Integrating Metaverse Technologies in Manufacturing: A Case-Informed Conceptual Framework and Future Directions

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DOI: https://doi.org/10.51244/IJRSI.2025.120700021

Received: 25 June 2025; Accepted: 27 June 2025; Published: 29 July 2025

ABSTRACT

The convergence of metaverse technologies with manufacturing marks a significant evolution in industrial transformation, enabling immersive, interconnected and data-driven production environments. This study aims to develop and validate a conceptual framework that captures the integration of metaverse components- such as digital twins, extended reality (XR), real-time data exchange and decentralised systems- within smart manufacturing ecosystems. The research seeks to clarify how these technologies contribute to operational efficiency, human-machine collaboration and value co-creation. To achieve this, the study employs a qualitative methodology comprising two main approaches: (1) a systematic synthesis of peer-reviewed literature and industrial reports to identify critical themes and theoretical constructs and (2) in-depth case study analysis of three global manufacturing leaders- Siemens AG, Hyundai Motor Company and Foxconn Technology Group. These firms were selected for their public and documented advancements in implementing industrial metaverse technologies. The findings coalesce into a four-dimensional conceptual framework encompassing technological infrastructure, organisational capabilities, human-machine interaction and value co-creation. The case studies demonstrate how each firm embodies these dimensions: Siemens leverages digital twins for real-time simulation and operational optimisation; Hyundai employs XR for workforce training and remote monitoring and Foxconn integrates immersive interfaces and blockchain to enhance collaboration and transparency. Together, these case studies validate the framework's relevance and practical applicability. The paper concludes by proposing a research agenda focused on theoretical development, standardisation, socio-technical adaptation and evaluation metrics. These directions aim to guide future inquiry and inform strategic implementation. The study contributes both a structured understanding and actionable insights for academics, practitioners and policymakers navigating the evolving industrial metaverse.

Keywords: digital transformation, digital twins, Industry 5.0, industrial automation, manufacturing, metaverse

INTRODUCTION

Manufacturing has evolved through four industrial revolutions, each redefining production systems and socio-economic structures. The first industrial revolution, beginning in the 18th century, introduced mechanisation powered by steam engines and railroads, shifting labour from manual to machine-driven processes. The second revolution brought electricity and mass production via assembly lines. In the 1960s, the third revolution introduced automation using electronics, computing and early internet technologies. The fourth industrial revolution- popularised as Industry 4.0 in Germany in 2011- represents a digital transformation characterised by cyber-physical systems, real-time data exchange and intelligent, interconnected factories. It integrates technologies such as Artificial Intelligence (AI), Industrial Internet of Things (IIoT), robotics, quantum computing and nanotechnology to enable smart, adaptive systems and globally networked value chains (Varshney, Garg, Pandey, Singhal, Singhal & Sharma, 2024).

Emerging within this Industry 4.0 landscape, metaverse technologies offer new possibilities for immersive design, training, and collaborative manufacturing. The term 'metaverse' derived from 'meta' (beyond) an 'universe', refers to persistent digital environments that enhance or replicate real-world experiences. These environments are built on technologies including augmented and virtual reality (AR/VR), blockchain, Artificial

Intelligence, spatial computing, cloud services and 5G connectivity (Lee, Braud, Zhou, Wang, Xu, Lin, Kumar, Bermejo & Hui, 2021; Koohang, Nord, Ooi, Tan, Al-Emran, Aw, Baabdullah, Buhalis, Cham, Dennis, Dutot, Dwivedi, Hughes, Mogaji, Pandey, Phau, Raman, Sharma, Sigala, Ueno & Wang, 2023). From AR-based retail apps to blockchain-enabled logistics, these technologies are increasingly integrated into everyday industrial and consumer activities.

The convergence of metaverse technologies with Industry 4.0- and its evolution into Industry 5.0- has the potential to enhance customisation, reduce costs, improve sustainability and optimise operations. Firms such as Boeing, Tesla, Ford and Bosch are already applying digital twins, immersive simulations and AI-powered automation to reduce errors and accelerate product development (Nah, Eschenbrenner & Chen, 2025). Platforms like NVIDIA Omniverse and Microsoft Mesh enable global teams to design, simulate and collaborate in real time.

Despite growing adoption, scholarly discussions often examine these technologies in isolation, without a unified perspective on their integration withing manufacturing (Nleya & Velempini, 2024; Fernandez-Carames & Fraga-Lamas, 2023). This study addresses that gap by developing a conceptual framework that explain how metaverse technologies are applied in manufacturing contexts. Supported by case studies, the research explores pathways for adoption and value creation, aiming to inform both academic inquiry and industrial practice.

LITERATURE REVIEW

The concept of metaverse has evolved from a fictional idea in Neal Stephenson's Snow Crash into a rapidly emerging technological paradigm. Despite the absence of a universally accepted definition (Ritterbusch & Teichman, 2023), it has gained momentum, especially after Facebook's rebranding as Meta in 2021 (Ng, 2022). Early applications emerged in the gaming industry, where immersive environments and virtual worlds laid the foundation for later technological developments (Narin, 2021). Scholars broadly agree on core features of the metaverse, including immersive 3D spaces persistent digital environments and avatar-based interaction. For instance, Davis et. al (2009) define it as a network of interactive 3D environments, while Mystakidis (2022) presents it as a persistent, multi-user space that merges physical and digital realities. Lee et al (2022) highlight its real-time interaction capabilities and Buhalis & Karatay (2022) emphasize ambient intelligence and value co-creation.

Although the metaverse is gaining traction across sectors, its application in manufacturing remains underexplored (Amaizu et al., 2024). The broader historical context of industrial evolution provides a useful backdrop. From steam-powered mechanisation in Industry 1.0 to automated, data-driven systems in Industry 4.0- originally conceptualised in 2011 German high-tech strategy initiative (Xu et al., 2021)- the sector has steadily advanced toward greater digital integration. Industry 5.0 now represents a shift toward human-centric, intelligent systems emphasising collaboration between humans and machines (Groumpos, 2021; Martinez-Gutierrez et al., 2024).

Within this trajectory, the industrial metaverse has emerged as a transformative development. It combines technologies such as AI, digital twins, cloud computing and edge computing to create digitally replicated environments aimed at enhancing productivity and sustainability (Guo et al., 2024; MIT Technology Review Insights, 2024).

While the metaverse spans both consumer and enterprise domains, its manufacturing applications are uniquely promising. Nleya & Velempini (2024) distinguish between consumer-facing uses – such as social interaction- and enterprise uses, such as immersive simulations and digital twins. Sectors like healthcare, education and retail are already deploying these technologies for training, remote service delivery and customer engagement (Jung et al., 2024; Gleim et al., 2024). However, manufacturing faces adoption barriers including system complexity, integration costs, data security and workforce readiness (Gupta et al., 2024; Bhattacharya et al., 2023).

Salminen & Aromaa (2024) document industrial metaverse applications across 18 firms, primarily in training and collaboration, while also noting persistent regulatory and cybersecurity challenges. Sector-specific implementations- from automotive to fashion, biotechnology and energy- demonstrate both the scope and variability of adoption (Wei et al., 2024; Kim & Oh, 2022; Diak & Diak, 2025; Casciani et al., 2022; Unver, 2023; Chen, 2025).

While much of the literature celebrates successes in the industrial metaverse, numerous implementations falter due to technological, organisational and interoperability barriers. Arthur D. Little (2023) notes that even major players like Microsoft faced setbacks- shutting down its AltspaceVR Platform and restructuring its industrial metaverse division due to limited scalability and adoption challenges. These outcomes often stem from fragmented data systems, poor interoperability and weak alignment with legacy operations. Acknowledging such failures offers a more balanced perspective and underscores the need for strategic coherence and organisational readiness in metaverse adoption.

Despite growing interest, a unified conceptual framework guiding metaverse integration in manufacturing is lacking. Current research is fragmented, offering insights in isolation rather than as part of a coherent model. This study addresses that gap by proposing an integrated framework informed by literature and empirical case studies and by outlining strategic pathways for future research and implementation.

RESEARCH OBJECTIVES

To examine and synthesize existing academic and industry literature on metaverse technologies- such as digital twins, AR/VR, Artificial Intelligence, blockchain and cloud computing- and their relevance within the context of Industry 4.0 and Industry 5.0 in manufacturing.

To investigate real world applications in manufacturing through case studies of Siemens Ag, Hyundai Motor Company and Foxconn Technology Group, with a focus on implementation strategies, challenges and benefits.

To develop and validate a conceptual framework for integrating metaverse technologies in manufacturing.

To identify key enablers, barriers and strategic pathways for successful adoption of industrial metaverse technologies and propose a future research agenda.

RESEARCH METHODOLOGY

This study adopts a qualitative exploratory research design to develop a conceptual framework for integrating metaverse technologies into manufacturing. Two primary methods were employed: a literature synthesis and multiple case study analysis. Relevant academic and industry sources were reviewed to identify key technologies and thematic dimensions. Case studies of Siemens AG, Hyundai Motor Company and Foxconn Technology Group were selected based on their adoption of digital twins, AR/VR and AI. Siemens AG, Hyundai Motor Company and Foxconn Technology Group were selected as case studies due to their documented leadership in industrial metaverse adoption. These firms represent diverse manufacturing sectors- engineering, automotive and electronics- and have successfully implemented key technologies such as digital twins, Extended Reality, Artificial Intelligence and blockchain technology to transform product design and lifecycle management (Siemens AG, 2024). Their initiatives span design, training and supply chain optimisation, offering multidimensional insights into metaverse integration. Recognised in industry analyses (Arthur D. Little, 2023; MIT Technology Review Insights, 2024), these companies exemplify both technological maturity and strategic intent, making them ideal for examining practical applications of the proposed conceptual framework. Data were gathered from reports, publications and publicly available data. The integrated findings informed the proposed framework and highlighted key enablers, challenges and pathways for strategic implementation and future research.

CASE STUDY ANALYSIS

Siemens AG:

Siemens AG has been at the forefront of industrial digitalisation, leveraging metaverse technologies primarily through its digital twin solutions and collaborations with platforms such as NVIDIA Omniverse. Siemens' "industrial metaverse" initiative integrates simulation, automation and real-time data across product design and manufacturing. By using immersive 3D environments and AI-driven simulation, Siemens enhances prototyping, predictive maintenance and workforce training. These technologies map to the framework's technological infrastructure and human-machine interaction dimensions. The company's strong digital culture and investment in talent development demonstrate mature organisational capabilities.

Hyundai Motor Company:

Hyundai employs metaverse tools in both product development and manufacturing operations. It launched "Hyundai Mobility Adventure" on Roblox for stakeholder engagement and digital twin environments for factory simulation and robot-human interaction testing (Mogaji, 2023). This illustrates alignment with value co-creation, allowing internal teams and external partners to co-design processes and experiences. Hyundai's use of AR/VR for employee training and maintenance simulations enhances human-machine interaction while improving productivity and safety. Challenges include workforce upskilling and ensuring cross-platform interoperability.

Foxconn Technology Group:

Foxconn integrates digital twins, AI and IoT to manage its massive production networks. Its "Smart Manufacturing" initiative leverages real-time monitoring, predictive analytics and edge computing for supply chain optimisation and defect reduction. The company's use of blockchain for supply chain traceability reflects a commitment to transparency and innovation. Foxconn's model illustrates all four framework dimensions, with a particular emphasis on technological infrastructure and organisational readiness for scale. However, data governance and privacy issues remain key concerns.

DISCUSSION

The case studies validate the proposed conceptual framework (See Figure 1) by demonstrating its applicability across diverse manufacturing contexts. All three firms exhibit integration of metaverse technologies along the four foundational dimensions:

Technological Infrastructure: This dimension includes the core technologies enabling immersive and interconnected virtual environments. It refers to the tools, systems, platforms and infrastructures that make it technically possible to build, operate and scale metaverse applications in manufacturing environments.

Digital Twins: It means virtual replicas of physical manufacturing systems that is continuously updated with real-time data from sensors, IoT devices and other sources. It allows for monitoring, simulation and optimisation of physical entities in a digital environment (Sharma, Kosasih, Zhang, Brintrup, & Calinescu, 2022).

Immersive Environments (AR/VR/MR): Immersive environments, encompassing Augmented Reality, Virtual Reality and Mixed Reality- collectively referred to as Extended Reality (XR)- enable visualisation, simulation and remote collaboration. XR is expected to benefit from 6G's ultra-reliable connectivity and low latency (Kalla et al., 2022). VR creates a strong sense of presence (Slater & Sanchez-Vives, 2016), AR overlays digital elements onto the real world and MR blends both for dynamic, real-time interaction (Milgram & Kishino, 1994).

Industrial Internet of Things (IIoT): It means network of smart sensors enabling real-time data collection and integration from factory equipment. Integrated with Metaverse platforms, IIoT enhances visibility, supports immersive interaction with digital twins and drives data-informed decision-making across smart factory environments (Ahmed et al., 2023).

Artificial Intelligence (AI): It enhances manufacturing process by enabling predictive analytics, real-time decision systems and intelligent automation. It improves efficiency, quality and maintenance through data-

ISSN No. 2321-2705 | DOI: 10.51244/IJRSI |Volume XII Issue VII July 2025

driven insights and adaptive control architectures in smart factories (Kim, Kong, Lee, & Lee, 2021).

Blockchain Technology: This technology enables decentralised, tamper-evident ledgers that enhance transparency, traceability and security across manufacturing processes. It supports supply chain integrity, smart contracts and immutable transaction records, making it ideal for industrial data-sharing and auditing (Casino, Dasaklis & Patsakis, 2019).

Organisational Capabilities: Technological readiness alone is insufficient without requisite organisational capabilities. This dimension includes:

Change Management: This involves fostering organisational readiness for digital transformation through clear leadership, commitment, vision alignment and proactive strategies that encourage adaptability and reduce resistance to the adoption of metaverse technologies.

Digital Skills & Training: Focuses on equipping the workforce with essential digital competencies, including immersive technology usage, data interpretation and platform navigation to enable effective participation in metaverse-enabled manufacturing environments.

Cross-functional Integration: Requires seamless collaboration among Information Technology, operations, engineering and design departments to ensure cohesive planning, deployment and scaling of metaverse tools across various functional areas within the manufacturing process.

Infrastructure Investment: Entails sustained financial and strategic commitment to modernise legacy systems, upgrade digital infrastructure and adopt open, interoperable platforms that support the scalability and performance needs of industrial metaverse applications.

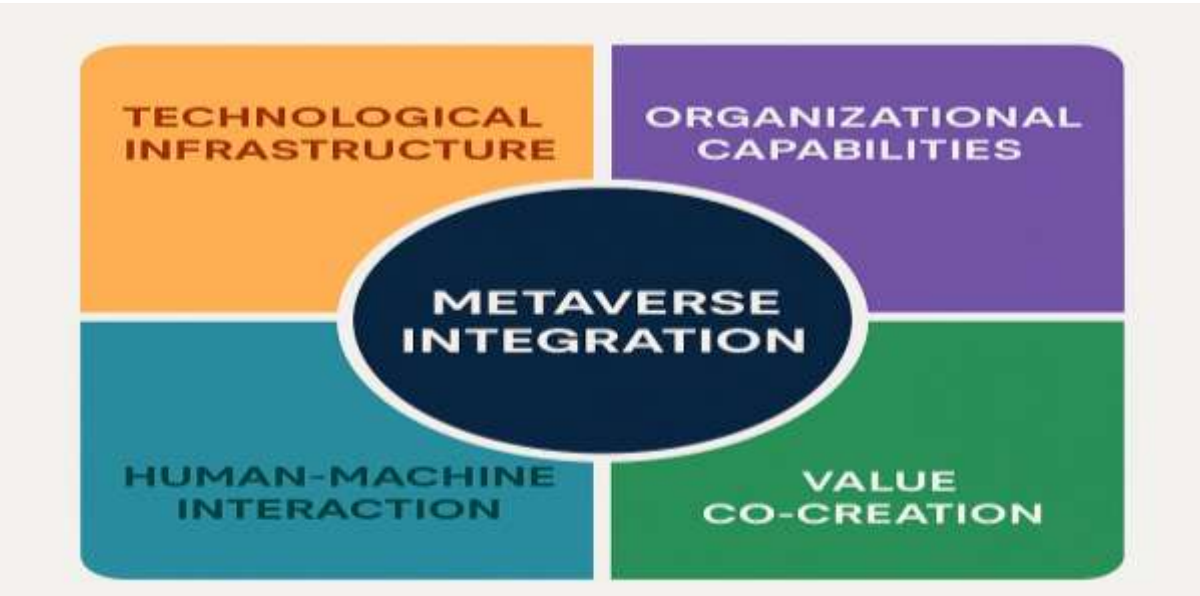

Figure 1

Conceptual Framework of the study

Source: Author’s own elaboration

Human-Machine Interaction: As Industry 5.0 places emphasis on human-centric innovation, this dimension focuses on enhancing collaboration between machines and humans. This dimension includes:

Immersive Training: Virtual and augmented reality environments replicate real-world factory settings, enabling safe, cost-effective and repeatable training scenarios that enhance skill acquisition, reduce errors and prepare workers for complex tasks.

Collaborative Interfaces: Human-machine collaboration is facilitated through user-friendly, real-time interface that enable seamless interaction with AI systems and robots, improving productivity, adaptability and decision-making across manufacturing workflows.

Ergonomics and Safety: Extended Reality tools support ergonomic design by visualising workspace layouts and simulating physical interactions, helping reduce worker fatigue, prevent injuries and enhance safety in dynamic industrial environments.

Value Co-Creation: The ultimate aim of integrating metaverse technologies is to enable and enhance value creation across the manufacturing lifecycle. This includes:

Product Customisation: Immersive virtual environments enable customers to actively participate in the design process, allowing rapid prototyping, personalised product development and enhanced customer satisfaction through real-time visual feedback and iteration.

Supply Chain Optimisation: Metaverse technologies provide real-time visibility and seamless collaboration across the supply chain, enabling better co-ordination among suppliers, manufacturers, distributors and improving responsiveness, efficiency and overall value delivery.

Sustainability: Advanced simulations and digital modelling support waste reduction and energy efficiency by optimising resource planning and process flows, helping manufacturers meet sustainability targets while reducing their environmental impact.

Innovation Ecosystems: Collaborative partnerships with technology firms, startups and research institutions foster open innovation, enabling co-development of novel metaverse-driven solutions tailored to specific manufacturing challenges and market demands.

Building on the validated framework, Figure 2 represents a lifecycle view of how metaverse technologies are typically integrated in manufacturing, from exploration through transformation.

Figure 2

Lifecycle of integrating metaverse technologies in manufacturing

Source: Conceptualised by the author

The integration of metaverse technologies into manufacturing processes unfolds through a dynamic lifecycle comprising four progressive stages: exploration, adoption, optimisation and transformation (Figure 2). In the exploration stage, firms assess the strategic potential of immersive and intelligent technologies- such as digital twins, extended reality (XR) and blockchain through research and development activities, feasibility assessments and small-scale pilots. For instance, Siemens began exploring digital twin technologies in controlled settings to simulate and test manufacturing environments (Siemens AG, 2024). The adoption stage involves early implementation within targeted operational areas, often supported by leadership commitment, digital infrastructure investment and workforce training. Hyundai, for example, deployed XR tools for maintenance simulations and employee training (Njoku, Nwakanma & Kim, 2023), showcasing early adoption that aligns with value co-creation and human-machine interaction.

As firms progress to the optimisation stage, metaverse applications are scaled and embedded across functions, supported by interoperable platforms and real-time data exchange. Foxconn exemplifies this phase with its integrated use of Artificial Intelligence, Internet of Things and blockchain for predictive analytics and transparent supply chain operations. Finally, the transformation stage marks a strategic shift where metaverse technologies are deeply embedded in business models, enabling collaborative innovation, sustainability and organisational agility. This is evident in Siemens' industrial metaverse vision, where immersive digital environments support global co-engineering, smart factory control and sustainable design practices. Understanding this lifecycle is essential to guide firms in navigating technological complexity, aligning internal capabilities and realising the full strategic potential of the industrial metaverse.

Cross-Cutting Challenges and Strategic Pathways:

Despite promising developments, the integration of metaverse technologies into manufacturing presents several cross-cutting challenges that transcend individual companies or sectors. One major concern is data privacy and cybersecurity, particularly in decentralised environments that involve real-time sharing across multiple stakeholders. Without robust safeguards, risks of data breaches and system vulnerabilities may undermine trust and adoption.

Lack of standardisation in metaverse platforms, protocols and data formats also impedes interoperability, making integration with existing manufacturing systems complex and costly. In parallel, the absence of established evaluation metrics complicates performance tracking and return-on-investment assessments.

Regulatory ambiguity further hampers the progress. Emerging technologies like blockchain, AI and XR often outpace policy development, leading to uncertainty around compliance, liability and data ownership. Additionally, digital inequality presents a critical barrier- many small and medium-sized enterprises lack the financial and human capital needed to engage with advanced digital infrastructures.

To address these challenges, strategic pathways must include multi-stakeholder standardisation efforts, targeted government incentives, cross-sector collaboration and workforce development programs focused on digital literacy. Building trust through transparent governance models and ethical AI frameworks will also be vital to scale the industrial metaverse responsibly and inclusively.

CONCLUSION AND FUTURE RESEARCH DIRECTIONS:

This study proposed and validated a conceptual framework for integrating metaverse technologies into manufacturing through the lens of four foundational dimensions: technological infrastructure, organisational capabilities, human-machine interaction, and value co-creation. By synthesising relevant literature and analysing real-world case studies—Siemens, Hyundai, and Foxconn—the research demonstrated how immersive technologies, digital twins, AI, and blockchain are already reshaping industrial operations. These firms illustrate varying levels of maturity and strategic emphasis, yet consistently highlight the transformative potential of the industrial metaverse.

The findings underscore that successful metaverse adoption extends beyond technical deployment; it requires systemic change, including leadership alignment, workforce upskilling, and collaborative ecosystems. Cross-cutting challenges such as interoperability, data governance, regulatory gaps, and digital inequality must be addressed for the industrial metaverse to scale sustainably.

Future research should build on this framework by conducting empirical studies across different regions, sectors, and firm sizes to test generalisability. There is also a need to develop standardised evaluation metrics, explore human-centric design in virtual environments, and investigate the socio-ethical implications of industrial immersion. As technologies continue to converge, the metaverse will play a central role in shaping the next frontier of digital manufacturing.

This paper serves as a foundation for academics, practitioners, and policymakers to understand and shape the evolving landscape of Metaverse integration in manufacturing. By advancing a research agenda grounded in practical relevance and theoretical rigour, it contributes meaningfully to the future of industrial innovation.

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