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Landscape and use cases for the industrial metaverse

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Technical Report ITU FGMV-37

Landscape and use cases for the industrial metaverse

Summary

This Technical Report offers an in-depth background and a comprehensive view of the current landscape on the industrial metaverse, by exploring its current development stage, market analysis, key players, emerging technologies, challenges and opportunities. A section of applications, including case studies of successful implementations, provides practical insights. The report also focuses on standardization issues of industrial metaverse, covering technical difficulties, ethical, legal, and security concerns, and economic implications.

Keywords

Industrial metaverse, Use cases, Augmented reality, Virtual reality, Metaverse, Digital twin

Note

This Technical Report is an informative ITU-T publication. Mandatory provisions, such as those found in ITU-T Recommendations, are outside the scope of this publication. This publication should only be referenced bibliographically in ITU-T Recommendations.

Change Log

This document contains Version 1.0 of the ITU Technical Report on "Landscape and use cases for the industrial metaverse" approved at the 7th meeting of the ITU Focus Group on metaverse (FG-MV) held on 12-13 June 2024.

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Additional information and materials relating to this report can be found at: https://www.itu.int/go/fgmv. If you would like to provide any additional information, please contact Cristina Bueti at tsbfgmv@itu.int.

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1 Scope

The report provides a detailed background of the industrial metaverse, discussing its current development stage, market analysis, and key players. It identifies emerging technologies and outlines the challenges and opportunities in this field. Furthermore, the report presents several applications and successful implementations of the industrial metaverse. The standardization of the industrial metaverse, along with its technical, ethical, legal, security, and economic aspects, is also explored.

2 Reference

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-T X.1400] Recommendation ITU-T X.1400 (10/2020), *Terms and definitions for distributed ledger technology*

[ITU-T M.3080] Recommendation ITU-T M.3080 (02/2021), *Framework of artificial intelligence enhanced telecom operation and management (AITOM)*

[ITU-T Y.4600] Recommendation ITU-T Y.4600 (08/2022), *Requirements and capabilities of a digital twin system for smart cities*

3 Terms and definitions

3.1 Terms defined elsewhere

This Technical Report uses the following terms defined elsewhere:

3.1.1 artificial intelligence [b-ISO/IEC 2382]: Interdisciplinary field, usually regarded as a branch of computer science, dealing with models and systems for the performance of functions generally associated with human intelligence, such as reasoning and learning.

3.1.2 asset [b-ITU-T X.1400]: Representation of value.

3.1.3 augmented reality (AR) [b-ITU-T P.1320]: An environment containing both real and virtual sensory components. The augmented reality continuum runs from virtual content that is clearly overlaid on a real environment (assisted reality) to virtual content that is seamlessly integrated and interacts with a real environment (mixed reality).

3.1.4 blockchain [b-ITU-T X.1400]: A type of distributed ledger which is composed of digitally recorded data arranged as a successively growing chain of blocks with each block cryptographically linked and hardened against tampering and revision.

3.1.5 digital twin [b-ITU-T Y.4600]: A digital representation of an object of interest.

3.1.6 Internet of things (IoT) [b-ITU-T Y.4000]: A global infrastructure for the information society, enabling advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies.

3.1.7 interoperability [b-ITU-T Y.101]: The ability of two or more systems or applications to exchange information and to mutually use the information that has been exchanged.

3.1.8 metaverse [b-ITU FGMV-20]: An integrative ecosystem of virtual worlds offering immersive experiences to users, that modify pre-existing and create new value from economic, environmental, social and cultural perspectives.

NOTE- A metaverse can be virtual, augmented, representative of, or associated with the physical world.

3.2 Terms defined in this Technical Report

None.

4 Abbreviations and acronyms

This Technical Report uses the following abbreviations and acronyms:

AR Augmented Reality

AI Artificial Intelligence

CPU Central Processing Unit

DLT Distributed Ledger Technology

GPU Graphic Processing Unit

HMI Human Machine Interface

IEEE Institute of Electrical and Electronics Engineers

ICT Information and Communication Technology

IoT Internet of Things

IT Information Technology

ML Machine Learning

MR Mixed Reality

SDGs Sustainable Development Goals

SME Small Medium Enterprise

VR Virtual Reality

XR Extended Reality

3D Three-dimensional

5G Fifth Generation Network

6G Sixth Generation Network

5 Conventions

None.

6 Background

6.1 Overview

The emergence of the industrial metaverse has garnered significant public attention in recent times. It is revolutionizing the way individuals engage in the design, production, and interaction with physical entities across various industries. The industrial metaverse focuses on how digital information can be used to optimize interactions between people, physical goods, production asses, places, processes, supply chains, operations and equipment [b-WEF4]. By harnessing emerging technology, they enable the bidirectional knowledge flow between the physical and virtual worlds. As the industrial metaverse continues to evolve, it is crucial for industry leaders to grasp its intricate and multifaceted impact, enabling them to harness its potential for the betterment of their organizations and society as a whole.

The metaverse extends far beyond its initial consumer-centric roots, embodying a complex interplay of emerging technologies. While artificial intelligence (AI), blockchain, and cloud computing play pivotal roles, the metaverse hinges fundamentally on the integration of Internet of Things (IoT) and digital twins. Without these two foundational elements, the metaverse concept would be more difficult to implement and use. Alongside ancillary technologies like IMT-2020 (5G), these elements form the structural framework upon which the metaverse is built. Their convergence allows for a shift in business operations, which can revolutionize internal workflows but also redefine the dynamics of workforce management, customer engagement, and partnership strategies. Projections underscore the potential of this shift, with estimates suggesting a trillion-dollar market opportunity in annual revenue [b-Wipro].

The term "industrial metaverse" typically refers to metaverse applications tailored for industrial users [b-WEF]. It signifies a progression from digital twinning, extending beyond mere replicas of machinery or manufacturing plants. Essentially, it manifests as a persistent 3D platform implemented throughout an organization, spanning its value chain and product life cycle. This platform serves as a comprehensive model of the organization within its operational environment, facilitating the integration of processes, materials, machinery, and personnel in a seamless flow between the physical and virtual realms [b-WEF]. By fostering an open ecosystem that benefits all companies across industries is crucial. By breaking down the current silos and encouraging cross-industry partnerships, the industrial metaverse can create a marketplace for innovation.

Industry is an important application field of the metaverse. The industrial metaverse is a type of metaverse; it provides a new industrial ecosystem that is deeply integrated with into the physical industrial economy with a new generation of information and communication technology represented by, for example, XR, digital twin, and content generation. The ITU-T Focus Group on metaverse uses the definition for the industrial metaverse as a “metaverse under complex digital industrial ecosystem. The industrial metaverse realizes the mapping, interaction, and integration of virtual world and physical world in the industrial field.”

There are numerous definitions currently among the industrial metaverse landscape. These include but are not limited to:

- "A virtual world in which we can interact in real-time with photorealistic, physics-based digital twins of our real world." by Siemens [b-Siemens].

- "Industrial Metaverse enables industrial companies of all sizes to create closed-loop digital twins with real-time performance data, ideal for running simulations and AI-accelerated processes for advanced applications such as autonomous factories that rely on intelligent sensors and connected devices." by X and NVIDIA [b-Arthur].
- "Industrial Metaverse enables humans and AI to work together to design, build, operate, and optimize physical systems using digital technologies." By Microsoft [b-Arthur].
- "The industrial metaverse combines physical-digital fusion and human augmentation for industrial applications, and contains digital representations of physical industrial environments, systems, assets and spaces that people can control, communicate and interact with." By Nokia [b-Nokia].

For a more detailed summary of the current existing definitions of the industrial metaverse, see Appendix I.

Amidst the varied interpretations of the industrial metaverse, a crucial distinction emerges : true metaverse integration necessitates the interconnection of systems. Without this link, it resembles augmented reality applied to industry. The ability to use the metaverse lies in the seamless interconnection of digital twin and IoT technologies with visualization and interaction capabilities. Such integration can support industrial operations, elevating efficiency,and innovation. However, achieving this interconnection mandates the establishment of standards to bridge proprietary systems. Collaboration with external entities, be it other companies or vendors, underscores the imperative for standardized protocols and data to ensure seamless interoperability.

6.2 Development stage

The metaverse is often associated with social media platforms, gaming, or retail applications, but its most critical role in the future may lie in business applications. The industrial metaverse, driven by AI, complex systems simulation, data visualization, and connectivity, represents the next evolution of the 'digital twin' concept. These virtual models with real-world applications are utilized across various industries.

The changes initiated by the metaverse are bringing technology closer to the realm of Industry 4.0, also known as the fourth industrial revolution. This concept integrates advanced technologies like IoT, AI, and automation to transform traditional industries into smart, interconnected systems. These systems optimize production, enhance efficiency, and enable data-driven decision-making.

Frequently cited as the next phase of smart manufacturing (also known as Industry 4.0), the industrial metaverse marks a transition from cyber-physical systems to a fully virtualized world. The term "Industry 4.0" or the Fourth Industrial Revolution emerged about a decade ago, encompassing the deployment of various technologies capable of revolutionizing industry. These technologies include new cognitive tools, enhanced connectivity, virtual modeling such as digital twins, collaborative tools, and innovative manufacturing and supply chain techniques, incorporating advanced robotics and blockchain. Companies that have successfully implemented Industry 4.0 technologies have already experienced significant benefits, transforming their businesses in the process. [b-Arthur].

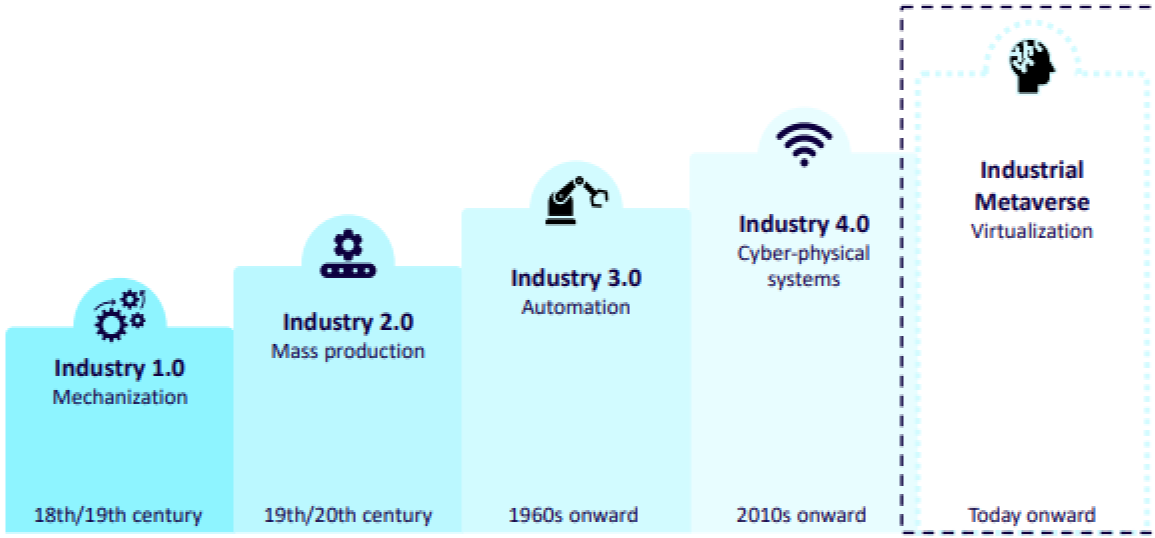

Figure 1: The Industrial Metaverse is often seen as the next phase of evolution after Industry 4.0. Source: [b-Arthur].

The industrial metaverse entails seamless communication and collaboration among humans, machines, devices, and processes, leading to a revolutionary transformation in manufacturing and primary industrial operations.

The industrial metaverse encompasses a range of applications, including smart factories equipped with sensors and interconnected devices, IoT-enhanced supply chains, robotic automation, advanced digital twins, diverse training scenarios, remote monitoring capabilities, and numerous other innovations. In the upcoming section, this document explores the technologies needed to drive the industrial metaverse.

7 Emerging technologies

The industrial metaverse is an evolving digital ecosystem that integrates a variety of advanced technologies to create immersive, interactive, and interconnected environments for industrial applications. Key technologies such as the ones depicted below form the backbone of the industrial metaverse.

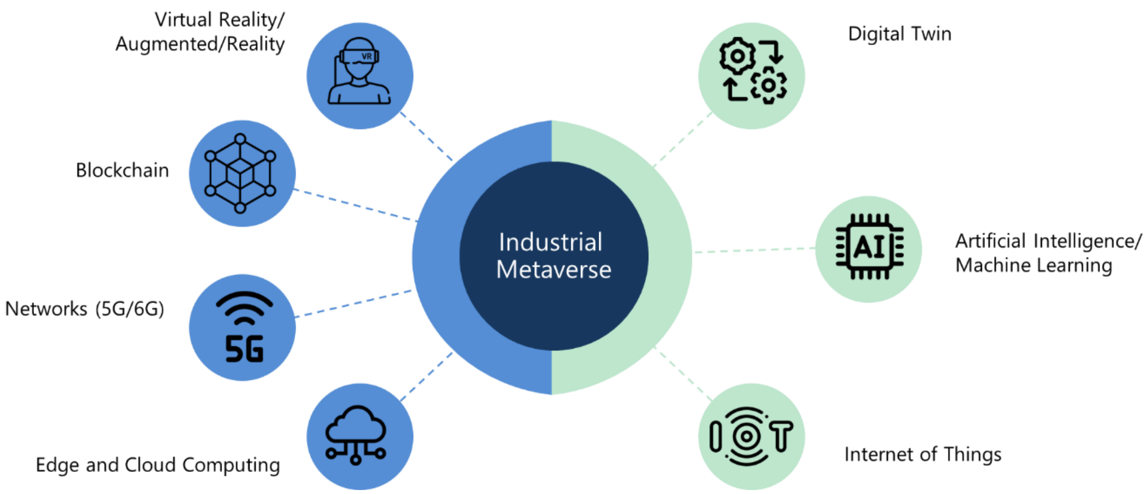

Figure 2: Technologies that support the industrial metaverse

7.1 Technologies that support the industrial metaverse

7.1.1 Digital twin and the industrial metaverse

At the foundational level, the industrial metaverse is based on digital twins. The digital twin as defined in ITU-T Recommendation Y.4600 is a digital representation of an object of interest [b-ITU-T Y.4600]. Digital twins are a foundational technology in the industrial metaverse, providing detailed virtual representations of physical assets, processes, or systems. They integrate all the data about a physical object to extent and at such high accuracy that they can mimic every aspect of an object as if it were real. [b-MIT]

These digital replicas facilitate real-time monitoring, diagnostics, and prognostics, enabling industries and business to pre-emptively address issues, optimize operations, and improve overall efficiency. Digital twins integrate seamlessly with AI, XR and blockchain, enhancing the metaverse with data-driven decision-making and customized experiences. As the industrial metaverse evolves, technology like digital twins will support advancements in this area.

7.1.2 Artificial Intelligence, Machine Learning and the industrial metaverse

Artificial intelligence is a driving technology behind intelligent decision-making within the industrial metaverse. AI’s capabilities in the industrial metaverse are multifaceted, ranging from enhancing operational efficiency to enabling predictive analytics and autonomous decision-making. The integration of AI with other metaverse technologies like digital twins and XR creates dynamic, intelligent environments where virtual interactions are not just reactive but proactive, anticipating user needs and adapting in real-time.

Generative AI, a subset of AI, is particularly influential in the industrial metaverse. It leverages machine learning algorithms to generate new data, designs, and scenarios, pushing the boundaries of innovation. For instance, generative AI can create more accurate digital twins that analyze real-time data to optimize energy use and improve overall system performance. [b-INCIT]

7.1.3 Extended Reality and the industrial metaverse

Extended Reality (XR) is a key enabler in the industrial metaverse, providing immersive and interactive experiences that are revolutionizing industrial processes. XR encompasses Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), each offering unique ways to blend digital content with the physical world. In the industrial metaverse, XR technologies are used for a variety of applications, including training and simulations, remote collaboration, design and prototyping, maintenance and repair and operational optimization.

The relevance of XR in the industrial metaverse is further underscored by its ability to cut costs, increase sustainability, and drive innovation. However, the full potential of XR is contingent on advancements in network infrastructure to handle the high data throughput and low latency required for these technologies to function optimally [b-IEEE2].

7.1.4 Blockchain and the industrial metaverse

Blockchain’s significance in the industrial metaverse stems from its ability to establish a decentralized, secure, and transparent framework for operations. It ensures the integrity of transactions and data exchanges, fostering trust among participants. Smart contracts, enabled by blockchain, automate processes, and enforce agreements without intermediaries. Additionally, blockchain facilitates asset management and interoperability, allowing for the seamless transfer of digital assets and information across different platforms. These capabilities are useful for the industrial metaverse, where digital interactions have tangible implications, making blockchain a building block for this emerging digital ecosystem [b-MDPI].

7.1.5 5G and future generations of networks and the industrial metaverse

5G connectivity is a critical technology for the industrial metaverse due to its ability to provide high-speed, low-latency networks that are essential for the real-time interaction and seamless data transfer required in the complex digital environments of modern industrial installations. The advanced capabilities of 5G (IMT-2020), such as higher data throughput and reliable connections, enable immersive experiences through XR technologies and support the vast array of interconnected devices and processes within the industrial metaverse. While 5G connectivity is pivotal for the current phase of technological advancement, it's imperative to acknowledge that it represents a step forward rather than the ultimate solution. As the demands of the digital landscape continue to evolve, the necessity for even more advanced connectivity, such as 6G (IMT-2030), will inevitably arise to meet the increasingly complex requirements of future innovations.

7.1.6 Cloud and edge computing and the industrial metaverse

Cloud and edge computing are essential technologies for the industrial metaverse, providing the necessary infrastructure for storage, processing, and delivery of vast amounts of data and applications. Cloud computing offers scalable and flexible resources that can support the heavy computational demands of the industrial metaverse, allowing for complex simulations and data analytics. Edge computing complements this by processing data closer to the source, reducing latency and enabling real-time interactions that are critical for immersive metaverse experiences.

Within this cloud and edge computing ecosystem, the role of Graphics Processing Units (GPU) and Central Processing Units (CPU) is paramount. GPUs excel in parallel processing tasks, making them ideal for rendering complex graphics and powering immersive experiences in the metaverse, while CPUs handle general-purpose computing tasks.

7.2 Industrial metaverse technology framework

The industrial metaverse technology framework comprises a set of interconnected layers and technologies that enable the seamless integration of digital and physical realms within industrial contexts. These include hardware infrastructure, software infrastructure, industrial systems, industrial platform, interaction layer.

These layers can be seen in the following figure which depicts how certain technologies play an important role in the industrial metaverse.

Note that the ITU-T Metaverse Focus Group (FG-MV) produced a complementary document documenting the reference framework of industrial metaverse [ITU-FGMV-imfwk].

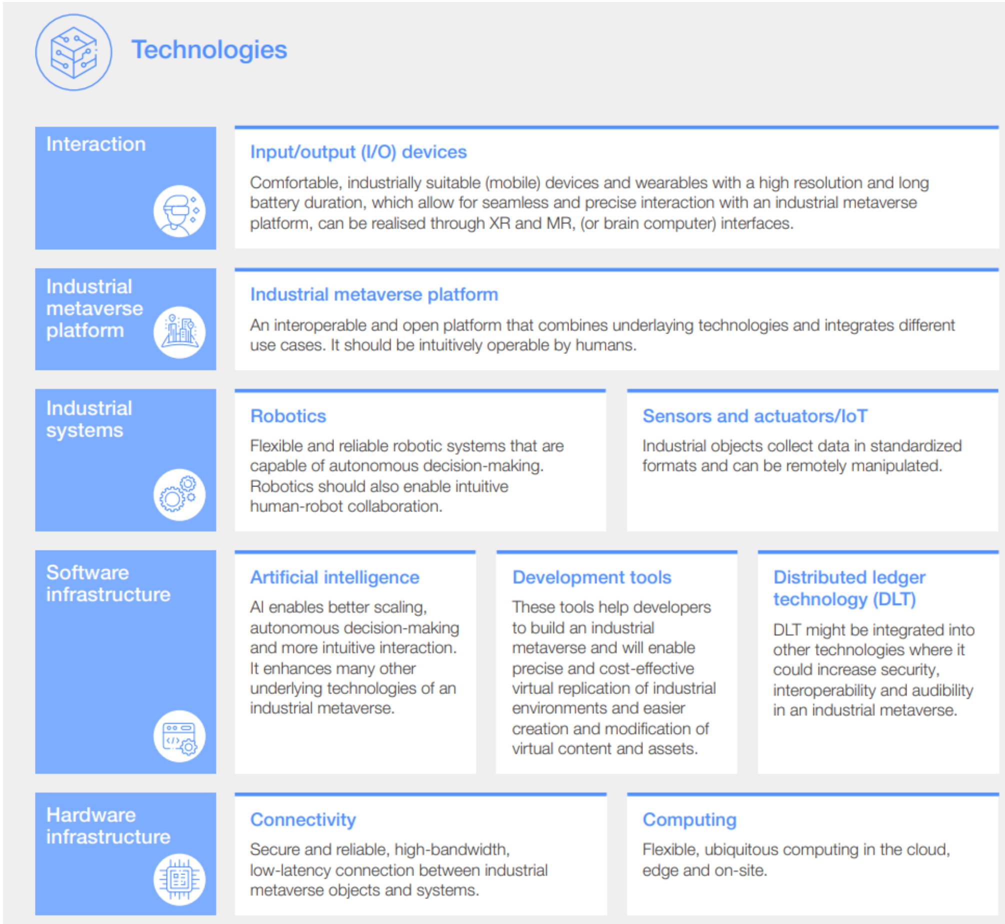

Figure 3: Emerging technologies within the five-layer technology framework. Source [b-Arthur]

Overall, these technologies collectively form the backbone of the industrial metaverse, enabling its transformational impact across industries.

7.2.1 Hardware infrastructure

The foundational layer is the hardware infrastructure, which includes connectivity and computing resources. It can be seen as the backbone that supports the entire metaverse ecosystem. Servers, edge devices, high-speed networks, and data centers play a crucial role here.

7.2.2 Software infrastructure

Building upon the hardware layer, the next layer is the software infrastructure. Technologies like AI, development tools, and distributed ledgers, such as blockchain. These components leverage the underlying hardware for efficient operation. They optimize resource utilization, enhance security, and enable seamless interactions within the metaverse.

7.2.3 Industrial systems

The center of the industrial metaverse lies within the industrial systems layer. These systems drive the operational aspects, automation, and real-world interactions. Imagine robotics, sensors, actuators, IoT devices, and other smart technologies working together. They form the backbone of practical applications within the metaverse.

7.2.4 Industrial Platform

Moving up the stack, the layer is the industrial platform, which acts as an open and interoperable platform. Its purpose is to combine various technologies, standards, and protocols. By doing so, it facilitates collaboration, data sharing, and innovation across industries.

7.2.5 Interaction layer

The top layer is the interaction, which bridges the virtual and physical worlds. It's where user engagement happens through input/output devices. XR devices—such as AR, VR, and MR—serve as the interface for immersive experiences and interactions within the metaverse.

8 Market analysis

While the consumer metaverse often garners the spotlight in media coverage, the industrial metaverse is likely to lead the way in commercialization. Research projects a $USD 100 billion industrial metaverse market by 2030, with significant revenue potential derived from digital twins, extended reality applications, and more [b-Nokia].

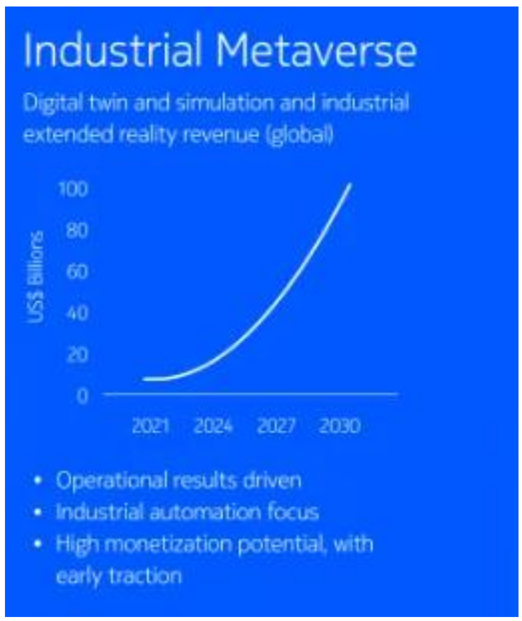

Figure 4: Industrial metaverse market projection. Source: [b-Nokia]

Driving this growth are sectors like manufacturing and logistics, which have long been pioneers in digitalization. These industries have leveraged technologies such as artificial intelligence (AI), extended reality, and digital twins for years, setting the stage for widespread adoption of the industrial metaverse across other sectors like railways, power utilities, and public safety [b-Nokia].

Research highlights a significant market opportunity in the industrial metaverse, with substantial investment capital entering the sector. Projections indicate that revenues for industrial digital twin and simulation, along with industrial extended reality, will likely reach $22.73 billion by 2025. This growth is fueled by the adoption of Industry 4.0 tools such as AI, machine learning, edge computing, and extended reality [b-MIT2].

From a broader, global economic perspective, the Metaverse is expected to have a number of impacts. As estimated by a report from IEEE on The Economics of the Industrial Metaverse, shown on the table below, significant economic development is expected to come from the industrial metaverse.

Table 1: Economics of the industrial metaverse. Source [b-IEEE].

Estimate by	Industrial Metaverse Size/Economic Opportunity Created	Remarks
ABI Research	The industrial metaverse's size in 2030: $100 billion	Bigger than the consumer metaverse and the enterprise metaverse combined
Market research company TrendForce	Key driver of global smart manufacturing: more than $540 billion by 2025	Some mechanisms to enhance smart manufacturing process: overlaying virtual models of products onto the real environment so that designers can see what a product will look like, immersive in-person training, ability to readily access the needed information for maintenance or repair tasks[36]
Microsoft's chief operating officer, Judson Althoff	The industrial metaverse's market opportunity in 2030: more than $200 billion	Key areas impacted: the design and manufacture of products as well as the optimization of operations
ABI Research	Revenues for industrial digital twins, simulation, and industrial extended reality (XR) in 2025: $22.73 billion.[12]	XR training (through VR/in-person with AR and mixed reality (MR)): hands-on education to improve safety performance without endangering anyone[37]

8.1 Industrial metaverse market drivers

For the industrial metaverse to scale responsibly and benefit all stakeholders in society, key market drivers must be considered. These drivers are expected to become more complex as the industrial market transcends international borders with varying political and legal systems [b-WEF].

8.1.1 Economic Factors

The industrial metaverse, with its combination of digital and physical spaces, holds significant economic potential. As organizations navigate this space, several key factors drive the industrial metaverse's adoption. First, fostering an open ecosystem that benefits all companies across industries is crucial. By breaking down the current silos and encouraging cross-industry partnerships, the industrial metaverse can create a marketplace for innovation. Startups and small businesses must find their place within this ecosystem to ensure inclusivity and prevent monopolies. Second, the industrial metaverse enables distributed work opportunities, redefining work. Geographical independence, new human-machine interactions, and detailed work context analysis become possible. In addition, resource optimization ensures efficient energy usage, reduced waste, and sustainable practices which have an impact on the bottom line. Finally, global connectivity and markets allow organizations to transcend borders, accessing broader markets and creating value internationally.

8.1.2 Environmental Considerations

As the industrial metaverse evolves its impact on the environment is multifaceted. While it presents challenges, such as energy consumption and e-waste, responsible adoption and innovative practices can lead to positive outcomes. The industrial metaverse market is influenced by several environmental factors that shape its trajectory toward sustainability and responsible growth. Digital transformation within the metaverse can decrease carbon emissions associated with traditional industrial practices [b-WEF2]. The industrial metaverse may reduce the need for movement of people and products, leading to resource conservation and energy savings. Through efficient resource utilization and waste reduction could occur through the use of the industrial metaverse.

Lastly, sustainable product design and testing which are facilitated virtually, may minimize material waste. Sustainable product design, facilitated virtually within the metaverse, holds significant potential for minimizing material waste by emphasizing principles such as product re-conditioning, material re-use, and design for disassembly. This approach can lead to much higher levels of circularity in the product life-cycle, ultimately contributing to a more sustainable future. However, as the industrial metaverse continues to evolve it is essential to ensure that the net environmental benefits outweigh the environmental costs throughout the entire industrial metaverse life cycle [b-WEF].

8.1.3 Legal Frameworks and Standardization

The responsible growth of the industrial metaverse necessitates robust legal frameworks that promote fair, ethical, and international coordinated regulations and standards [b-WEF]. These standards and frameworks address critical aspects such as data governance, privacy, intellectual property, and liability. By fostering trust and providing clear guidelines, the industrial metaverse can be created in an environment where innovation thrives while safeguarding the interests of all stakeholders. As the industrial metaverse passes borders, collaborative efforts among governments, industry bodies, and legal experts are essential to ensure a level playing field and shared prosperity.

8.1.4 Social Factors

The industrial metaverse has significant social implications. Key factors at play include designing the metaverse in a human-centric way, following Universal Design approaches. The industrial metaverse must prioritize user experiences, mental health, and work-life balance for all people, especially for persons with disabilities. The industrial metaverse may play a crucial role in the inclusion of people with disabilities, or vulnerable people with new job profiles and opportunities. Inclusive and accessible interfaces cater to diverse abilities and demographics. By ensuring equitable access to metaverse benefits, the industrial metaverse can contribute to social sustainability [b-MDPI2].

The industrial metaverse raises questions about privacy, consent, and data ownership. Clear ethical guidelines are necessary. Balancing innovation with responsible practice ensures trust and societal acceptance of the industrial metaverse [b-MIT].

9 Challenges in enabling the emerging industrial metaverse

The industrial metaverse is set to reshape industrial business operations and strategies, open new job profiles and work opportunities, but also presents challenges and risks for companies venturing into its domain. These challenges encompass various aspects of technology adoption, social equity, interoperability, cost barriers, regulatory compliance, and talent acquisition. In addition, there is a need for the development of a reference framework for the industrial metaverse. The ITU FG-MV has developed a deliverable that provides a main framework to implement the industrial metaverse from the overall and technical perspectives, including the elemental composition, specific modules, and entities of the industrial metaverse. [b-ITU FGMV-XX]

Key challenges faced in adopting industrial metaverse solutions, include concerns about modelling, cybersecurity and privacy, inadequate IT and data systems, the need for continuous adaptation to new technologies, limited staff experience, expensive and limited infrastructure, social concerns about the digital divide, lack of interoperability among metaverse solutions, and poor user experiences related to content and technology access [b-Wipro].

Addressing these challenges will be paramount for companies aiming to harness the transformative power of the industrial metaverse while navigating its intricate landscape of technological innovation, social dynamics, and regulatory complexities.

9.1 Connectivity

First and foremost, for the industrial metaverse to be useful, it must operate with seamless connectivity and communication between the various IoT devices, cloud computing, and artificial technologies it pulls from. For the industrial metaverse to succeed, it not only needs the proper hardware and software, but also the right connective tissue. [b-MIT] In addition to technologies such as digital twin and artificial intelligence, there needs to be connectivity solutions such as 5G or 6G which satisfies the strong bandwidth and latency requirements of visualization and interaction tools along with those of industrial processes.

A key aspect of this seamless connectivity is high-speed internet connectivity via 5G wireless technology and fiber-based connections. Edge computing is also necessary to improve latency between visualization devices and computing platforms, and blockchain can be a useful building block because it can assist in the provision of a secure environment. All of these technologies currently exist, it is a matter of bringing them all together and connecting them simultaneously.

9.2 Computational power

The importance of computation power in the context of the industrial metaverse cannot be overstated; it is the engine that drives the complex simulations, real-time data process and sophisticated AI algorithms that are needed. Ensuring sufficient computational power to handle the vast amounts of data and the high-fidelity simulations required by the industrial metaverse will certainly be a challenge for implementation of the industrial metaverse.

Furthermore, as the industrial metaverse becomes more widespread, it will lead to growth in the amount of data provided, as well as the need for a significant amount of computational capability to process it. The growing need for holographic communication, virtual reality (VR), digital transactions, and decentralized interaction, along with changes in social, economic, and governance systems, requires major upgrades to current information and communication technology (ICT) infrastructure, network capacity, and transmission speed for the industrial metaverse's development. [b-Siemens2].

9.3 Interoperability

Interoperability within the industrial metaverse is a multifaceted challenge that is crucial for creating a seamless and unified digital ecosystem. It involves ensuring that different systems, platforms, and applications can communicate and operate together effectively. This challenge is compounded by the diverse range of technologies and standards that must be harmonized, from the underlying network infrastructure to the software interfaces and data formats. It is made more complex because of the interaction with physical industrial systems.

For industries to adopt the metaverse, there will need to be open and interoperable solutions that allow seamless, real time, and concurrent collaboration. For workers to perform their jobs in the metaverse, there will be a need to eliminate all access barriers towards a seamless interaction between the physical human and the working avatar, and the avatar with the systems and platforms. The inability to seamlessly transfer avatars or content across different platforms poses a significant challenge to developing a robust, inclusive, and expansive industrial metaverse. In order to overcome this, it requires, among other things, open APIs, compatible data formats and accessible platforms. Standards and interoperability protocols are essential to prevent fragmentation and ensure a cohesive user experience. The goal is to integrate the industrial metaverse using a common language [b-MIT]. Doing so will allow users to connect their avatar and other technologies to many others in a simultaneous way.

Achieving interoperability is essential for the industrial metaverse to reach its full potential, allowing for the smooth transfer of data and assets, and enabling all users, regardless of their abilities, to navigate between different virtual environments without barriers. However, it requires a collaborative effort among industry stakeholders, standardization bodies, and regulatory agencies to overcome the technical and regulatory hurdles that currently exist.

9.4 Ethical, legal, and security concerns

Legal and regulatory issues surrounding the industrial metaverse span a wide spectrum, including concerns related to reputation and identity, personal data protection, security and resilience, jurisdictional laws, and asset ownership. Navigating these complexities requires careful adherence to evolving legal frameworks.

As the industrial metaverse becomes more prevalent, a host of ethical, legal, security and privacy concerns emerge. Security, in particular, is of paramount importance. Current research highlights that the metaverse's benefits extend beyond internal operations to encompass the entire partner ecosystem and supply chain [b-Arthur]. However, this collaborative approach necessitates sharing significantly more data than traditional commercial partnerships, demanding a fresh mindset and cultural shift. Consequently, data protection is a key aspect of privacy regulations in the metaverse [b-hyperspace]. Metaverse platform owners should implement robust security measures to safeguard sensitive company data and users' data from unauthorized access, breaches, and misuse. Implementing privacy-enhancing technologies (PETs) are crucial in safeguarding user's personal data in the metaverse.

Industries are demonstrating that the industrial metaverse will reshape business practices [b-Siemens2]. Notably, protecting intellectual property in digital assets requires innovation. Analogous to the broader metaverse, where real-world goods are virtually depicted and traded, questions arise about safeguarding property rights against virtual replicas. The challenge extends to purely virtual goods, often governed by licensing and usage rights. Additionally, the traditionally localized scope of intellectual property rights poses practical challenges in the cross-border metaverse, including prosecution and law enforcement [b-Platform]. These considerations underscore the need for robust legal and ethical frameworks to ensure responsible growth within the industrial metaverse.

From a legal perspective, the industrial metaverse raises significant questions about jurisdiction and regulation. The metaverse must operate within existing legal frameworks, prompting inquiries about which laws are applicable—whether it's the laws from the data subject's country of origin or those of the platform operator [b-Platform]. Compliance with labor laws is also essential, including adherence to working hours, health protection measures such as when using VR glasses, and co-determination within the company [b-Platform]. Furthermore, prosecuting crimes in the metaverse presents numerous challenges, particularly when the real identities behind avatars are unknown.

On an ethical level, the industrial metaverse's success hinges on equitable development of digital connectivity. Without this, its adoption in highly industrialized societies could exacerbate the economic disparity among nations.

9.5 Economic implications

Implementing the industrial metaverse entails substantial investment, posing a significant barrier to entry for many companies and actors in global regions. While cost barriers may be mitigated for organizations that have already adopted complementary technologies such as cloud computing, AI, and AR/VR, the upfront investment remains a considerable hurdle.

The economic implications of the industrial metaverse are multifaceted and present both challenges and opportunities for businesses. At the firm level, the initial phase of integrating the metaverse into operations is likely to be capital intensive. Companies will face substantial expenses securing the accessibility of their metaverse and in nurturing and equipping their workforce with the necessary skills to navigate and utilize complex metaverse technologies effectively, encompassing both training for existing personnel, both technical and non-technical end-users, and the acquisition of new talent [b-IEEE]. Additionally, there will be ongoing costs associated with the maintenance and updating of these technologies to ensure they remain functional and secure. Accessibility should be considered in the design process of any service or product, if left to be adopted at a later stage it may add additional costs.

Despite these challenges, the potential for cost savings and efficiency improvements is significant. The industrial metaverse can streamline operations, reducing issues like downtime which can be costly for firms. Enhanced data analytics within the metaverse can enable companies to monitor and manage costs more effectively, leading to better resource allocation and waste reduction.

9.6 Digital divide and capacity

The industrial metaverse has the potential to exacerbate existing disparities in access to technology, spanning racial, disabilities, income, generational, and regional divides. While it holds promise in breaking down geographical barriers and engaging diverse communities, it also risks widening existing inequities.

A critical challenge confronting companies is the scarcity of talent equipped with the requisite skills to support industrial metaverse strategies. The demand for professionals proficient in 3D and physical modeling, avatar design, and legal expertise in metaverse-related issues presents a significant hurdle in realizing the full potential of metaverse applications.

Additionally, from a user interface perspective, in order to become a stable part of day-to-day industrial operations, the platform that combines these tools must be accessible, intuitive, and graspable to employees without exceedingly high training costs. This refers to advanced human-machine interface (HMI), which pulls together VR, AR, and MR visualization technologies, integration of accessibility requirements, as well as other types of visualization for complex data interpretation, sometimes integrated with AI [b-Arthur].

10 Industrial metaverse applications

The industrial metaverse is not merely a concept of the future but a rapidly evolving reality reshaping industries across the board, from automotive manufacturing to aerospace engineering. As businesses continue to adopt virtual reality (VR), augmented reality (AR), and digital twinning, they are discovering a multitude of innovative use cases that are revolutionizing traditional industrial practices. Some of these applications, such as factory optimization and training, are horizontal in nature, offering scalability across industries. However, others, like aviation and heavy industries, are more industry-specific, requiring tailored investments and specialized knowledge to fully leverage their potential. From optimizing welding processes to enhancing helicopter design, the industrial metaverse is proving to be a versatile toolset, offering unprecedented opportunities for efficiency, collaboration, inclusion, and innovation.

10.1 Aviation and the industrial metaverse

In the aviation sector, the advent of the industrial metaverse signifies a paradigm shift towards advanced digital integration. The industry is at the forefront of exploring the multifaceted applications of this technology. The convergence of virtual and augmented realities within the metaverse is facilitating a transformative approach to aircraft design and manufacturing processes.

The creation of digital twins represents a pivotal advancement, enabling manufacturers to replicate aircraft in a virtual environment. This innovation permits exhaustive testing and simulation protocols, thereby obviating the necessity for physical prototypes to accrue flight hours. Consequently, this translates into substantial cost savings and a marked reduction in safety risks for testing personnel.

Furthermore, the industry is capitalizing on the metaverse to reimagine the passenger experience, employing virtual reality constructs to elevate the in-flight environment. The industrial metaverse is also instrumental in the development of a 'digital thread'—a comprehensive data integration framework that encapsulates all pertinent information from the genesis of an aircraft. This includes design specifications, component inventories, and exhaustive certification documentation, extending to the minutiae of the supply chain.

In summary, the industrial metaverse is emerging as a cornerstone in the evolution of aviation, heralding a new era of digital craftsmanship and immersive user experiences. The strategic implementation of these virtual constructs is set to redefine the aerospace sector, underscoring the symbiosis between technological innovation and industrial progress. All major aviation vendors have built a metaverse solution to support their developments, and interconnection is key to work with their partner ecosystem.

10.2 Digital twins for factory optimization

Digital twins have become integral to the optimization of factory operations, serving as a nexus between physical processes and their virtual counterparts. These dynamic models simulate manufacturing environments, enabling the preemptive identification of inefficiencies and the strategic planning of facility development.

The utilization of digital twins in factory settings facilitates the exploration of various production scenarios, optimizing machine utilization rates and spatial configurations. This virtual optimization translates into tangible benefits, such as the negation of the need for additional production lines, thereby conserving financial and spatial resources.

In the context of factory optimization, digital twins serve as a foundational element for simulation-based planning. By creating a virtual representation of a manufacturing facility, stakeholders can conduct thorough analyses and identify potential errors in the planning phase, effectively mitigating risks prior to physical implementation. This preemptive strategy enhances the efficiency of the construction process and sets the stage for subsequent operational optimization.

The deployment of digital twins has been documented to significantly augment factory capacity and productivity. These virtual models enable continuous improvement through the analysis of value stream data, informing decisions that lead to increased efficiency and reduced resource consumption.

Digital twins and the industrial metaverse are pivotal in redefining factory optimization. They provide a comprehensive view of the manufacturing lifecycle, from initial design to final production, ensuring that factories operate at peak efficiency with minimized environmental impact. The strategic application of these technologies is instrumental in achieving operational excellence in the manufacturing sector.

10.3 Heavy industries and the industrial metaverse

Heavy industry has begun harnessing the industrial metaverse to enhance the automation and efficiency of manufacturing processes. The integration of robotics within production lines, while beneficial, introduces the risk of operational disruptions due to malfunctions or deviations in robot behavior. To mitigate this, there is a growing reliance on collaboration with equipment manufacturers and system integrators, who bring specialized expertise for support, real-time troubleshooting, and maintenance.

The application of edge computing and AI within the industrial metaverse enables rapid resolution of robotic malfunctions and facilitates predictive maintenance to preempt potential issues. Moreover, the metaverse allows for real-time consultation with remote experts, providing simultaneous support across various locations. Digital twins and simulations within this virtual space offer insights into the operational conditions of the past, present, and future, empowering operators to diagnose and rectify issues in geographically distant facilities.

At the forefront of this technological evolution, a leading heavy industry manufacturer has initiated a project to leverage the industrial metaverse for real-time, virtualized robot care and maintenance. This initiative represents a significant leap in the application of metaverse technology, aiming to revolutionize the maintenance paradigm by enabling virtual interventions and predictive analytics within the manufacturing sector. The project underscores the potential of the industrial metaverse to transform traditional industrial operations into interconnected, intelligent systems capable of self-optimization.

10.4 Electric vehicle manufacturing and the industrial metaverse

Electric vehicle manufacturing has begun to leverage the industrial manufacturing in its factory planning and optimization. This virtual environment enables manufacturers to design and refine multibillion-dollar production facilities in a completely virtual setting, even taking into consideration requirements from diverse drivers. The result is an accelerated production timeline, enhanced operational efficiency, and improved sustainability, all contributing to a faster time to market.

Within the industrial metaverse, logistics and production planners can address issues in real-time, visualizing and determining optimal equipment placement and workflow. This capability significantly reduces risks and ensures the success of large-scale construction projects before substantial capital expenditures are incurred.

The metaverse also facilitates a collaborative ecosystem, allowing manufacturers to operate across virtual factories globally. A unified data approach enables real-time global changes, fostering seamless updates and coordination among teams.

Digital twins, or virtual replicas of physical facilities, are a cornerstone of this approach, allowing for exhaustive testing and validation within a controlled virtual environment. By simulating the factory's layout and assembly processes, potential challenges can be anticipated and addressed preemptively, ensuring the factory's design and operation are optimized from the outset.

10.5 Product design in the industrial metaverse

Product design has already be digitized for decades, pioneered by aerospace vendors but now spread over most industries. However supply chains have become far more complex and are bringing together diverse partner ecosystems that require tight integration to achieve faster design schedules and quicker time-to-market.

What the industrial metaverse brings is the ability to link these partner ecosystems together, enabling a better sharing of tasks and ensuring testing and integration of prototypes before there are even manufactured. The combination of digital twinning for physical properties and volumetric composition for external appearance enables complete integration testing for components from different origins, ensuring accelerated development schedules and integration safety when actual build takes place.

10.6 Buildings and the industrial metaverse

The industrial metaverse stands to significantly enhance operational methodologies within building operations and construction sectors. Utilizing a synergy of VR, AR, and digital twin technologies, the metaverse facilitates a multifaceted approach to project management, from inception to execution.

Digital twins serve as dynamic, virtual representations of physical structures, enabling meticulous planning and predictive analytics. They are instrumental in simulating construction processes, identifying potential design conflicts, and optimizing maintenance protocols, thereby streamlining the entire construction lifecycle.

VR and AR technologies provide immersive platforms for stakeholder engagement, allowing for virtual walkthroughs and interactive exploration of construction models. This not only bolsters collaborative efforts among project teams but also enhances client involvement and approval processes.

The metaverse's real-time data integration and analytics capabilities offer project managers a granular view of construction progress. This facilitates resource allocation, schedule optimization, and cost management, leading to leaner construction practices with minimized resource expenditure.

Leveraging the metaverse for safety training translates to a risk-free environment where construction personnel can engage in emergency response drills and safety protocol familiarization, thus mitigating on-site accidents and ensuring regulatory compliance.

The metaverse's capacity to simulate various operational or construction methodologies and material impacts aids in the evaluation of environmental footprints, promoting sustainable construction and operational practices and aiding in the attainment of sustainable building standards.

10.7 Training with the industrial metaverse

In the context of industrial evolution, the automotive and manufacturing sectors are poised to leverage the metaverse's capabilities to enhance workforce training methodologies. The metaverse, an integrated network of VR/AR applications, and digital interconnectivity, offers a sophisticated platform for developing intricate simulation-based training modules. These modules facilitate the replication of complex work processes and scenarios, providing a virtual yet realistic practice ground for technical skill acquisition. The implementation of such advanced virtual training paradigms is anticipated to significantly elevate the competency levels of personnel, ensuring seamless integration of digital proficiencies in alignment with the physical operational demands of the industry. This strategic integration of the metaverse into workforce development initiatives represents a forward-thinking approach to cultivating a technically adept workforce, ready to navigate and excel in the technologically rich landscape of modern industry.

Industries can leverage the metaverse for workforce training in several ways:

- Enhance Learning Experiences: AR/VR can enhance worker training outcomes, proving to be more effective than traditional hands-on methods. It's a cost-effective, faster, and safer alternative. The metaverse allows for the creation of highly immersive experiences that simulate real job sites, enabling workers to interact with virtual models of equipment they will use in their roles.

- Customizable Scenarios: Training programs in the metaverse can be tailored to specific industry needs. Workers can be exposed to a variety of scenarios, including rare or complex situations that would be difficult or impossible to replicate in real life. This ensures they are well-prepared for any challenges they may encounter on the job.
- Remote Training: Workers can be trained remotely, eliminating the need for physical access to expensive machinery. This flexibility allows for training at home or other locations before setting foot on the actual job site.
- Continuous Learning: The metaverse supports ongoing education and skill development. Workers can regularly update their knowledge and skills to keep pace with the latest industry advancements, without the need for frequent physical retraining sessions.
- Safety and Risk Management: The metaverse allows workers to experience hazardous situations without any real-world risk. They can learn how to respond to emergencies, such as equipment malfunctions or safety breaches, in a safe and controlled virtual environment.
- Technical Skill Development: As technical roles like welding and pilot training become more sophisticated, the metaverse offers tools that can elevate the training process, equipping workers with the necessary high-level skills.
- Data-Driven Insights: The metaverse can track and analyze a worker’s performance during training sessions, providing valuable data that can be used to personalize learning paths and improve training effectiveness.
- Reduced Downtime: By training workers in the metaverse, industries can minimize the downtime associated with traditional training methods. Workers can train without interrupting production, as they don’t need to use actual equipment that would otherwise be in operation.
- Inclusive Learning Experiences: VR can enhance diverse worker training outcomes. By designing accessible learning environments people with diverse needs may access to training. By removing interaction barriers, including physical and geographical challenges, VR training can be more effective than traditional hands-on methods. It is an inclusive, digital-divide braking, cost-effective, faster, and safer alternatives. The metaverse allows for the creation of highly immersive experiences that simulate real job sites, enabling diverse workers to interact with virtual models of equipment they will use in their roles.

11 Opportunities and benefits

Imagine a scenario where logistics experts seamlessly collaborate with robotics assistants in virtual warehouses, while a plant manager inspects faulty equipment from her desk miles away, and a team of product designers, engineers, and marketers collaborates on creating new sneakers via a 3D platform [b-Wipro].

Businesses across various industries will likely reap a multitude of opportunities and benefits. Business leaders are recognizing the potential of this transformative technology, envisioning operational enhancements, strategic advantages, and financial gains that can accelerate innovation, streamline processes, foster collaboration, and expand market reach.

11.1 Improved design and engineering

One of the most significant advantages is the creation of a highly immersive, accessible, and interactive environment for remote collaboration. This virtual space allows engineers, designers, and stakeholders to work together from different geographical locations as if they were in the same room, fostering innovation and speeding up the development process.

Collaborative work environments enable team members from different departments or locations to innovate without the constraints of costly travel or extensive physical prototyping. It will also allow for those potential workers who are house ridden to enter the job market. Photorealistic environments combined with simulations allow for comprehensive testing and validation of product designs or plant facilities, fostering greater innovation [b-MIT]. Photorealistic environments combined with simulations allow for testing diverse user interaction comprehensive testing by end users and validation of product designs or plant facilities, fostering greater accessibility and inclusion.

11.2 Improved manufacturing processes and enhanced options

Another opportunity lies in the optimization of manufacturing processes. By creating digital twins of machinery and production lines, companies can simulate and analyze operations to identify inefficiencies and predict potential issues before they occur. This predictive maintenance can save significant amounts in operational costs by reducing downtime and extending the life of equipment.

Through simulations and real-time data collection, manufacturers gain insights to optimize equipment, minimize downtime, and predict and prevent failures [b-Deloitte].

11.3 Skills development

The industrial metaverse can enhance training and skill development. VR/XR simulations can provide employees, and diverse abilities employees with hands-on experience in a safe and controlled environment, which is particularly beneficial for high-risk industries. These simulations can be used to train workers on new equipment, safety protocols, and emergency response procedures without the need for physical resources. The metaverse offers remote access to expert skills and virtual training, enabling employees to receive hands-on training on complex machinery without disrupting operations [b-Deloitte].

11.4 Knowledge dissemination

The metaverse has the potential to democratize access to industrial expertise. Small and medium-sized enterprises (SMEs) can leverage metaverse platforms to gain insights and advice from leading industry experts, leveling the playing field with larger corporations. This could lead to a more inclusive and diverse industrial landscape where innovation is not limited by company size or resource availability.

11.5 Virtual commissioning and plant design

The industrial metaverse can revolutionize virtual commissioning and plant design by providing a comprehensive virtual environment where every aspect of a plant can be designed, tested, and optimized before physical construction begins. This virtual approach allows for the identification and correction of design errors early in the process, saving time and resources. It also enables the simulation of plant operations to ensure systems work correctly and efficiently, which can significantly reduce the time and cost associated with traditional commissioning. By leveraging the industrial metaverse, companies can achieve a more streamlined, cost-effective, and risk-mitigated pathway to launching new facilities.

11.6 Supply chain management and virtual warehousing logistics

The industrial metaverse can significantly enhance supply chain management and virtual warehousing logistics by providing a digital twin of the entire supply network. This virtual representation allows for real-time monitoring and simulation of supply chain operations, enabling managers to identify bottlenecks and optimize logistics. Additionally, it supports supply chain resilience, providing better situational awareness of what is occurring across the supply chain. The industrial metaverse will enable faster responses to disruption, such as geopolitical events that may reduce availability of material from a certain location or supplier.

It also facilitates scenario planning, where different strategies can be tested virtually to improve efficiency and responsiveness to market changes. Moreover, the metaverse can train employees in warehouse management systems without the risk of disrupting actual operations, leading to a more skilled workforce adept at handling complex logistics challenges [b-Deloitte].

11.7 An inclusive working environment for all

The industrial metaverse can revolutionize job creation, job profiles, and access to the labour market to people who are usually unable to work. The ILO reports that 16% of the world's population has a disability. The employment rate for disabled people is significantly lower than for non-disabled people [b-ILO]. As an example, in Europe only 50.6% of persons with disabilities are employed, compared to 74.8% of persons without disabilities. The unemployment rate of persons with disabilities in the EU, aged 20-64 is 17.1% compared to 10.2% of persons without disabilities, and the EU activity rate of persons with disabilities (percentage of active persons in relation to total population) is only 61.0% compared to 82.3% of non-disabled people [b-EUROPARL]. Moreover, women with disabilities, young disabled persons and persons with high support needs are more likely to be discriminated against and excluded from the labour market [b-ANED].

This situation can change by providing accessible needs fostering a virtual working environments for all. The metaverse can also prove to be useful when designing new physical facilities where every aspect of a plant can be tested, and optimized before physical construction begins. This virtual approach allows for the identification and correction of design errors early in the process, saving time and resources. It also enables the simulation of plant operations to ensure systems work correctly, and safely for all people which can significantly reduce the time and cost associated with traditional commissioning. By leveraging the industrial metaverse, companies can achieve a more inclusive, and risk-mitigated pathway to launching new facilities.

11.8 Improved business practices

The industrial metaverse can provide significant benefit for critical business areas by offering a virtual platform for innovation, collaboration and optimization.

11.8.1 Business intelligence

Leveraging the industrial metaverse, companies can enhance marketing and sales efforts, optimize product recycling processes, and gain valuable business insights through advanced analytics and data visualization [b-Deloitte].

11.8.2 Customer Focus

The industrial metaverse offers immersive customer experiences and virtual aftermarket services, transforming customer support processes and enhancing overall customer satisfaction [b-Deloitte].

11.8.3 Impactful and faster innovation

The industrial metaverse can accelerate innovation by providing a virtual environment where ideas can be tested and developed at an unprecedented pace. It eliminates the physical and logistical constraints of traditional product development, allowing for rapid prototyping and iteration. This leads to not only faster innovation cycles but also more impactful outcomes, as the metaverse's capabilities enable a deeper exploration of creative solutions and their immediate virtual application, potentially transforming industries with greater speed and efficiency.

11.8.4 Scaling business across global markets

The industrial metaverse can be a catalyst for businesses looking to scale across global markets. By providing a unified metaverse virtual platform for global industrial operations, it enables companies to collaborate and innovate without geographical limitations. This facilitates the sharing of expertise and resources, leading to more efficient global operations. Additionally, the metaverse's immersive experience can help businesses understand and adapt to diverse market needs more quickly, allowing for rapid expansion and a stronger global presence. Ultimately, the industrial metaverse can serve as a bridge, connecting disparate markets into a cohesive, interactive business ecosystem.

11.8.5 Business analytics and decision-making

The industrial metaverse enhances decision-making and analysis by providing a rich, interactive simulation environment where complex data can be visualized and manipulated in real-time. This immersive metaverse platform allows decision-makers to test various scenarios and assess outcomes in a virtual setting, leading to more informed and strategic choices. The ability to analyze data within a three-dimensional context also aids in identifying trends and insights that might be overlooked in traditional two-dimensional formats, ultimately improving the accuracy and impact of business decisions.

12 Standardization of industrial metaverse

The industrial metaverse represents a frontier for innovation and collaboration, promising transformative impacts on industries worldwide. However, to unlock its full potential, standardization plays a pivotal role in shaping its development and ensuring seamless interoperability across digital worlds.

The International Telecommunication Union (ITU) plays a crucial role in shaping the standardization landscape for emerging technologies, including the metaverse. One of its contributions is through the ITU-T Focus Group on the metaverse, which is dedicated to exploring the technical aspects and standardization requirements of this transformative digital environment. Additionally, the ITU-T Study Groups undertake important standardization work related to the metaverse, focusing on aspects such as interoperability, interconnectivity, security, and privacy. As the metaverse continues to evolve and gain traction across industries, it is essential for these ITU-T Study Groups to continue their efforts in developing and refining standards that will ensure the seamless integration and operation of metaverse technologies across industries. By fostering interoperability and consistency through standardized protocols and frameworks, these standards play a vital role in laying the foundation for a successful and sustainable industrial metaverse. Therefore, it is imperative to encourage and support their ongoing work in addressing the standardization needs of this dynamic digital landscape.

International standards serve as the backbone of the industrial metaverse, facilitating collaboration, integration, and scalability within its ecosystem of interconnected virtual environments [b-GS1]. By adhering to established standards, the industrial metaverse can deliver significant benefits, including improved efficiency, sustainability, and alignment with Sustainable Development Goals (SDGs) by leaving no one behind [b-IEC]. Moreover, standards foster interoperability, enabling the integration of diverse solutions and empowering small and medium-sized enterprises to participate in the metaverse landscape [b-IEC].

Efforts to standardize the industrial metaverse technologies are essential for enterprises to transition from isolated pilot projects to fully integrated operations. Standardization efforts encompass various aspects, including accessibility, content creation, distribution, and information exchange, all aimed at creating a seamless user experience for all within the metaverse [b-WEF3]. Establishing industry standards ensures consistency and compatibility across the industrial metaverse, enabling companies to collaborate effectively and intertwine their business processes.

The Metaverse Standards Forum brings together industry partners to build an open metaverse and focuses on the different segments of the metaverse ecosystem and their interoperability: 3D assets and their management, privacy and security, real/virtual world integration, industrial metaverse, volumetric media interoperability [b-MSF].

Amid the rapid pace of digital transformation, regulatory frameworks must keep pace to ensure user safety and address the complexities of a fragmented metaverse landscape [b-ISO]. International standards provide vital guidance and roadmaps for effective governance and regulation, laying the groundwork for a harmonized ecosystem that fosters innovation and compliance [ISO]. Collaboration among standards development organizations, such as ITU, ISO, IEC and MSF are essential in cultivating a shared understanding and terminology within the metaverse ecosystem, facilitating progress towards common goals [b-ISO].

While significant strides have been made in standardizing metaverse technologies, more work remains to be done. Continued collaboration and coordination among stakeholders are crucial to address emerging challenges and further refine standardization efforts, ensuring that the industrial metaverse evolves into a cohesive, interoperable, and safe environment for all users.

13 Conclusion

As seen in this report, there are significant market and social opportunities for the industrial metaverse. The diverse case studies highlighted underscore the potential benefits and applicability of the industrial metaverse across various industries, sectors, and workforce profiles. However, it's crucial to acknowledge that the industrial metaverse is still in the developmental phase, and the challenges it poses must be addressed effectively. One promising approach to solving some of these challenges is through the establishment of international standards. By fostering interoperability and consistency, these standards can pave the way for seamless integration and widespread adoption. Anticipating continued adoption in the coming years, it's imperative to ensure that this adoption is founded on sound technology and principles, fostering a robust and sustainable metaverse ecosystem for the future.

In addition, to address these challenges effectively and ensure a cohesive global approach, the establishment of a Global Initiative for Industrial Metaverse is paramount. A global initiative can serve as a platform for collaboration, innovation, and consensus-building, enabling the industry to overcome hurdles collectively and pave the way for a sustainable and inclusive metaverse ecosystem.

Appendix I Examples of key players in the field

Market leaders across various industries will play a crucial role in shaping the industrial metaverse landscape. The industrial metaverse has several key players driving its development and adoption. Companies like Siemens, NVIDIA, PTC and Dassault are at the forefront, collaborating to create an interoperable industrial metaverse. Siemens, with its Xcelertor platform and NVIDIA's Omniverse are supporting the digital industry and enabling the creation of complex digital twins and simulations that can interact with real-world systems.

Nokia is actively shaping the industrial metaverse, leveraging its expertise in network and communication technologies to power this emerging virtual space. Nokia's research supports creating digital representation of physical industrial environment that can be controlled and interacted with, thus optimizing systems, processes and infrastructure [b-Nokia].

Other significant contributors include Unity Technologies, known for their real-time 3D content creation platform, which supports the development of an immersive and interactive industrial metaverse [b-MIT].

Additionally, companies like Meta, Microsoft, NetEase and Valve are also key players in the global industrial metaverse market, contributing to its value and expansion [b-MIT]. These companies bring experience in digital platforms, cloud computing, and AI which are essential components of the industrial metaverse.

Moreover, industrial automation companies like GE, Schneider Electric, and Rockwell Automation are also contributing to the industrial metaverse space. They are building connected platforms that integrate product lifecycle management and infrastructure, further enhancing the capabilities of the industrial metaverse.

As the landscape evolves and crosses international borders, addressing economic, environmental, legal, social, and political factors will be crucial. Ultimately, it is the collaboration and leadership of market players across industries that will shape the trajectory of the industrial metaverse [b-Wipro].

These key players actively shape the market landscape through the development of cutting-edge solutions, strategic partnerships, and acquisitions. Their offerings span a wide range of industrial metaverse products and services, including AR, VR, IoT integration, and advanced data analytics platforms. These players strive to solidify their positions and capture significant shares in this rapidly expanding market [b-Globe].

For a more detailed perspective on the industrial metaverse market see [PMR].

Appendix II Definitions of Industrial metaverse

The following list of definitions are not exhaustive and may not encompass all possible interpretations or meanings.

Definition	**Source**
An integrative ecosystem of virtual worlds offering immersive experiences to users, that modify pre-existing and create new value from economic, environmental, social and cultural perspectives.	ITU-T Focus Group on metaverse
The industrial metaverse is redefining how people and machines collaborate to design, build, operate, and optimize physical systems using immersive technologies in the cloud for improvements in sustainability and efficiency. Remote operational technology and simulations are empowering effective monitoring of processes, proactive problem solving, and interaction from a safe distance. The industrial metaverse is powered by the combination of many innovative technologies that deliver immediate financial value, sustainability, and employee efficiency through process optimizations, modelling, digital analysis, and AI-based predictions.	Microsoft The data driven future of industries - Microsoft Industry Blogs
The industrial metaverse is the convergence of individual technologies that, when used in combination, can create an immersive three-dimensional virtual or virtual/physical industrial environment. As technology evolves, the industrial metaverse will likely allow access to these immersive 3D environments from any internet-connected device, including virtual reality (VR) and augmented reality (AR) devices, as well as smartphones, tablets, laptops, and equipment, from anywhere in the world.	Deloitte Exploring the industrial metaverse | Deloitte Insights
The industrial metaverse—a metaverse sector that mirrors and simulates real machines, factories, cities, transportation networks, and other highly complex systems—will offer to its participants fully immersive, real-time, interactive, persistent, and synchronous representations and simulations of the real world.	Siemens & MIT MITTR_Siemens_The-Emergent-Industrial-Metaverse.pdf (technologyreview.com)
The industrial metaverse is the concept of a digital world to mirror and simulate real machines and factories, buildings and cities, grids and transportation systems. By seamlessly integrating technologies like cloud and edge computing, industrial AI and digital twins, the industrial metaverse can optimize processes and drive sustainable practices, ultimately shaping the future beyond simulation.	Siemens Industrial Metaverse - Digital Transformation - Siemens Global Website

Industrial metaverse enables industrial companies of all sizes to create closed-loop digital twins with real-time performance data, ideal for running simulations and AI-accelerated processes for advanced applications such as autonomous factories that rely on intelligent sensors and connected devices.	Siemens & Nvidia Creating the Industrial Metaverse: Siemens Xcelerator + NVIDIA Omniverse - Thought Leadership
Industrial metaverse is a blending of the digital and physical world that accelerates efficiency through engineering, manufacturing, and field service. While still in its early stages, the vision is for it to enable real-time collaboration, connectivity, and spatially aware context within industrial environments.	PTC What Is Industrial Metaverse? | PTC
The "industrial metaverse" is a term commonly applied to the set of metaverse applications designed for industrial users. As the next evolutionary step of digital twinning, the industrial metaverse extends beyond a digital replica of a machinery or a manufacturing plant. In fact, it can be defined as a persistent 3D platform that is implemented across an organization, value chain and product life cycle, serving as a digital reflection of an entire organization in its operational environment. In its combinatory nature, it integrates processes, materials, machines and people in a bi-directional flow between real and virtual worlds. It builds on enabling technologies, including extended reality (XR), robotics, sensors and actuators as part of the internet of things (IoT), artificial intelligence (AI), development tools, blockchain, computing and connectivity.	WEF https://www3.weforum.org/docs/WEF_Exploring_the_Industrial_Metaverse_2023.pdf
The industrial metaverse combines physical-digital fusion and human augmentation for industrial applications and contains digital representations of physical industrial environments, systems, assets and spaces that people can control, communicate, and interact with.	Nokia, MIT Technology Review The industrial metaverse: A game-changer for operational technology | MIT Technology Review
The Industrial Metaverse is an important application field of the Metaverse, which is a new industrial ecosystem that deeply integrates next-generation information and communication technologies such as AR, digital twins, and content generation with the physical industrial economy. Compared with the creation of surreal content and user experience in consumer scenarios, the scenes and objects constructed in the Industrial Metaverse are a concrete physical system with clear problems to be solved, organizational relationships, and tasks. Thanks to the solid technological foundation and clear industrial scenarios in the industry field, the future Industrial Metaverse may be the direction for the prioritized implementation of Metaverse applications.	IEEE White paper: THE INDUSTRIAL METAVERSE REPORT IEEE Xplore Full-Text PDF:
Although there is no generally accepted definition of the Industrial Metaverse, it can be pictured as an emerging user-centred space that connects and	ABB

enhances the digital and physical worlds by integrating various recent technological trends such as digital twins, machine learning, the Internet of Things (IoT), mixed reality and 5G.	Industrial Metaverse | ABB
IDC defines the metaverse as "an evolution of today's internet that leverages mobile devices, augmented and virtual reality headsets and next-generation networks to create persistent and continuous user experiences with a strong sense of presence."	IDC Is the 'Industrial Metaverse' the Next Big Thing? | IndustryWeek
Industrial Metaverse is a new man-in-loop digital twin system of the real industrial economy, through the interconnection of industrial digital resources, supported by DT, XR, NFT, NPL, as well as AI technologies, and driven by real-time information in industry. Industrial Metaverse simulates all industrial factors including man (workers and engineers), machine (products and equipment), material (raw resources and components) as well as the industrial process (production and maintenance) and the economic activity (pricing and trade).To generate a virtual-real interactive and full-chain collaborative space, Industrial Metaverse reintegrates industrial data with a variety of new technologies, and it realizes the decentralized sharing of industrial digital resources (including industrial product models, cloud platforms, product process information, etc.)	Zheng, Z. et al. (2022). Industrial Metaverse: Connotation, Features, Technologies, Applications and Challenges. In: Fan, W., Zhang, L., Li, N., Song, X. (eds) Methods and Applications for Modeling and Simulation of Complex Systems. AsiaSim 2022. Communications in Computer and Information Science, vol 1712. Springer, Singapore. https://doi.org/10.1007/978-981-19-9198-1_19
What is the metaverse? At Capgemini, we define it as a blended space of virtual and physical interactions that can be used to improve the customer experience. For major brands, this technological evolution is often interpreted as the creation of richer and deeper interactions with the people who buy their products and services, whether they're at home or at play.	Capgemini What is the industrial metaverse - from digital twins to an 'internet of experiences' | Capgemini
We conclude that the Industrial Metaverse is best defined as a "connected whole-system digital twin with functionalities to interact with the real system in its environment, allowing decision makers to better understand the past and forecast the future."	Author D. Little The Industrial Metaverse | Arthur D. Little (adlittle.com)
The industrial metaverse is, as the report defines it, a combination of technologies that "mirrors real machines, factories, cities, transportation	IMD

networks, and other highly complex human systems." In common with the consumer and enterprise metaverse segments, it will provide immersive, real-time experiences.	Understanding the industrial metaverse - I by IMD
The term industrial metaverse refers to an interconnected digital ecosystem specifically designed for the manufacturing industry. It represents a paradigm shift in how we conceptualize and engage with the processes involved in designing, producing, and operating within the manufacturing sector. This concept draws inspiration from the broader metaverse, a concept typically associated with virtual, shared spaces created by the convergence of physical and virtual reality.	Mazer What Is Industrial Metaverse? Definition & Meaning - Mazer (mazerspace.com)
The defining point of the industrial metaverse is that it allows for persistent, digital representations connected to aspects of the physical world. The precise blend of physical and digital aspects required to make an industrial metaverse is up for debate.	Hexagon Understanding the Industrial Metaverse - Hexagon's Manufacturing Intelligence Blog (hexagonmi.com)
The industrial metaverse is a hybrid collaborative space that facilitates the real-world environment with contextualized virtual data and digital platforms that are constantly available for all stakeholders of industrial processes for remote collaboration and self-services.	Oculavis The Industrial Metaverse. Definition, applications and potentials in mechanical engineering & the industry (oculavis.de)
It is a specific application of the metaverse concept in the manufacturing, construction, and engineering sectors. The industrial metaverse aims to create a virtual environment where engineers, designers, and other stakeholders can collaborate in real-time, regardless of their physical location. Users can access virtual representations of products, machinery, and entire manufacturing facilities in the industrial metaverse and simulate different scenarios to optimize designs, identify potential issues, and make informed decisions. This has the potential to significantly improve efficiency, lower costs, and reduce the environmental impact of industrial processes. Still, in its early stages of development, the industrial metaverse has the potential to revolutionize the way industrial processes are designed, executed, and maintained.	Emeritus What is Industrial Metaverse and Why You Should Care About it (emeritus.org)
The industrial metaverse can create a relationship between physical devices and the digital world. The industrial metaverse would utilize the digital twin to achieve the link between the physical devices and the digital world.	SMEClabs (1) What is industrial metaverse? | LinkedIn
Industrial Metaverse is a new ecology of deep integration between new information and communication technologies and the real economy represented by the Internet of Things, artificial intelligence, and digital twin,	C&T RF Antennas Inc

whose ultimate goal is to promote the efficient development of real industry and build a new manufacturing and service system covering the whole industrial chain and the whole value chain. The industrial metaverse, a precise reconstruction, and re-creation of social and physical attributes in the real world by the digital world is the materialization of artificial intelligence in the real world, moreover, it is an important part of the real world and real economy.	What is Industrial Metaverse? - C&T RF Antennas Manufacturer (ctrfantennasinc.com)

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