchange, interaction, and utilization of digital twins. These transactions extend beyond mere data sharing—they involve collaborative simulations, joint asset optimizations, and cross-enterprise analytics (Martínez-Gutiérrez et al., 2024). The role of digital twin platforms in these transactions is critical, as they serve as collaborative spaces for Digital Twin-driven industrial applications (Reim et al., 2023). Transactions facilitated within a decentralized platform ecosystem enable traceable interactions, ensuring that data integrity and operational transparency are maintained (Schmück et al., 2025). Moreover, blockchain-enabled digital twin collaboration platforms allow multiple industrial stakeholders to co-develop and share digital assets, fostering a distributed and trust-based industrial environment (Li et al., 2023). By enabling multi-party decision-making and seamless asset utilization, the Industrial Metaverse unlocks new operational efficiencies and innovation potentials for digital twins.

Digital Twins: The Core Enablers for Value Creation. At the heart of the Industrial Metaverse are digital twins, which serve as both operational entities and digital assets. These digital twins vary in scope—from component-level replicas to full-scale industrial systems (Ivanov, 2023). Their integration enables real-time condition monitoring, predictive analytics, process automation, and AI-driven decision-making (Guo & Mantravadi, 2024). The role of digital twins extends beyond simulation; they are becoming dynamic business assets, enabling new forms of data-driven decision-making, remote asset control, and automated service execution (Van Dyck et al., 2023). Additionally, digital twin business models are emerging, shifting enterprises toward outcome-based service monetization and value-added offerings (Schmück et al., 2025). A particularly promising development is the rise of modular digital twins, which enable customized sustainability optimizations, adaptive production processes, and long-term asset lifecycle management (Werner et al., 2024). By embedding real-time data intelligence into industrial workflows, digital twins act as decision-support engines, fundamentally reshaping how industrial processes are managed and monetized.

Technological Enablers Powering Industrial Metaverse and Digital Twins. The Technological Enablers of the Industrial Metaverse—IoT, cloud computing, AI, big data analytics, mixed reality (AR & VR), and blockchain—form the foundation for digital twin functionality. These technologies empower digital twins to operate autonomously, synchronize with real-world assets, and enable intelligent machine-to-machine interactions (Martínez-Gutiérrez et al., 2024). Rather than being a standalone technology, the Industrial Metaverse serves as an integrating framework that connects existing IT and OT solutions to create an interoperable and scalable industrial environment (Schöbel & Leimeister, 2023). This integration unlocks new business models, where digital twins generate economic value through servitization, asset-as-a-service, and predictive maintenance contracts (Werner et al., 2024).

3 Methods

To explore and understand new phenomena, particularly how digital twins unlock economic and business-related value creation in the industrial context, we subscribe to the notion that qualitative and inductive research is most effective. Consequently, we pursued an inductive approach, adopting a qualitative perspective as outlined by Corbin and Strauss (2014). In particular, our research aims to answer the question: *"Which intrinsic capabilities of digital twins unlock business value in the industrial context, what conditions must be met for their effective deployment, and what are the key value drivers enabling their impact?*

Applying the systematic analytical framework by Gioia, Corley, and Hamilton (2013), we identified three intrinsic digital twin characteristics, five environmental requirements, and four key value drivers in industrial environments along the product and production value chain. This approach allowed us to categorize the fundamental characteristics of digital twins into distinct yet interconnected elements, each contributing unique value to facilitate effective digital twin business applications. Our study delineates the four predominant business value drivers and their impact across different stages of the product and production value chain. Accordingly, our findings highlight the critical environmental requirements necessary for digital twins to fully realize their business potential, providing a framework for understanding the prerequisites that Industrial Metaverse must meet.

3.1 Data Sampling and Data Collection

For data collection, we employed theoretical sampling to identify a diverse range of industrial organizations, which can be categorized into two groups: (1) traditional production and manufacturing companies actively using, implementing, or applying digital twins, and (2) organizations engaged in Industrial Metaverse-related initiatives. These include large corporations and startups spanning immersive social interaction and simulation platforms, manufacturers and OEMs, as well as digital infrastructure, hardware, and solution providers (Yin, 2009). To qualify for inclusion, organizations had to meet the following criteria: (1) active involvement in Industrial Metaverse, industrial simulation and interaction platforms, digital twin solutions or related technologies; (2) identification as distinct organizational entities; and (3) willingness to disclose sufficient information to evaluate their relevance to our study.

Our primary data source consisted of exploratory semi-structured interviews, designed to gain an in-depth understanding of the underlying value creation mechanisms of digital twins and the development and deployment of Industrial Metaverse projects. From April 2023 to February 2024, we conducted 54 interviews with business executives, project managers, and domain experts from various stakeholders, including industrial producers, component manufacturers, platform providers, service vendors, and technology enablers. The interviews ranged in duration from 11 to 72 minutes, averaging 52 minutes, and were transcribed within 24 hours of completion. This process yielded 1,205 pages of double-spaced text. To minimize bias and ensure consistency, we established a common research protocol, maximizing the logic of replication across interviews.

3.2 Data Analysis

Our data analysis adhered to the Gioia et al. (2013) framework, emphasizing inductive theory development (Glaser & Strauss, 2017). To ensure rigor and mitigate bias, three researchers independently coded the data, subsequently comparing and refining their codes through collaborative discussions to reach consensus on the final interpretations (Lofland et al., 2022). This iterative process continued until theoretical saturation was achieved (Glaser & Strauss, 2017).

The analysis commenced with Open Coding (Corbin & Strauss, 2014), during which researchers identified and categorized primary concepts related to the digital twin value creation mechanisms. Through collaborative alignment, these codes were refined to ensure consistency. Following this, we engaged in a process of Axial Coding. Here, we explored the relationships among the initial codes to identify overarching patterns, leading to the development of second-order themes. Finally, through Aggregation, we consolidated these second-order themes into higher-level abstract categories (Gioia et al., 2013). This aggregation led to the synthesis of the dominant business value mechanisms of digital twins as shown in Figure 2 and the intrinsic digital twin characteristics and environmental requirements as presented in Figure 3. These consolidated dimensions, along with the secondary themes and primary concepts, form the structure of our findings. Throughout this process, we engaged in extensive discussions and consultations with academic peers not involved in the study to validate our emerging data structure and ensure the reliability of our findings (Guba & Lincoln, 1994).

Figure 2: Coding Tree for the Key Value Mechanisms of Digital Twins

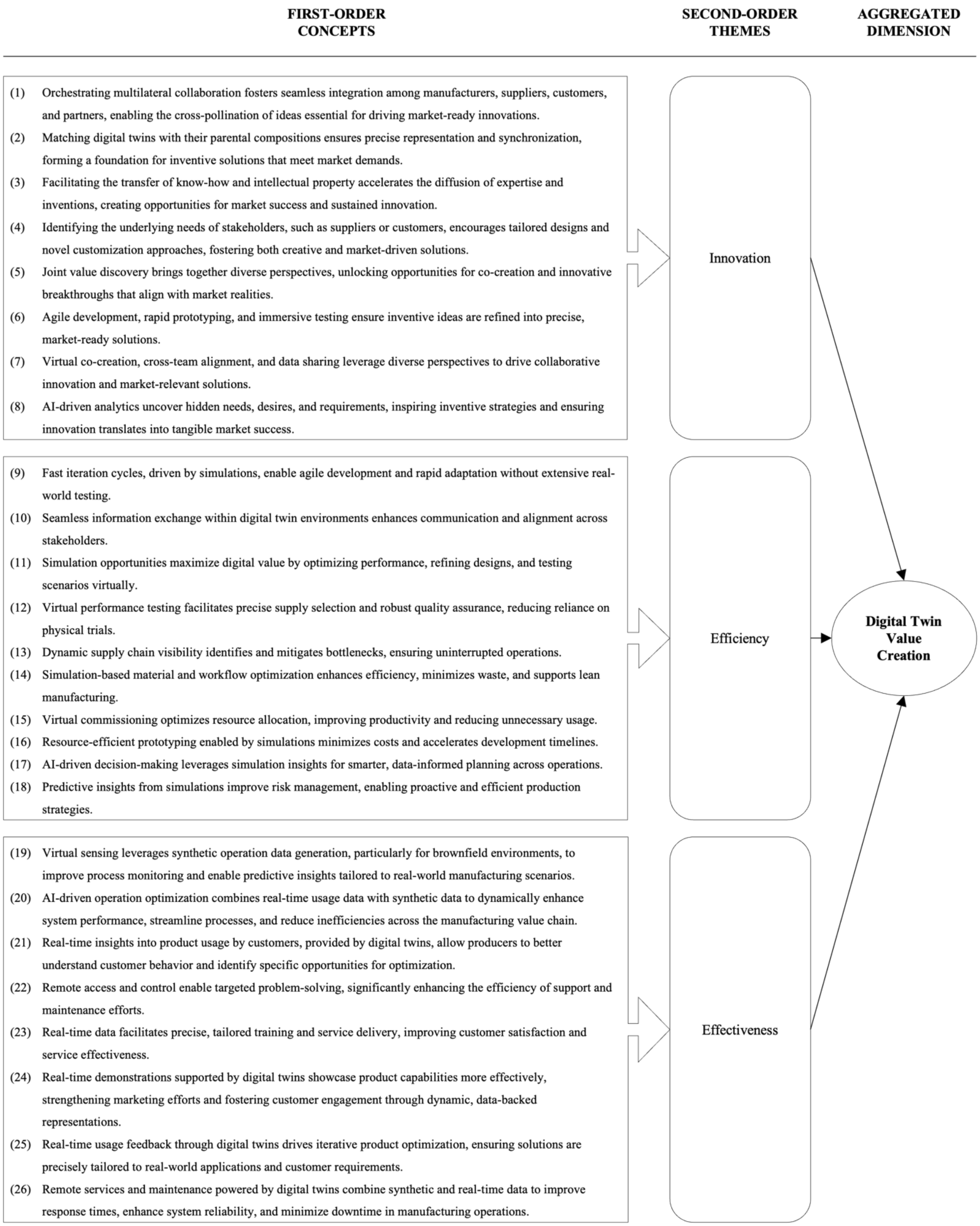
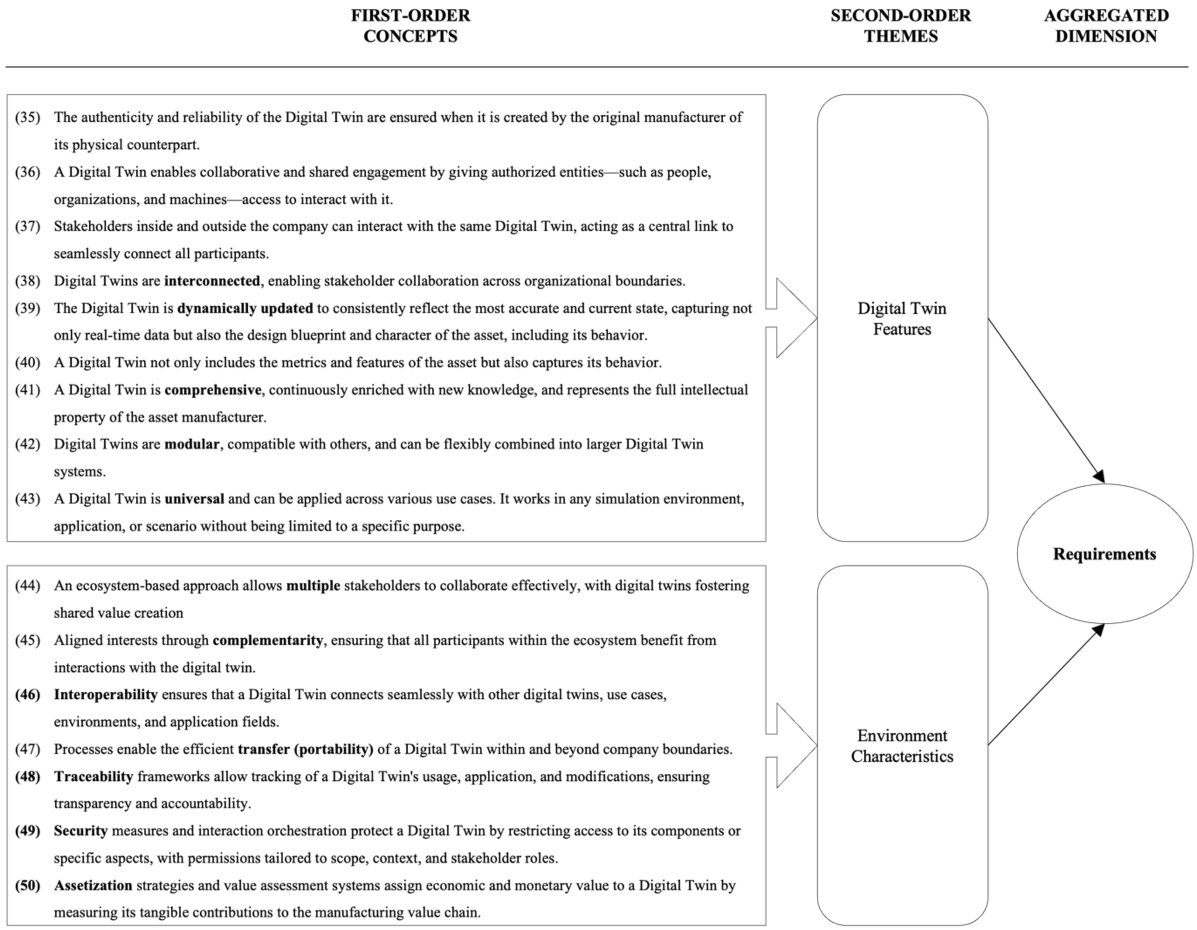


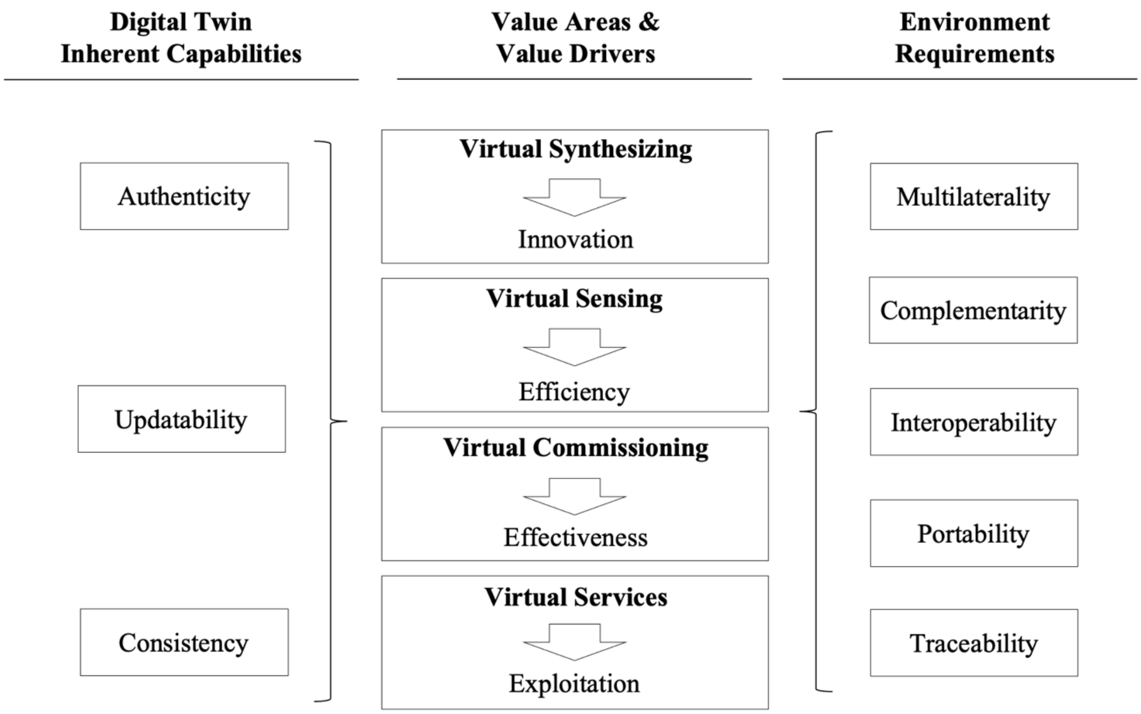
Figure 3: Coding Tree For The Digital Twin Intrinsic Characteristics & Requirements



4 Findings

This study investigates the inherent capabilities of digital twins, and the environmental conditions required to unlock their full potential. Digital twins represent an emergent technological approach in industrial contexts, providing transformative opportunities for value creation across the product and production lifecycles. However, their inherent capabilities can only be fully realized when deployed in environments that align with their specific requirements. Through this research, we identified four dominant value areas in industrial value chains, where the inherent capabilities of digital twins meet the necessary environmental conditions, creating the optimal context for leveraging their maximum potential. These value areas are (1) Virtual Synthesizing in the product development stage, (2) Virtual Commissioning as a transitional phase transferring values from upstream product development and production cycles into commissioning downstream production, (3) Virtual Sensing in the operational phase of production, and (4) Virtual Iterating, which connects and feeds operational data back into upstream R&D processes to drive continuous improvement. In these four areas, digital twins act as enablers of business value by fostering innovation**,** efficiency**,** effectiveness, and exploitation as dominant value drivers, each aligning with specific use cases, as illustrated in Figure 4.

Figure 4: Value Areas And Drivers Arising From The Matchmaking Of Inherent Capabilities & Environmental Conditions Of Digital Twins



4.1 Intrinsic Requirements of Digital Twins

Our findings indicate that digital twins must meet three key intrinsic requirements to serve as enablers of novel value creation and overarching business value drivers. The first intrinsic requirement is authenticity, which ensures that digital twins accurately reflect their physical counterparts. Authenticity is critical, particularly when digital twins are created by the original manufacturer, as it guarantees the reliability and trustworthiness of the digital representation. By embedding the full intellectual property (IP) of the physical asset, authentic digital twins provide the foundation for effective decision-making, simulation, and optimization processes.

The second requirement is updatability, which ensures digital twins remain synchronized with their physical counterparts through continuous data integration. This capability allows decision-makers to access accurate, real-time information that reflects current operational conditions, enabling timely and informed adjustments that improve responsiveness and efficiency.

The third intrinsic requirement is consistency, which extends beyond physical attributes to encompass the operational behavior, lifecycle, and performance data of an asset. A consistent digital twin provides a comprehensive representation, enabling predictive maintenance, robust simulations, and precise planning. By capturing the full lifecycle data of the asset, digital twins allow for deeper insights and alignment with strategic decision-making.

However, while these intrinsic requirements define the foundational capabilities of digital twins, they alone are insufficient to unlock the full potential of this technology. The ability of digital twins to deliver transformative value depends on their deployment within environments that meet specific contextual conditions. Without this alignment, the value of digital twins remains constrained, leading to unmet expectations and suboptimal outcomes.

4.2 Environmental Conditions

Our findings identify five critical environmental mechanisms that are essential for fully harnessing the six intrinsic features of digital twins to unlock their potential for creating business value. These conditions form the contextual foundation necessary for digital twins to function effectively within the manufacturing value chain.

Multilaterality plays a foundational role, ensuring engagement among multiple stakeholders, including suppliers, customers, internal teams, and even interactions with other digital twins. This mechanism enables digital twins to integrate diverse perspectives and contributions, fostering collaboration across various entities and levels of complexity.

Complementarity, as the second mechanism, ensures that the roles, expertise, and objectives of stakeholders are aligned to achieve collective benefits. By promoting synergies and reducing redundancies, complementarity supports mutually beneficial interactions. This alignment enables digital twins to act as focal points for cohesive, goal-driven collaboration. Together, multilaterality and complementarity create a collaborative ecosystem that facilitates value creation across the entire value chain, fostering shared goals and distributed contributions. By involving diverse actors, the environment ensures that digital twins enhance alignment and cooperation across varying roles and objectives.

Interoperability is the third critical mechanism, allowing digital twins to operate seamlessly across diverse environments and interact effectively with other digital twins. This capability integrates digital twins into broader ecosystems, preventing isolation and enabling participation in interconnected networks. Interoperability ensures cohesive and efficient operations by facilitating smooth communication and coordination across systems and processes.

These three mechanisms collectively establish a foundation for modularity, which allows digital twins to be deconstructed and recombined with other systems or digital twins as needed. Modularity supports scalability and adaptability, ensuring that digital twins can evolve alongside changing business needs and technological advancements.

Portability ensures that digital twins remain adaptable across varying operational contexts, platforms, and technological environments. This mechanism enables digital twins to function effectively in different settings, whether transitioning between systems, stakeholders, or geographical locations. Portability facilitates seamless integration, ensuring that digital twins maintain their relevance and usability across diverse scenarios.

Traceability, as the fifth mechanism, is essential for recording, monitoring, and auditing all interactions with a digital twin. This capability fosters transparency and accountability by documenting modifications, usage, and engagements with the digital twin. Traceability helps prevent misuse or unauthorized changes, reinforcing trust and ensuring operational integrity. Additionally, it creates opportunities for incentivizing digital twin usage by establishing clear records and enabling compliance with regulatory and organizational standards.

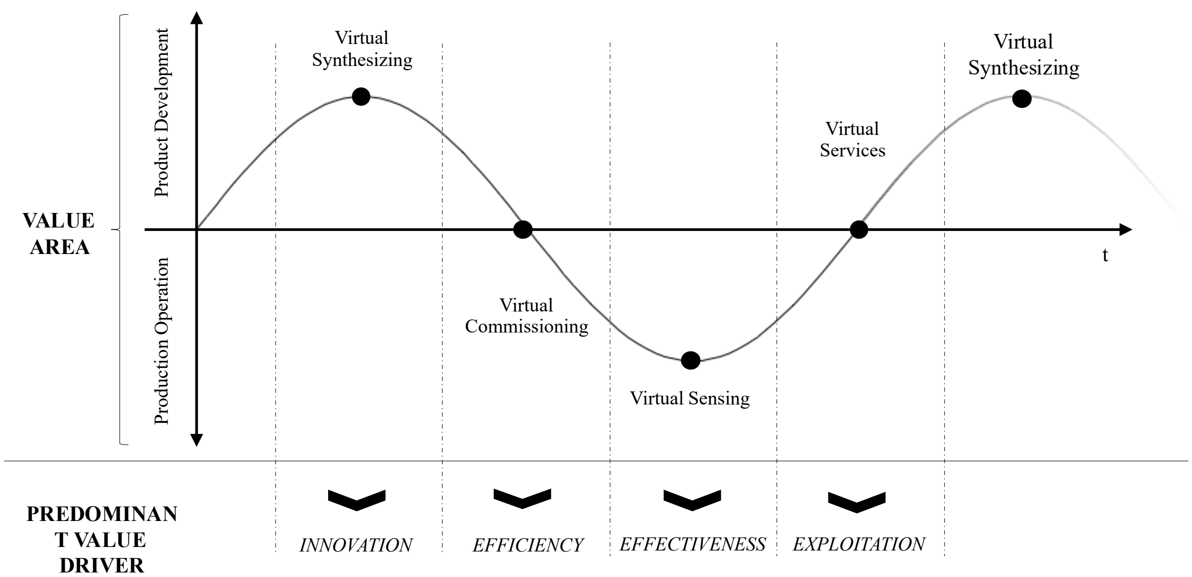
By meeting these environmental conditions, digital twins are empowered to fully leverage their intrinsic features, driving innovation, efficiency, effectiveness, and exploitation. Together, these mechanisms establish the foundational conditions that enable digital twins to transcend their technical origins and evolve into pivotal enablers of strategic business success.

Ultimately, these five conditions highlight the need for an ecosystem-oriented approach that connects assets, stakeholders, and digital twins. This orientation enhances synergies, fosters collaborative innovation, and promotes system-wide efficiencies. By embedding digital twins within a larger ecosystem, the environment amplifies their impact on business processes and outcomes, culminating in what can be referred to as the Industrial Metaverse.

4.3 Value Areas and Business Value Drivers in the Industrial Value Chain

The interplay between the intrinsic requirements of digital twins and the environmental conditions gives rise to four distinct value areas within the industrial value chain. These areas represent specific stages of product and production activities where digital twins create significant value, see Figure 5.

Figure 5: Value Areas And Value Drivers Of Digital Twins



Virtual Synthesizing emerges at the forefront of research and development, where digital twins enable the innovative integration and interaction of components and systems. This value area facilitates collaborative R&D by allowing virtual assembly and testing of complex systems from multiple component providers. By accelerating innovation, reducing time-to-market, and enhancing product quality, virtual synthesizing ensures that digital twins serve as critical tools for iterative and informed development processes

Virtual Commissioning focuses on the preparatory phases before full-scale production. In this value area, digital twins simulate and test physical systems in controlled virtual environments, identifying potential issues and optimizing operational settings before actual implementation. Virtual commissioning reduces the risks and costs associated with physical trials while enhancing the speed and precision of bringing systems online, fostering operational efficiency.

Virtual Sensing addresses the operational phase of production systems, where digital twins simulate sensor outputs or generate synthetic data. This value area is particularly relevant in scenarios where physical sensor data are unavailable or unreliable, such as in aging infrastructure or brownfield environments. By enabling continuous oversight, decision-making support, and predictive maintenance, virtual sensing ensures operational effectiveness through data-driven insights.

Virtual Services (Iteration) leverages operational, and usage data captured through digital twins to drive continuous improvements in R&D processes. This dynamic feedback loop enables iterative refinements to product designs and system configurations, informed by real-world performance data. By fostering innovation and adaptability, virtual iterating ensures that digital twins contribute to exploitation, allowing systems and products to evolve in response to changing requirements and market conditions.

4.4 Dominant Business Value Drivers of Digital Twins

The subsequent sections explore these interconnected elements, illustrating how digital twins advance operational and strategic goals, transforming the manufacturing value chain. Digital twins demonstrate a significant capacity to create business value, driven by their ability to enhance innovation, efficiency, effectiveness, and exploitation. These four drivers represent the core mechanisms through which digital twins transcend their technical foundation to generate measurable impacts across the manufacturing value chain. Foundational mechanisms such as synthetic data generation, virtual sensing, and virtual commissioning underpin this transformative potential.

Innovation emerges as a key business value driver facilitated by digital twins, primarily due to their capacity to bridge technological advancements with strategic opportunities. Digital twins enhance virtual prototyping, enabling businesses to test and refine prototypes in a simulated environment using synthetic data. This capability reduces the reliance on costly physical iterations, accelerates time-to-market, and fosters creativity. Additionally, data-driven ideation integrates synthetic and real-time data to uncover actionable insights into market trends and operational constraints, enabling systematic exploration of novel opportunities.

Through immersive co-creation, digital twins provide a collaborative virtual space for cross-functional and cross-organizational teams. This environment promotes multilateral interactions, fostering creative problem-solving and dynamic innovation. The ability to conduct scenario exploration empowers businesses to evaluate "what-if" scenarios without disrupting real-world operations, providing critical strategic insights. Furthermore, risk-free experimentation enabled by digital twins allows bold ideas to be tested without incurring significant risks or costs.

Digital twins also accelerate product development by integrating design, testing, and feedback processes into a unified digital platform. This streamlining reduces development cycles while enhancing the capacity for innovation. Customizable solutions enabled by digital twins allow businesses to tailor products and services to specific customer needs, leveraging insights from virtual sensing. Moreover, cross-domain integration breaks down organizational silos by connecting diverse data streams, fostering a holistic approach to innovation. Collectively, these features position digital twins as essential tools for transforming innovation into a continuous, data-driven process that aligns technical capabilities with strategic business goals. Predominantly, innovation is fostered in the value area of virtual synthesizing, as the collaboration of component providers in R&D enables novel designs and more aligned product compositions.

Efficiency, as a driver of business value, is strongly supported by digital twins' ability to optimize operations, resource utilization, and system reliability. The integration of synthetic data generation, virtual sensing, and virtual commissioning enables organizations to identify and eliminate inefficiencies. For instance, predictive maintenance powered by real-time data anticipates and addresses asset failures before they cause disruptions, significantly reducing downtime and associated costs. Similarly, process optimization leverages synthetic data simulations to identify bottlenecks and streamline workflows, enabling leaner operations and optimal resource allocation. Real-time insights derived from virtual sensing ensure dynamic updatability, enabling digital twins to reflect the current state of operations. This synchronization supports timely and informed decision-making, while optimized resource allocation ensures that labor, materials, and energy are utilized with precision. Additionally, digital twins contribute to energy efficiency by simulating energy usage and identifying opportunities for improvement, aligning operational practices with sustainability goals.

The modularity of digital twins enhances scalability and flexibility, allowing seamless integration into existing systems and ensuring interoperability across departments and applications. This avoids duplication of effort and fosters collaboration. Furthermore, waste reduction is achieved through virtual commissioning, enabling businesses to refine production processes virtually before implementation. Supply chain visibility facilitated by digital twins allows organizations to integrate end-to-end data, enabling rapid responses to disruptions and enhanced coordination across the value chain. Through these mechanisms, digital twins transform operational efficiency into a proactive, data-driven approach that delivers sustained business value**.** Efficiency is predominantly unlocked in the value area of virtual commissioning, as products and production cycles can be virtually tested and refined, enabling faster and more efficient trial-and-error processes in achieving desired outcomes.

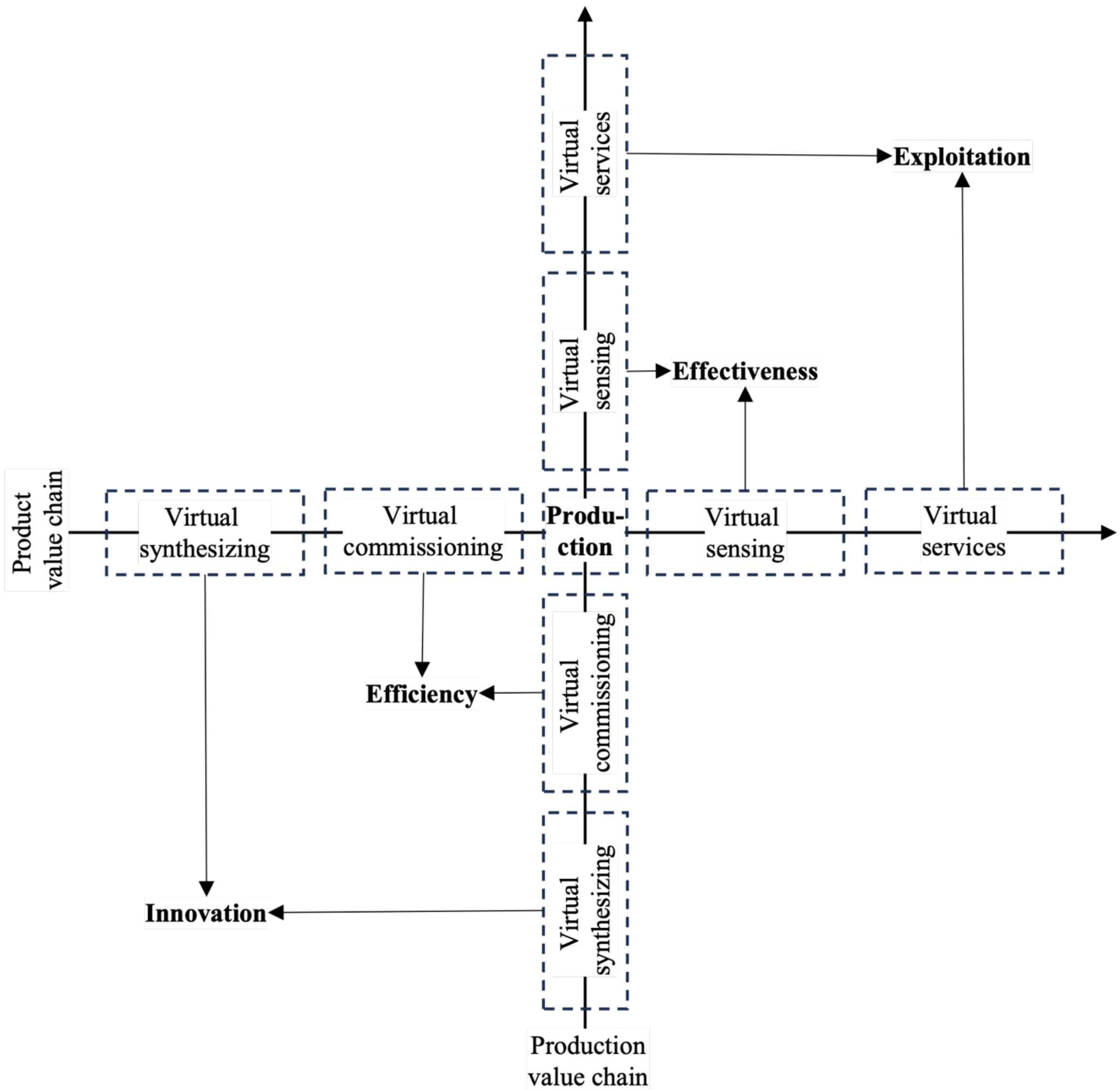
Effectiveness as a driver of business value creation is rooted in improving decision quality, stakeholder alignment, and adaptability. Digital twins provide traceability, enabling comprehensive tracking of asset usage, modifications, and lifecycle. This capability ensures transparency and accountability, aligning operations with regulatory compliance and organizational goals. Furthermore, security protocols safeguard sensitive data and intellectual property, ensuring that only authorized stakeholders have access, thereby reinforcing trust and collaboration.

The authenticity and reliability of digital twins are crucial to their effectiveness. By being created by the original manufacturer of the physical counterpart, digital twins maintain a dependable and accurate representation. This accuracy forms the foundation for high-quality decision-making. Behavioral simulation captures the dynamic features and behaviors of physical assets, enhancing predictive capabilities and operational planning.

Real-time insights derived from virtual sensing ensure decisions are informed by the most current operational data. This improves responsiveness and enables agile adjustments to changing conditions. By creating a single source of truth, digital twins align stakeholders around accurate, shared information, fostering collaboration and alignment. Additionally, the ability to deliver customization allows businesses to tailor products and processes to specific customer requirements, enhancing satisfaction and differentiation. Finally, digital twins support business adaptability by simulating market changes and dynamically adjusting operations, ensuring exploitation and relevance. These interconnected capabilities highlight how digital twins enhance effectiveness across strategic and operational domains, driving long-term business value. Effectiveness is predominantly unlocked in the value area of virtual sensing, where digital twins stream reliable synthetic data in previously inaccessible environments, enriching IoT systems and ensuring data consistency.

Exploitation represents the ability of digital twins to iteratively transfer and harmonize upstream product and production data into downstream usage, thereby enabling continuous optimization and value creation. Through their capability to track data across the entire lifecycle, digital twins facilitate the systematic exploitation of operational insights for the development of new product versions, the refinement of production processes, and the enhancement of digital business models. By integrating real-time performance data with historical trends, digital twins ensure that past learnings are effectively leveraged for future improvements. This exploitation of data-driven insights fosters continuous evolution, aligning product and production adaptations with market needs and technological advancements. Exploitation is predominantly driven by virtual iterating, where digital twins act as enablers of seamless data flow across the value chain, ensuring that past performance informs future innovation and process enhancements.

Figure 6: Dominant Business Value Drivers Of Digital Twins



The role of digital twins in value creation extends beyond their individual applications in Virtual Synthesizing, Virtual Commissioning, Virtual Sensing, and Virtual Exploitation. Their fundamental impact arises from their ability to harmonize multiple data sources and generate a comprehensive, unified lifecycle dataset—encompassing both direct production items and their associated stakeholders, as well as the broader production environment and product-centric components. By overcoming data silos and addressing real-time data gaps, digital twins establish a trustworthy and consistent data foundation, serving a diverse range of use cases across the industrial landscape. However, the extent to which digital twins realize their full value depends on the alignment of their inherent capabilities with the environmental conditions required for their optimal functioning. These dependencies determine the extent to which digital twins can enhance industrial efficiency, drive innovation, facilitate operational effectiveness, and foster new exploitation opportunities. Figure 6 illustrates these match-making opportunities, linking digital twin applications to their respective value drivers and positioning these drivers along the product and production lifecycle perspectives.

5 Discussion

This study contributes to the ongoing discourse on digital twins by providing both theoretical advancements and managerial insights. From a theoretical perspective, our research extends existing literature by shifting the focus from a predominantly technology-centric view of digital twins to a value-centric perspective, identifying key characteristics that drive business value and the environmental conditions necessary for their effective deployment. By linking DTs to the emerging Industrial Metaverse, we offer new insights into how digital twins function within decentralized, platform-based industrial ecosystems, expanding on prior research in Industry 4.0 and supply chain resilience (Dolgui & Ivanov, 2023; Ivanov, 2023). From a managerial perspective, our findings provide a structured framework to help organizations navigate the complexities of digital twin implementation, emphasizing value creation, strategic integration, and ecosystem collaboration. We outline practical recommendations for firms looking to leverage digital twins beyond operational efficiency, positioning them as strategic enablers of innovation, predictive analytics, and cross-organizational collaboration in platform-driven industries. In the following sections, we further elaborate on the theoretical and managerial contributions of our study, highlighting its implications for future research and practice.

5.1 Theoretical Contribution

This study extends and enriches the current state of research on digital twins by advancing theoretical and conceptual understanding in three key areas: (1) the intrinsic characteristics of digital twins as enablers of value creation, (2) the environmental conditions necessary for their effective deployment, and (3) the role of digital twins in shaping industrial ecosystems, particularly within the Industrial Metaverse. Through a systematic empirical approach, we identify distinct value-driving mechanisms and the conditions that facilitate digital twin-based value creation across product and production systems and value chains.

From Technology-Centric to Value-Centric Perspectives. Much of the existing literature on digital twins has focused on technological enablers and implementation methodologies, with an emphasis on their integration within manufacturing and supply chain operations (Kritzinger et al., 2018; Lu et al., 2022). Ivanov (2024) proposed a seven-element framework for digital twins in supply chain and operations management, emphasizing technology, people, and organizational integration. Similarly, Semeraro et al. (2021) provided a systematic review of the digital twin paradigm, highlighting research gaps related to its conceptualization and practical deployment. Our study advances this discourse by shifting the focus from a technology-centric perspective to a value-centric perspective. Instead of merely considering digital twins as technological constructs that replicate physical assets, we identify three key characteristics that define their ability to create value. This distinction enables a more nuanced understanding of how digital twins facilitate efficiency, decision-making, and business transformation beyond their technical implementation. Additionally, Van Dyck et al. (2023) introduced the concept of interconnected digital twins, emphasizing their role in digital manufacturing and data-driven decision-making. Our research extends this by considering how digital twins function within industrial ecosystems, particularly in platform-based environments.

Clarifying Environmental Requirements for Digital Twins. The success of digital twin implementations depends on their alignment with specific environmental conditions. Prior studies have outlined enabling technologies such as IoT, cloud computing, and AI (Kusiak, 2023), but there has been limited discussion on the organizational and ecosystem-level conditions required for effective digital twin utilization (Psarommatis & May, 2023a). Our findings contribute by identifying five essential environmental requirements that digital twins must meet to unlock their full business potential. We build upon Guo & Mantravadi (2024), who explored digital twins in lean supply chain management and emphasized the importance of waste elimination, logistics optimization, and real-time information flow. Our study extends this discussion by highlighting how environmental factors—such as standardization, data interoperability, and collaborative ecosystems—enhance digital twin effectiveness in complex industrial settings. In doing so, we provide a guiding framework for organizations seeking to implement digital twins, ensuring that necessary technical, organizational, and ecosystem-wide conditions are met. This perspective aligns with discussions on digital twin standardization and performance measurement (Psarommatis & May, 2023b), yet extends beyond to include strategic and ecosystem-level considerations.

Positioning Digital Twins within the Industrial Metaverse. The integration of digital twins into broader platform ecosystems remains an underexplored area, despite growing interest in Industry 4.0 and 5.0 paradigms (Lu et al., 2021; Romero & Stahre, 2021). Our study bridges this gap by analyzing how digital twins interact with digital trust mechanisms in the emerging Industrial Metaverse. Unlike prior studies that examine digital twins in isolated industrial settings, we conceptualize them as dynamic entities within a multi-stakeholder ecosystem, where decentralized and hybrid platform structures play a pivotal role. This aligns with Dolgui & Ivanov (2023), who explored the role of the Metaverse in supply chain and operations management. Our study extends this by emphasizing the necessity of digital trust and interoperability between decentralized platform structures and digital twin ecosystems, aligning with Schmück et al. (2025). Furthermore, Li et al. (2023) proposed blockchain-enabled digital twin collaboration platforms, highlighting the potential for secure, decentralized industrial interactions. Our research builds upon this by outlining the conditions necessary for seamless digital twin integration into blockchain-based industrial environments. By doing so, we extend discussions on digital twins as socio-technical systems (Ivanov, 2024; Lu et al., 2021), moving beyond their operational role in manufacturing and supply chains to their strategic role in industrial transformation. This aligns with but also extends research on predictive modeling and smart manufacturing (Kusiak, 2023; Luo et al., 2023), offering a future-oriented perspective on how digital twins will evolve as integral components of industrial ecosystems.

Digital Twins and Platform Collaboration. Another emerging research direction is the collaborative potential of digital twins within platform ecosystems. Reim et al. (2023) emphasized the role of digital twins in enabling collaboration on digital platforms. While prior studies have examined the technological feasibility of digital twin platforms, our study contributes by identifying the governance structures, business models, and interoperability challenges that shape digital twin-enabled collaboration within industrial networks. Moreover, Choi et al. (2023) introduced the ABCDE framework for platform supply chain innovations, emphasizing the importance of transparency, data security, and adaptive decision-making in blockchain-driven industrial ecosystems. Our study integrates these perspectives by exploring how digital twins function as enablers of adaptive decision-making and cross-organizational collaboration within digital industrial platforms.

Implications for Future Research. Our findings offer multiple pathways for future research:

- The value-centric perspective introduced in this study invites further investigation into business model innovations enabled by digital twins.

- Our conceptualization of environmental requirements provides a structured approach for evaluating digital twin readiness in different industrial contexts.
- By linking digital twins to platform ecosystems, our study opens avenues for research on governance, interoperability, and digital trust mechanisms within decentralized industrial environments.
- Future research can build upon our findings by investigating the evolution of digital twin-based business models in the context of industrial metaverse platforms.
- The role of AI-driven intelligent digital twins (iDTs), as proposed by Ivanov (2023), presents another critical avenue for exploration, particularly in the stress-testing and resilience of digital supply chains.

By integrating these perspectives, our study makes a substantive theoretical contribution to the literature on digital twins, industrial ecosystems, and platform-based innovation. It offers a conceptual foundation for future empirical studies that seek to explore the evolving role of digital twins in industrial transformation and digital business models.

5.2 Managerial Contribution

Our findings highlight that the effective realization of digital twins' value drivers fundamentally depends on the matchmaking between their inherent capabilities and the appropriate environmental conditions. Only when these capabilities are aligned with the right contextual factors can they fully unfold their potential. This matchmaking occurs in four distinct areas along the product and production lifecycle:

- Virtual Synthesizing, where innovation is fostered by optimizing composition mechanisms between suppliers and component manufacturers.

- Virtual Commissioning, where efficiency is enhanced by enabling a faster, cost-effective transition into a steady-state of production or product deployment through virtual testing and validation.
- Virtual Sensing, where effectiveness is improved by addressing data incompleteness in steady-state production or product operation through the generation of synthetic data via digital twins.
- Virtual Exploitation, where digital services are iteratively refined by transferring upstream product or production data into the next downstream product or production cycle, enabling new forms of data-driven exploitation in digital business models.

These four value areas provide managers with a structured approach to resource allocation when implementing digital twins. Given that the field of digital twins and the Industrial Metaverse is still emerging, often underexplored and underutilized, it is crucial to identify "low-hanging fruits"—areas where digital twins can generate maximum impact with minimal risk. By leveraging the Value Areas, Value Drivers, and Environmental Conditions, managers can adopt a goal-oriented perspective, ensuring that digital twin integration is designed with the desired business effects in mind, rather than pursuing technology adoption without a clear value proposition.

Moreover, our study provides a framework for assessing the authenticity of digital twins, helping managers differentiate between true digital twins and limited digital representations. Not every digital model of a physical component qualifies as a digital twin. A genuine digital twin must incorporate inherent, application-independent capabilities, which lead to Authenticity, Updatability, and Consistency. These three criteria must be met independently of the specific use case to ensure meaningful impact when digital twins are deployed in the appropriate environment.

Finally, our study contributes to expectation management regarding digital twin implementation. It provides a structured perspective to prevent inflated hype, which can negatively impact the perception and adoption of digital twins if initial expectations are misaligned or if they are deployed in unsuitable environmental conditions. A negative industry narrative, once formed due to unrealistic expectations or improper applications, is difficult to correct. By offering clear guidance on effective adoption, our study facilitates a realistic and sustainable integration of digital twins, ensuring that their value drivers are fully leveraged to generate measurable business impact.

Disclosure Statement

No potential conflict of interest was reported by the author.

Data Availability Statement

Data supporting the findings of this study are available on a reasonable request from the authors.

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