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Metaverse for Manufacturing: Leveraging Extended Reality Technology for Human-Centric Production Systems

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Abstract: As we progress towards Industry 5.0, technological advancements are converging; this movement is realised by the increasing collaboration between humans and intelligent digital platforms and further enabled by the interactive visualisation modes provided by Metaverse technology. This research examines the practical applications and limitations of Metaverse technology providing insights into the transformative possibilities it offers for the manufacturing sector. Specifically, the research was guided by the core objective to trace the evolution of Metaverse technology within manufacturing. This study provides a comprehensive and state-of-the-art analysis of the adoption and impact of Metaverse technologies in the manufacturing sector. While previous research has explored aspects of Industry 4.0 and digital transformation, this study specifically focuses on human-centric manufacturing (human-in-the-loop) applications of Metaverse technology, including augmented reality, virtual reality, digital twins, and cyber-physical robotic systems. Findings from the systematic literature review indicate that Metaverse technologies, primarily augmented reality and virtual reality, have evolved into powerful tools in manufacturing. They are widely adopted across sectors in the industry, transforming processes such as product design, quality control, and maintenance. Augmented reality and virtual reality offer intuitive ways to visualise data and interact with digital twins, bridging the gap between physical and virtual realms in manufacturing. A roadmap and scenarios for the introduction of Metaverse technology in manufacturing are provided with suggested adoption timespans. Furthermore, the systematic literature review identified barriers hindering the wider adoption of Metaverse technology in manufacturing.

Keywords: Metaverse; human-centric manufacturing; human-in-the-loop; Industry 4.0; Industry 5.0; extended reality (XR); Cobots; edge computation

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Academic Editor: Antonio Caggiano

Received: 5 December 2024
Revised: 20 December 2024
Accepted: 21 December 2024
Published: 2 January 2025

Citation: Egbengwu, V.; Garn, W.; Turner, C.J. Metaverse for Manufacturing: Leveraging Extended Reality Technology for Human-Centric Production Systems. *Sustainability* **2025**, *17*, 280. https://doi.org/10.3390/su17010280

1. Introduction

As we progress towards Industry 5.0, technological advancements are converging; this movement is realised by the increasing collaboration between humans and intelligent digital platforms as enabled by the Internet of Things, cyber-physical systems, artificial intelligence, big data, advanced analytics, and cloud-based simulations [1–3]. The industrial Metaverse system, described by Lee and Kundu [4], emphasises real-time interactions with physical entities and augments visualisation in the configuration layer of cyber-physical systems (CPS), acting as a manufacturing workspace's digital twin.

One of the emerging facets in this evolution is the Metaverse, a term initially coined in Neal Stephenson's 1992 novel "Snow Crash" but further explored in science fiction works like William Gibson's "Neuromancer". Unlike its fictional origins, today's Metaverse, defined by Ritterbusch and Teichmann [5], represents a decentralised three-dimensional online environment, allowing users to interact through avatars socially and economically in virtual spheres distinct from the physical world.

The emergence of Metaverse technology, encompassing virtual and augmented reality, artificial intelligence, and internet connectivity, is revolutionising various industries [6]. The manufacturing sector stands to gain significantly from these advancements [7]. Within various Metaverse technologies, computer-mediated reality is seen as a transformative force for industrial methods, promising enhanced efficiency and competitiveness in a rapidly evolving digital economy. As the boundaries between digital and physical realities blur, understanding the role of various Metaverse technologies in future production and innovation becomes essential. This paper explores how the manufacturing sector embraces these transformative Metaverse technologies.

The industrial Metaverse system, described by Lee and Kundu [4], emphasises real-time interactions with physical entities and augments visualisation in the configuration layer of cyber-physical systems (CPS), acting as a manufacturing workspace's digital twin. Within this context, cyber-physical production systems (CPPS) emerge as a subset of CPS, focusing on enhancing the interplay between virtual and physical components in production setups [8].

Distinguishingly, the industrial Metaverse mirrors fundamental infrastructures, from machines to supply chains, into the virtual domain, allowing for swift problem identification and resolution [9]. This mirroring can predict issues before they escalate or materialise, presenting a proactive approach to industrial challenges. This transformative phase in manufacturing is fuelled by the integration of CPPS with key technological drivers such as extended reality, digital twins, artificial intelligence (AI), blockchain technology, and the Internet of Things (IoT) [10]. This synthesis lays the foundation for intelligent factories characterised by unprecedented interconnectivity and automation.

Digital twins, as highlighted by [11], are rooted in detailed modelling and simulation techniques that offer virtual representations of physical systems, providing unprecedented capability to monitor, analyse, and predict system behaviours. This inherently dynamic technology seamlessly integrates data from physical models, sensors, and operational history, resulting in continuous optimisation of manufacturing processes. According to [12], it is not just about creating a mirror image; the real value lies in the digital twin's ability to be context-aware, adapt to changes, and autonomously make decisions that enhance efficiency.

Blockchain technology, known for its immutability and decentralisation, offers the potential of a trustworthy platform to store critical manufacturing data. From production timelines to quality metrics, blockchain could ensure transparent and verifiable information transfer, fortifying trust across the manufacturing value chain [13]. The harmonisation of blockchain with digital twins adds an additional layer of protection for data composing such virtual replicas, ensuring that they remain reliable and free from tampering. It is the case that for some organisation, especially SMEs (small- and medium-sized enterprises), Metaverse equipment and training time costs are a potential hinderance to use [14]. In such cases where cost structures limit individual company investment in the Metaverse, a group or community response may provide the answer. Xin et al. [15] examined the costs of utilising Metaverse technologies in the sustainable production, supply, and retailing of clothing, as well as provide a model based on game theory to explore the development of a Metaverse ecosystem for the apparel industry. Xie et al. [16] find that Metaverse platforms that offer a high level of functionality and services, secured by distributed ledger technology such as Ethereum, but produce lower carbon emissions in their provision are more likely to be chosen by manufacturers; these authors also explore the use of NFTs (non-fungible tokens) to distribute virtual representations of apparel securely.

The exploration of new technological frontiers often leads to the emergence of specific domains with remarkable applications and outcomes, as Gong et al. [17] emphasised. Within this context, practical application of Metaverse technologies, particularly augmented reality (AR), are having a transformative impact on industries such as aerospace, notably revolutionising processes such as the visualisation of non-destructive testing (NDT). NDT is a pivotal technique in aerospace manufacturing, permitting the evaluation of components without causing damage. An experimental study conducted by Ababsa [18] sought to assess the practicalities and challenges of an AR application in the realm of non-destructive testing (NDT), employing the use of the HoloLens1 headset, a state-of-the-art mixed reality device to enhance the interpretation of NDT data. Developed with the Unity 3D platform in conjunction with Vuforia, it allows maintenance technicians to directly visualise measurements from ultrasonic transducers on parts such as the Airbus A380′s engine casing. At the retailing interface, Zhang et al. [19] found that for a Chinese automotive manufacturer, it was found that their digital sales presence befitted from the inclusion of social interactions between customers facilitated by Metaverse technologies. Xie et al. [16] provide a case study involving metaverse mixed reality technology and its use by human workers in the robot-assisted manufacture of a gearbox assembly; this research found that the operator workload was reduced, and their view and control of their local workstation improved. Jamshidi et al. [20] investigated metaverse technologies in conjunction with a digital twin simulation system for the examination and development of complex electronic circuits most commonly used in the telecommunications industry. The application of additive manufacturing (or 3D printing) may also benefit from Metaverse interfaces in the direct design and production of personalised plastic injection modelled parts (in a process known as additive digital moulding), allowing for multi-person design teams and component manufacturers in the supply chain to work together on bespoke products [21].

Following on from this introduction section, the paper is organised as follows: 2. Systematic literature review of Metaverse technology use in manufacturing; 3. Metaverse concepts and evolution; 4. Metaverse Roadmap—Industry 5.0 Human-Centric Manufacturing; 5. Discussion; 6. Conclusion.

2. Methodology and Research Questions

A qualitative approach was employed to study Metaverse technology adoption in manufacturing for this study. This was due to the research questions encompassing a broad range of inquiries, including understanding the evolution of the technology, identifying barriers to adoption, recognising impact areas, and proposing recommendations. These multifaceted questions require a versatile approach that can identify the state of the art in Metaverse technology, requiring a systematic literature review approach. In order to address the outlined ambition, the research is guided by the following questions:

- RQ1: How has Metaverse technology adoption evolved across the manufacturing industry?
- RQ2: What are the primary barriers to Metaverse technology adoption in manufacturing?
- RQ3: How will Metaverse technology impact manufacturing practice in the future?

Our qualitative approach helped extract valuable insights from the content of journal articles by identifying emerging themes, patterns, and critical contextual information that shed light on the evolution and nuances of Metaverse technology adoption [22]. The qualitative systematic review used for this study retrieved published articles and conference materials from 2010 to August 2024 (Figure 1 shows the amount published each year from 2010 to 2023 only). These years were purposively selected, retrieved, and analysed in order to provide a broad overview of the evolution of Metaverse technologies used in manufacturing. Data were sourced from several databases, including Scopus, Science Direct, and Google Scholar. The Science Direct database was used mainly for the search, with direct downloads from publishers based on the search.

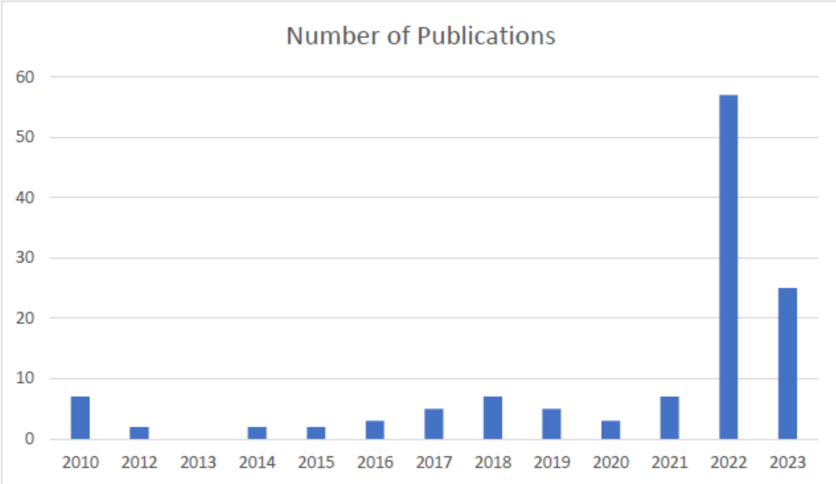

Figure 1. Number of Metaverse-related publications available each year since 2010.

The specific search terms and strategies used were Metaverse; virtual reality (VR); augmented reality (AR); mixed reality (MR); digital twin; cyber-physical systems (CPS); manufacturing, Industry 4.0; Industry 5.0; smart manufacturing; digital manufacturing; extended reality (XR); virtual prototyping; virtual training; virtual workspace; virtual factory; immersive technologies; human–computer interaction (HCI) in manufacturing; virtual supply chain; virtual simulation in manufacturing; real-time collaboration in manufacturing; virtual environment in manufacturing; technology in manufacturing.

All journal articles and conference publications containing the specified words were included in the search. At the same time, books, unpublished materials, and materials earlier than 2010 were excluded from the search. Other exclusion criteria included unrelated, unavailable full-text papers; grey literature (all works not formally published in books/journals); and duplicated journal articles. Based on the inclusion and exclusion criteria, one hundred and thirty journal articles and conference-published presentations were included and retrieved for this study. The systematic review/analysis includes direct quotes from the articles reviewed, qualitative analysis, and a discussion of findings related to the literature review in response to achieving the set objectives.

The scope of the study search spanned from the year 2010 to 2024. This served the purpose of encompassing studies conducted over the past decade, thus allowing for a robust assessment of the evolving impact of Metaverse technologies within the manufacturing sector. The search was conducted in July–August 2024, yielding an initial corpus of 1346 records. The integrity of the dataset was upheld through meticulous data refinement processes. Duplicate records were eliminated, ensuring that redundant contributions were not made to the final selection. After this initial screening, the titles and abstracts of the retrieved articles underwent thorough scrutiny. At this stage, studies not written in the English language were excluded, aligning with the language criteria of the meta-analysis.

Furthermore, a contextual relevance criterion was applied, retaining only those studies that applied Metaverse technologies within manufacturing contexts, either for production or human-supportive purposes. The inclusion criteria were formulated precisely to ensure the selection of studies that would provide robust insights into the impact of Metaverse technologies in manufacturing. The criteria mandated that the selected studies (1) demonstrate empirical characteristics; (2) adhere to experimental design paradigms, including quasi-experimental designs and case studies; (3) employ measurement instruments or assessments of established validity and reliability; and (4) document outcome measures for experimental and control groups.

The concept of extended reality (XR) is instructive in scoping Metaverse technologies. It has been described by Mann et al. [23], who reframe the XR definition to include multisensory technologies and, in so, provide a sensory technology set known as mediated reality (MR) in the context of an all reality (All R) definition (shown in Figure 2). All R is a definition "that includes not just interactive multimedia-based "reality" for our five senses but also includes additional senses (like sensory sonar, sensory radar, etc.), as well as our human actions/actuators' [23]. Mann et al. [23] describe the All R definition as one that allows a user-defined mix of virtual and real elements to be blended depending on the particular use and foresee its extension to include the simultaneous use of multiple multimedia visualisation and sensing systems (as they arise) with the *R notation for All R.

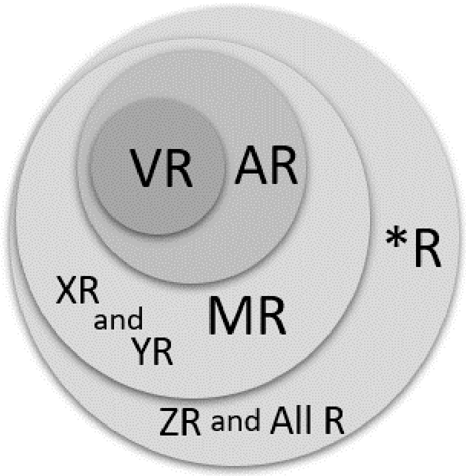

Figure 2. The primary constituent realities of all reality (All *R) (adapted: Mann et al., [23]).

3. Metaverse Concepts and Evolution

Metaverse unites two fundamental concepts: "meta", denoting something beyond, and "verse", implying the universe itself. Notably, identical ideas under different names date back to the 1980s, underscoring the profound historical roots of Metaverse technology [24]. These range from digitisation, digital twin, and cyber-physical systems to virtual reality, blockchain, Web3, and artificial intelligence, all connecting manufacturing with the Metaverse [7,25]. Metaverse technology emerges as a facilitator, fortifying established frameworks and initiatives such as Industry 4.0 and 5.0, along with the transformative vision of Society 5.0. This evolution traces a trajectory from digital to universal manufacturing [25].

The Metaverse is an immersive digital environment combining elements of the physical and virtual worlds, allowing users to interact with virtual avatars and objects [26]. It is a multi-user platform that leverages technologies such as virtual reality (VR), augmented reality (AR), artificial intelligence (AI), and blockchain to create a persistent and interconnected virtual universe [27,28]. The term "Metaverse" combines "meta", meaning virtual and transcendent, and "verse", referring to the world or universe [7,25]. The Metaverse is not limited to a single definition, and there is ongoing debate and exploration to refine its scope and capabilities [5,29]. It represents a vision of a future digital space where individuals can seamlessly navigate and interact with virtual environments, objects, and other users [29].

The gaming industry has been the foremost beneficiary of Metaverse technology thus far, leveraging its 3D immersive experiences and collaborative capabilities to significant effect [7,25,27,30]. The development of 3D digital simulation has paved the way for extended reality, encompassing augmented, virtual, and mixed-reality environments. As an enabling technology, extended reality introduces avatars, virtual spaces, and interactive objects into the Metaverse ecosystem, augmenting the immersive experience [7]. Moreover, Wang et al. [31] have proposed a comprehensive seven-layer Metaverse architecture to elucidate the intricate web of technologies and entities underpinning the Metaverse's growth. These layers, arranged from the base to the pinnacle, consist of infrastructure, human interface, decentralisation, spatial computing, creator economy, discovery, and experience. These layers serve as the framework for technology development and growth [7,31].

In recent years, the concept of the Metaverse has garnered attention and interest across a range of industries, such as education, hospitality and tourism, healthcare, banking, manufacturing, and smart cities [32–39].

3.1. Evolution of the Metaverse

The need for an innovative and efficient solution to critical design and manufacturing problems led to the adoption and evolution of Metaverse technology systems in manufacturing. With the advent of Industry 4.0, manufacturing industries have identified and begun to embrace cyber-physical systems, the Internet of Things, augmented reality, and robotics as solutions to production problems and fast changing consumer needs. These innovative technologies have led to new opportunities for business models, the creation of new jobs, and production technology in manufacturing [40].

Virtual reality (VR)- and AR (augmented reality)-based technologies are being actively used in manufacturing for the support of maintenance tasks. Metaverse technology may also have a role to play in the management of other manufacturing stages such as assembly, design, and operations planning; such technologies are already being used in human worker training for manual assembly operations.

Metaverse technology has evolved in recent years and has opened possibilities for geographically dispersed teams to work together in real time on complex design and planning activities [41]. When integrated with physical assets, Metaverse technology is an important ingredient in linking data processing and analytics software with the control of machinery as intelligent cyber physical systems (CPS) [42]. CPS has been adopted in different manufacturing sectors as it has filled the interaction gap between interconnected computing systems and complex robotic systems, allowing for human interaction and oversight of often highly automated machine systems. When linked with the visualisation power of Metaverse technology, CPS has enabled manufacturing process automation and control, robotic surgery, intelligent building management, and in the future may be the basis for semi- and fully autonomous smart manufacturing systems and supply chains. While smart manufacturing refers to the use of advanced technologies to optimise and automate production processes, smart or intelligent products are characterised by integrating technological features and capabilities to enhance the functionality and value of the product offering [43]. In solving common manufacturing industry challenges, digital solutions as outlined above have been explored with Industry 4.0 as an umbrella term for the current digitally interconnected industrial stage that is being adopted across many sectors.

One prominent technology introduced during the Industry 4.0 paradigm is the digital twin. The digital twin is intended to provide a real-time digital description of a physical asset, with its use originating from the aerospace field this technology is rapidly being adopted for manufacturing applications [44]. Despite its effectiveness, presenting extensive datasets (often supplemented with live streaming data from monitored assets) and information in a digital twin poses a significant challenge [45]. The use of AR is one reaction to the need to summarise and present complex data in a context specific and accessible way to digital twin users. Experimenting with an AR application that visualises digital twin data of a CNC milling machine in a manufacturing environment, Zhu et al. [46] demonstrate that the combination of both technologies empowers the operator to effectively monitor and control the machine tool while concurrently interacting with and managing the digital twin data. The use of AR technology to visualise the digital twin data seamlessly integrates the physical and virtual aspects of the digital twin in a highly intuitive manner [46]. In the years preceding the integration and widespread use of Metaverse technologies in manufacturing, human workers were tasked with executing repetitive, unchanging duties meticulously crafted to enhance the overall performance of manufacturing systems.

In recent years, digitisation and use of technology in the clothing and textile manufacturing industry have evolved from manual processes, inventory, data collection, material sourcing, fabric design, and distribution to much easier, faster, and less lead time processes. With AR/VR and other Metaverse technologies, the conventional textile and clothing supply chain concept, models and practices have evolved. Digital tools are now being used to transform the stages of "product design and development, sourcing, manufacturing, distribution, and retail, and in reverse and return logistics" [47].

The industrial Metaverse system is a technology subset embraced by manufacturing industries as it enhances interaction with physical objects in real time, as a digital twin in the workspace and/or as a cyber-physical system. Workforce productivity, reduction of operational costs, and the improvement of operator safety, among others, are advantages of Metaverse technologies that have made manufacturing industries adopt the concept [4].

According to [48], the following manufacturing functions have successfully employed AR and VR technologies in their operations:

- Product design and evaluation;
- Repair and maintenance;
- Warehouse management;
- Plant layout;
- CMC simulation;
- Quality control and assembly.

Retailers have initially used AR and VR to promote goods and services to customers and provide interactive experiences in shops and showrooms. In recent years, however, advancements in software algorithms and the lower costs of AR and VR devices have made such technology use viable in a new range of applications. Different manufacturing sectors, such as remote assistance, maintenance, assembly line monitoring, and education/training, have embraced extended reality (XR) to enhance productivity [48].

Product design and development, one of the major sectors/phases in the manufacturing industry, involves a complex process of creativity, drafting, and market position analysis, which requires a diverse array of personnel often drawn from different functional backgrounds. With Metaverse technologies providing the visualisation and interaction functionality for learning platforms, design engineers can obtain the required knowledge and technical experience to complete their tasks in collaboration with marketing people, manufacturing engineers, and finance personnel. Furthermore, visualisation technologies, especially those involving simulation, aid in the evaluation of product designs enabling the detection of errors earlier on avoiding additional and unnecessary production costs. Maintenance and repair activities form an essential activity in the manufacturing industry, previously manual fault detection and identification practices meant that proactive maintenance actions were limited. This activity has progressed with Metaverse technologies, particularly AR and VR, making the repair process easier to perform and faster, especially when employing active monitoring of assets and predictive/prognostic scheduling of maintenance actions. Maintenance efficiency and quality become more accessible when AR is utilised for guidance and training of operatives, while VR is more suitable for support actions and initial problem diagnosis within complex assets or interacting asset groupings [22].

Customer needs are usually considered in manufacturing when the quality of products is determined so the product can stand against competition in the market. To ensure this, a visual inspection approach was often done to check the quality in manufacturing industries. AR technologies have been used to train quality control workers to reduce the rigours that come with manual inspection. The workers can check the quality by moving around the outlet and wearing AR glasses. Checking quality is also made easier with the IoT sensors embedded in the outlet products. With AR, there is an assurance that the correct product details are provided, and that unintentional mistakes are eliminated [48].

The use of manual machines and operation processes in manufacturing slows down work. It reduces efficiency, as presented in an experiment on using AR/MR and extended reality (XR) applications in an automobile brake disc manufacturing company. The work of Catalano et al. [49] applied Metaverse technologies to identify the differences between an operator on site and a second operator situated remotely who exploited the advantages live connected VR technology. Building a simulation model, the research presented the advantages and speed of using Metaverse technologies, especially in the remote interaction with production processes for automotive brake discs [49].

Transparent AR head-mounted displays have been embraced in manufacturing as they aid the direct access of visual guidance in front of the operator's view while allowing "hands-free" movement for the worker and a safety aspect for the protection of workers eyes from splinters. This technology is still in the adoption stage, though its acceptance is growing [50].

As manufacturing industries embrace Industry 4.0 technologies in their manufacturing processes, a few have begun to embrace Industry 5.0. Industry 4.0 focuses on system autonomy, with the aim of achieving full automation within a factory. More recently, questions focused on the application of resilience in the manufacturing supply chains, assets, and processes along with renewed urgency to address sustainability issues have led to the inception of Industry 5.0. Envisioned in an outline by the European Commission in 2021 [51], Industry 5.0 also incorporates a new central pillar, that of human centricity and the enhanced role of humans in the oversight, mediation, and knowledge exchange with automated and autonomous cyber-physical systems in manufacturing. Differing from Industry 4.0, the I5.0 paradigm seeks to move on from the goal of full automation and autonomous operation, provided by the hardware technology developments in computing, robotics, and machine tools and AI-enhanced software. Instead, I5.0 seeks to actively involve humans in the completion of manufacturing tasks and decision-making loops, harnessing human knowledge and providing assistance in semi automation and part autonomous interactivity with shop floor workers and managers alike. Metaverse technology may aid this transition to human-centric automation leveraging knowledge resources of workers through collaborative technology, on the road to achieving sustainable mass personalised production [31]. A highlighted key technology in the development of Industry 4.0 towards human-centric Industry 5.0 is that of collaborative robots (Cobots). A Metaverse technology, Cobots can safely work with humans in assembly tasks. This innovation has aided manufacturing by aiding rather than replacing humans [52].

3.2. Barriers and Challenges to Metaverse Technology Adoption

Park and Kim (2022) offer a comprehensive exploration of the Metaverse, exploring the Metaverse domain's taxonomy, components, applications, and open challenges. Park and Kim [53] identify challenges such as insufficient skilled personnel and research into the effect of E2E (end-to-end) learning technologies (such as those enabled by deep learning techniques) and their integration. Allam et al. [32] discuss the barriers faced when implementing Metaverse technology. These challenges encompass environmental, economic, and social dimensions, allowing organisations to anticipate and address such barriers before and during the technology implementation phase.

As manufacturing companies increasingly rely on digital twins and other virtual representations of their assets and processes, it becomes critical for them to ensure the confidentiality, integrity, and availability of their data; achieving this requires the implementation of cybersecurity measures and the development of formal communication protocols, among other actions [54]. By understanding these challenges, organisations can gain insights into potential security concerns and devise effective strategies to guard against them. Similarly, Wang et al. [31] have also explored the fundamentals and security and privacy considerations of the Metaverse.

Yang et al. [55] argue that to harness the potential of the Metaverse fully, manufacturers must prioritise data exchange and interoperability among systems and platforms. This entails establishing standards and protocols that facilitate the integration of technologies through shared data formats.

Additionally, there is a recognised shortage of workers skilled in the use of Metaverse technology, as highlighted by Rachmadtullah et al. [56]. Incorporating Metaverse technology in manufacturing requires employees to be proficient in the use (and sometimes development and deployment) of augmented reality and other extended reality technologies.

The identified barriers to Metaverse technology adoption in the manufacturing sector, in order of importance, are summarised in Table 1. Nee et al. [57] illustrate the central challenge to Metaverse technology adoption as the use of such technology at product design time along with its use during the manufacturing process. The possibility for the end-to-end use of real-time connected Metaverse deployed simulations and visualisation infographics adds an additional scope, where the end-of-life treatments of returned products (conveyed through reverse logistics adapted supply chains) may also be supported. In terms of mixed reality device latency issues, works such as those of Naguib et al. [58] and Sehad et al. [59] point toward the use of higher speed and increased bandwidth promised in the 6G data transmission specification.

Table 1. Barriers to adoption of metaverse technology.

Category	Barriers	
Technical barriers	Accuracy, registration, and latency issues in tracking and superimposition of augmented information. High accuracy requirements for augmented reality applications in manufacturing. Low latency is required to maintain virtual objects' stability in augmented reality displays.	[41,57,60]
	Lack of tailored software approaches for Metaverse technology in manufacturing. Limited protocols for Metaverse technology integration. Challenges related to the interoperability of Metaverse technology. Security concerns in the implementation of Metaverse technology. Complexity management issues in adopting Metaverse technology. Lack of "ready-to-use" AI algorithms and toolsets—no "inventory" of current methods to support Metaverse applications and Industry 5.0 objectives. Registration challenges, involving correct placement of virtual objects in augmented spaces. Technical challenges associated with AR interfacing technology	[47,49,57,60]

Table 1. *Cont.*

Category	Barriers	
Organisational barriers	Resistance to major strategic changes in conservative manufacturing sectors. Employee support and recognition of technology benefits. Organisational barriers related to manufacturing strategy. Top management issues influencing technology adoption.	[61,62]
Human factors	Employee support and recognition of the benefits of technology adoption. Impact of Metaverse technology on workers' roles and tasks. Organisational structure, culture, and management support affecting technology adoption. Ergonomic challenges associated with long-term usage of AR devices. Visual discomfort, depth perception problems, and fatigue among AR users. Resistance to change from traditional methods in developing countries. Fear of new technologies and their acceptance by workers; lack of trust in the result provided and visualised through the Metaverse.	[60–63]
Environmental barriers	Power consumption and cloud-located data processing, such as "server farms", increase carbon emissions. Lack of available technology and technology readiness in many manufacturing organisations. Power supply limitations in developing countries. Economic viability challenges in digitisation efforts. Regulatory barriers and cultural resistance in some manufacturing sectors, such as biotech.	[62,64]

3.3. Potential Impact Areas

Metaverse technology facilitates virtual product design, layout development, and prototype testing, leading to faster design iterations and reduced physical modelling costs [65]. Collaboration among design teams is also enhanced with this mode, both streamlining product development and expediting innovative product launches [65]. In addition, Metaverse technology offers immersive training and simulation experiences by replicating real-world manufacturing processes in virtual environments [66]. Recent research by Saeed et al. [67] investigated the use of training programmes not just to demonstrate the use of Metaverse technologies but to redesign existing company courses to use mixed reality technology. Saeed et al. [67] found that learning to use Metaverse technologies by workers was reported as being a short learning curve, and if designed correctly in terms of interactivity, Metaverse technologies were intuitive to use. In the same study, it was also the case that overall training costs were reduced by using Metaverse technologies, once initial materials were designed [67]. Mitra [68] puts forward the concept of a Metaverse-based training ecosystem where all training and education needs of an organisation are "augmented" with Metaverse technologies through a shared platform; in this way, cost savings may be achieved, and communities of practice are more likely to emerge. Hajjami and Park [69] provide a range of industry case studies of Metaverse-deployed training programmes, noting the value in interactive simulations of physical assets and manufacturing production lines can provide new insights for trainees while eliminating the need for physical mock-ups. Manufacturers also employ Metaverse technology for simulation and optimisation of existing production lines, identifying bottlenecks, enhancing efficiency, and minimising downtime [65]; its use also extends to the modelling and design of new production lines, allowing the 3D-immersive rendering of proposed solution options.

Metaverse technology can be used to enhance remote collaboration among manufacturing teams, facilitating interaction, information sharing, and immediate feedback regardless of geographical distances [70].

The Metaverse holds much promise in the area of supply chain management. When integrated with blockchain-type secure communication frameworks, supply chain management activities may take advantage of decentralised secure electronic information storage and sharing functionality, fostering transparency, traceability, and trust between manufacturers and their suppliers [71]. Furthermore, data analytics capabilities can also provide insights to optimise the real-time interaction between business [72] and manufacturing processes, manufacturing schedules and the requisite supply chain activities [71].

4. Metaverse Roadmap—Industry 5.0 Human-Centric Manufacturing

In the era of Industry 5.0, factory workers will increasingly interact with automated and, more often, semi-autonomous intelligent assistance systems. The suggested evolution of Metaverse technology can be seen as summarised in Table 2 below. As shown in Figure 3, workers could interact with such intelligent manufacturing systems through AR headsets, handheld devices, gestures, body movements, and worn sensors in protective work clothing. The digital twin concept holds the potential to provide both visual abstractions of the factory and round trip closed-loop interaction between humans and intelligent machine systems (in part as envisaged by Minskey et al. [73].

Table 2. Evolution of metaverse technology.

Time	Event	Description	Authors
Early 21st century	Industry 4.0 emergence	Around the early 21st century, Industry 4.0 emerged, ushering in a new manufacturing era. This period marked the integration of cyber-physical systems, the Internet of Things (IoT), augmented reality (AR), and robotics into manufacturing processes.	[74]
Early to mid-21st century	Augmented reality (AR) adoption	AR technologies have been continuously used to train quality control workers and inspect product quality in manufacturing, reducing errors and ensuring product accuracy.	[48,57]
Ongoing	Digital twins integration	The integration of digital twin technology into manufacturing processes began and continues to evolve.	[46]
	Collaborative robots	The introduction and integration of collaborative robots, or Cobots, capable of safely working alongside humans, started and continues to enhance productivity in manufacturing.	[52]
Emerging	Extended reality (XR) adoption	Different manufacturing sectors continue to adopt extended reality (XR), including AR and VR, to enhance various aspects of their operations, such as productivity, remote assistance, maintenance, and worker training.	[48]
	Shift to Industry 5.0	The concept of Industry 5.0, which focuses on mass customisation and the integration of human intelligence, started to gain attention as the next stage in manufacturing evolution.	[75]
	IRoT and IoRT	Enhanced human and Cobot interactions through Industrial-Tactile Internet of Things (ITIoT) and Internet of Robotic Things (IoRT)	[75]
	Physiology data through worn sensors	Through clothing-mounted sensors and smart textiles, workers' health and task-related movements can be sensed and captured in real time.	[40,76,77]
	LLM and GPT technology	Real-time processing of human qualitative and generated quantitative data fed through into automated development of new product designs and production scenarios.	

Tang et al. [78] investigated using AR and mixed reality technologies in the context of a digital twin model for smart warehouse and manufacturing management purposes integrated via AI technologies; the warehouse case study presented in their work also involves local processing via edge computing and compressed machine learning algorithms written for this hardware implementation. Mann et al. [23] suggest the use of additional interaction awareness between humans and machines in their model of HI (humanistic intelligence) involving people sensing machines and machines sensing people. Romero et al. [40] proposed the Operator 4.0 typology to scope the enhanced cooperation between humans and machines in industrial settings. Focussing on cyber-physical augmentation of workers, Romero et al. [79] also envisage the Virtual Operator 4.0 subtype of the Operator 4.0 typology where a subset of metaverse technologies assist a worker in the completion of a range of tasks through virtual reality simulations and representations. To Mann et al. [23], parameters such as GPS location, temperature, and other radar (and now LIDAR) sensing can detect non-connected obstacles between humans and machines, affording feedback as additional warning stimuli to humans in the form of visual and audio and touch-based responses; in the scenario of touch, force feedback may be provided by special gloves and in the future exoskeletons [80], allowing safe human and robot interactions and increasing the possibility for robots to learn highly dexterous manual tasks to offer the human additional assistance in similar future tasks (see Figure 3 for human worker augmentation). In more recent research, Xiang et al. [75] put forward the Industrial-Tactile Internet of Things (IoT) and describe technology that allows humans to both touch and feel through the means of a remote real-time-connected robot and provide haptic movements to control the manipulation of such machinery. Xiang et al. [75] introduce the Internet of Robotic Things (IoRT), whereby high-speed wireless communication standards such as 5G and 6G allow for real-time connection to the interconnection between and control of shop floor robots along with the advanced operation of such assets through the integration of localised end node edge computing utilising AI techniques and distributed processing of data. Such innovations in human–robot collaboration auger well for the next generation of Cobots, along with the potential to integrate more complex forms of AI, such as LLM GPT models formed of training data for improved robot movements based on human movement data [75].

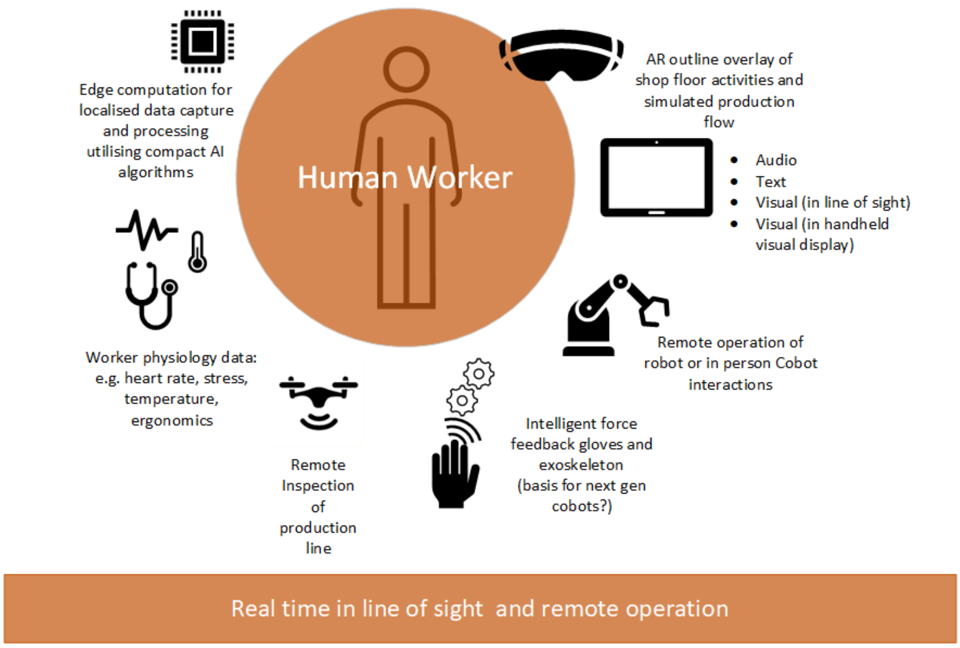

Figure 3. Augmentation of the human worker senses with Metaverse technologies for real-time round-trip interactions with intelligent manufacturing systems.

Luong et al. [38] also explore the use of innovations such as edge computing, utilising such technology to distribute the sensing and object recognition work involving visual data collected to the individual UAV platforms employed. In this way, UAV swarms can update digital twin platforms in a finer grain of detail and much nearer to real time [38].

In addition to AR visualisations, fully immersive VR has been used with factory floor simulations utilising 3D modelling tools [81,82] In Hosseini et al. [81], a complete set of shop floor systems have been simulated to provide a 3D digital twin visualisation, requiring

VR-headset-equipped users also to wear sensors that allow tracking of their motion in order to integrate their virtual avatar representation in real time within the model. Meng et al. [83] also make a case for using eye-tracking technology with headset devices and XR environments, allowing for the coordinated rendering of context and location-relevant graphical information in the wearer's line of sight.

Yao et al. [84] make the point that Metaverse environments for manufacturing will increasingly combine physical and digital worlds with social media and data retrieval systems through advanced machine learning techniques. Named wisdom manufacturing by Yao et al. [84], such a combination of social networks with digital and physical worlds is said to provide a way of utilising and integrating human knowledge into increasingly automated production systems. Yao et al. [84] also define the Metaverse as a more human-oriented interface, a complimentary system to the digital twin, and its role as an interactive technology and process-oriented platform for industrial manufacture.

Wang et al. [85] describe the four modalities of human–robot interaction (HRI) as the following:

- Vision in terms of image recognition and movement prediction.
- Auditory and language, such as natural language communication with machines.
- Physiological sensing, including human motion and vital signs detection and monitoring.
- Haptics such as robot sensing of both humans and objects and human sensing of both robots and objects.

Most often, through the use of adapted gloves, haptics can capture human movements and relay them to machines; similarly, machines may communicate tactile feedback to humans providing immersive shared environments and allowing complex remote manipulation of machines [75]. Haptic devices are predicted to evolve to provide simultaneous feedback of vibration, temperature, and the impression of force; as such, they are limited to the communication of one mode at a time only [75]. Wang et al. [75] also envisage the fusion of haptics and extended reality technology along with machine intelligence to provide the next generation of sensing Cobots for industrial and other uses, along with continuing developments in the kinematic design of haptic devices. Challenges remain with Cobot use, requiring further research in the areas of Cobot to human contact discovery and its mitigation; Cobot motion planning and control; flexible Cobot systems for completion of complex tasks [86]; and detection of non-sensor equipped objects in the real world such as "people, street furniture, and buildings" [83]. In the long term, the case could be made for brain/computer interfaces to improve the adaptation of tactile and XR environments to individual users' needs [83].

Health sensing in medical settings is now commonplace. However, the next generation of sensing technology and wearable devices/smart fabrics will allow for more flexibility and the potential for utilisation in industrial workwear solutions. Hassani et al. [76] investigated the development and use of smart materials for healthcare and, in particular, examined the potential for energy harvesting for self-sustained powering the embedded sensors without the need for batteries or other bulky power supply means. As described by Hassani et al. [76], diagnostic and health monitoring sensors are perhaps most appropriate for use in industrial workwear.

One particular limiting factor that must be overcome is the need for seamless integration between Metaverse technologies, requiring shared data descriptions that are interoperable across differing hardware platforms and software stacks [83]. Meng et al. [83] also make the point that human–computer interfaces must work in concert, even though the variety of tasks they may undertake and the functions they expose may require differing timescales, latencies, and datasets.

One particular trend to note in the future development of Metaverse technologies is the use and further development of edge computing [80], offering the possibility for localised round-trip processing of data using compact AI algorithms and partial co-located digital twin models of individual monitored objects; this trend may cut the cost of system deployment, increase response times, and may eventually reduce overall carbon emissions [87]. While a number of studies have found remote participation in meeting to be environmentally beneficial [88–90], Nleya and Velempin [91] provide a narrative arguing why Metaverse applications lead to overall reductions in carbon emissions despite the need for extensive computing power and its requisite energy needs. These authors put that the overall reduction in the need for physical meetings between team members, rapid advancement in the design process for new more sustainable products, more efficient production scheduling, and optimisation of production lines made possible through Metaverse technology means such systems lead to their selection as active agents of sustainable manufacturing [91].

Scenarios for Metaverse Technology Adoption in Manufacturing

Based on the analysis presented in the preceding sections of this paper and as shown below in Figure 4, four scenarios for Metaverse technology adoption in the manufacturing industry have been developed. This section discusses the scenarios in more detail while highlighting the potential impact they may have over the next 1–10 years regarding increasing automation and possible autonomy in manufacturing systems. In all scenarios, the human role is illustrated with the worker and customer as both knowledge providers and decision-makers, being aided rather than replaced by technology.

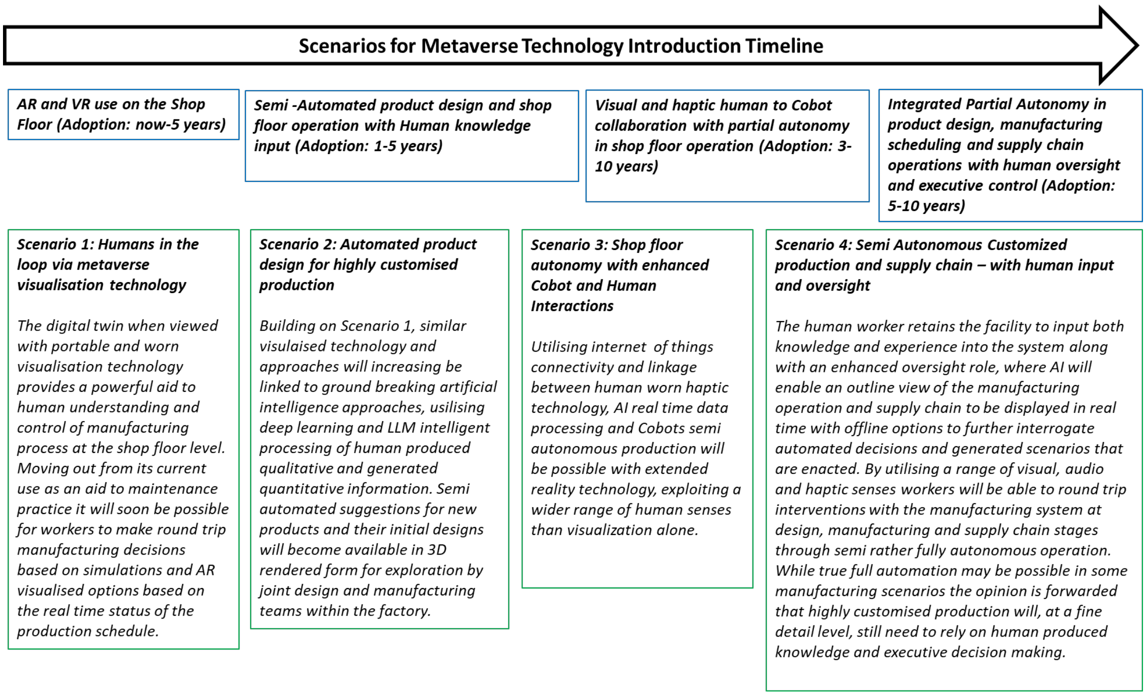

Figure 4. Scenarios for the introduction of Metaverse technology in manufacturing with suggested adoption timespans.

Scenario 1: Humans in the loop via Metaverse visualisation techniques

The need to keep humans in the decision-making loop is made by Turner et al. [92], who notes that people's decision-making capabilities and creativity inputs will be required to provide semi-autonomous systems with the necessary scope and context in developing highly customised products. In this context, the visualisation of complex manufacturing and product design solutions is paramount. AR-deployed simulations, viewable in situ on the shop floor, will allow workers to test scenarios and round-trip production level changes in real time [93]. Accessing and visualising wider digital twin implementations in mobile AR devices (such as tablet devices where graphics are overlaid on real world camera views) and VR static deployment situations (or safer VR Cave or restricted space type viewing situations, where virtual reality images are projected onto 180° or almost 360° curved screens) may eventually provide enterprise levels of control to various human job roles.

Scenario 2: Automated product design for highly customised production

The use of Metaverse technology for product design and development and managing projects with distributed team members is now becoming a reality for some organisations. Koohang et al. [65] focused their case study on the application of technology in product design and prototyping within the manufacturing industry. This investigation highlighted how the Metaverse can create prototypes, conduct simulations, and streamline the product development lifecycle. By leveraging this technology, manufacturers can significantly reduce both time and financial investments typically associated with prototyping using technologies such as virtual reality, augmented reality, digital twins, and data-connected simulation models. Prominent manufacturers, like Airbus and Boeing, have already embraced this approach and are utilising these technologies to accelerate their product development cycles while fostering a culture of innovation [65]. In a relatively early study, Owens et al. [70] explored the integration of Metaverse technology in the virtual management of projects within the manufacturing sector. The results revealed that Metaverse technologies such as virtual meeting spaces, digital avatars, 3D modelling, and simulations promoted role clarity, shared understanding, and seamless coordination among team members. At the retailing interface, Zhang et al. [19] have found that for a Chinese automotive manufacturer, the inclusion of social interactions was important for customer involvement and also a beneficial source of data for design teams. In future steps, Metaverse technology will increasingly be linked to ground-breaking artificial intelligence approaches, utilising deep learning and LLM intelligent processing of human-produced qualitative and generated quantitative information. Generated suggestions for new products and their initial designs will become available in 3D-rendered form for exploration by joint design and manufacturing teams within the factory. Nasrabadi et al. [94] provide a narrative and review on the use of "user-generated content" in the new product development process, finding that product designers can benefit from to access to both positive and negative consumer reactions at an early stage.

Scenario 3: Shop floor autonomy with enhanced Cobot and human interactions

Utilising the Internet of Things connectivity and linkage between human-worn haptic technology, AI real-time data processing, and Cobots, semi-autonomous production will be possible with extended reality technology, exploiting a wider range of human senses than visualisation alone. In effect, the IoT definition of Xiang et al. [75] may be widened, as suggested by the Internet of Robotic Things (IoRT) and the Tactile Internet of Things, utilising wireless communication standards such as 5G and 6G to allow real-time interconnection between and control of shop floor robots along with the advanced operation of such assets through the integration of localised end node edge computing utilising AI techniques and distributed processing of data. Along with the use of LLM and GPT models for Cobot training data [75], human workers will benefit from either exoskeletons or worn sensors, which will relay and exchange Cobot and human movements so that coordinated tasks may be completed with the human in control and able to "sense" and successfully guide Cobots where absolutely necessary. Visualisation technology such as AR will also be able to relay Cobot activity to the worker and suggest task completion strategies in graphical form. When a Cobot/robot is operated remotely, the AR representation may also show their presence in situ when the user is in a dedicated VR room set up or on the shop floor of another industrial facility, where perhaps a similar robot may be situated in the future development of that factory; the remote operation of a robot may also be considered as a "live" component of a wider simulation model. Xie et al. [16] have investigated mixed reality technology and its use in the robot-assisted manufacture of gearbox assemblies, finding that human worker/machine interaction and worker perceptiveness of their immediate surroundings improved and led to improved performance in the completion of manufacturing processes. In the quest for improved human machine interactivity, the work of Pang et al. [95] is pertinent in that they explored and categorised human vision and cognition in the context of manufacturing assembly processes, finding which mixed reality systems offer the best initiative interface for shop floor "human in the loop" activities.

Scenario 4: Semi-autonomous customised production and supply chain—with human input and oversight

In a recent case study by Fu et al. [96], options for integrating Metaverse technology into manufacturing operations were explored. The ability of customers to explore products and select options in their design is a facility valued by purchasers, according to the research of Fu et al. [96]. Companies such as Gucci and Zara have already incorporated elements of the Metaverse into their customer experiences, allowing fashion enthusiasts to explore features like a wardrobe and a digital realm called Zepeto, an augmented reality application [97]. Increasingly, customers can design their custom products through Metaverse interfaces provided initially in store and eventually through their own portable devices. This will provide LLM applications with a wealth of information and data beyond what is available from social media trawls and other data repositories.

Utilising a range of visual, audio, and haptic senses, factory workers can round-trip interventions with the manufacturing system at the design, manufacturing, and supply chain stages through semi-autonomous operations. While true full automation may be possible in some manufacturing scenarios, the opinion is forwarded that highly customised production will, at an acceptable detail level, still need to rely on human-produced knowledge and executive decision making.

The field of supply chain management in manufacturing has also witnessed the impact of Metaverse technology [31]. Multinationals such as General Electric (GE) have recognised the potential of the Metaverse in creating a robust supply chain. Companies can gain real-time insights, track product movements, and minimise errors by creating digital twins of their supply chains within secure Metaverse environments [31]. Soon, AI will enable an outline view of the manufacturing operation and supply chain to be displayed in real time with offline options to interrogate further automated decisions and generated scenarios that are enacted.

5. Discussion

This research clearly shows that the use of Metaverse technology in manufacturing has evolved significantly. Industry 4.0 and subsequent Industry 5.0 developments led to the integration of cyber-physical systems, the Internet of Things, augmented reality, and robotics. These innovations have streamlined manufacturing processes, created new job opportunities, and improved worker training.

From the systematic review findings, manufacturing industries adopting the evolutions in Metaverse technology have been limited by several barriers, broadly categorised into technical, technological, organisational, environmental, business, and non-technical. These challenges are rooted in the literature. Notable works that provide corroborating evidence are Park and Kim [53], Allam et al. [32], and Rachmadtullah et al. (2023) in particular. Specific challenges identified were accuracy, latency issues, registration barriers, external pressure, cultural barriers, management limitations, traditional manufacturing processes, lack of required technology training/skills, high investment and development costs, high maintenance costs, fear of job security, inadequate power supply to run the technologies (especially in developing countries), and unwillingness to change from "traditional ways of doing things", among other barriers. Rachmadtullah et al. [56] report a recognised shortage of workers and a need for training. This was also supported by the work of Park and Kim [53]. Allam et al. [32] also discussed challenges that can provide insights into the barriers faced when implementing Metaverse technology in their study. These challenges encompass environmental, economic, and social dimensions, allowing organisations to anticipate and address potential barriers during implementation. For X. Wang et al. [30] and Yang et al. [55], a significant barrier to adoption lies in dealing with complexities associated with integrating technologies and data sources; it is argued by these authors that manufacturers must prioritise data exchange and interoperability among systems and platforms to harness the full potential of Metaverse technologies. This entails establishing standards and protocols that facilitate the integration of technologies and data formats [55]. The findings of this paper's research on barriers to adoption deviates from the focus of studies such as [54], providing a wider range of perspectives on the emerging opportunities and challenges posed by the Metaverse.

The systematic review showed that the major impact areas of Metaverse technologies have been in product design [65], quality control [30], maintenance and repair [48], warehouse management [71], and assembly [66]. The meta-analysis shows a significant positive impact of Metaverse technology in manufacturing.

In answering the first research question posed by this study, it is clear that a range of companies are already benefitting from the use of Metaverse technology to enhance activities such as customer product experience and customisation through option selection; visualisation of maintenance processes and "on the job" training; interaction with digitally delivered MES and other enterprise software; and simulation of new product designs and factory layouts. Several barriers to the implementation of Metaverse technologies in manufacturing have been identified and categorised into technical, technological, organisational, environmental, business, and non-technical challenges. Key challenges include accuracy, latency, registration, cultural barriers, management limitations, and reluctance to depart from traditional practices. For the third research question, it is clear that innovations such as LLM and GPT will help inform new semi-autonomous manufacturing systems, and a new level of sensing-based interactivity will aid works to work with robotic implementations in terms of productivity and safety. At all times, humans will be aided in the completion of intricate physical production tasks and the understanding of complex multi-format data and information resources. The automated decisions and their implications will be explained to workers, with the final executive decision still in the hands of humans.

One prominent theme from this research is the versatility of Metaverse technology in manufacturing. Its application was observed across a spectrum of manufacturing areas including production flow; VR training; plant assembly; quality control; virtual training; assembly tasks; fault detection; VR assembly; monitoring and facility inspection; and assembly task support. Applications in each of the aforementioned areas demonstrate varying degrees of impact, reflecting the adaptability of Metaverse technology. This resonates with the systematic review's findings and is also supported in extant literature, for example, the works of Ren et al. [66], X. Wang et al. [30], and Koohang et al. [65].

While the meta-analysis did not aim to establish causality, deductive trends from the reviewed works offer valuable insights. It was observed that Metaverse technology's impact tends to be more substantial in areas such as production flow, assembly tasks, VR assembly, and fault detection. These areas witnessed effect sizes (d) at the higher end of the spectrum, indicating a pronounced positive influence. In contrast, quality control and monitoring and facility inspection exhibited relatively lower effect sizes.

Several factors contribute to the observed impact of Metaverse technology in manufacturing. Firstly, advancements in augmented and virtual reality have enhanced the immersive capabilities of these technologies, enabling better training, assembly guidance, and fault detection. Secondly, integrating Metaverse technology with Industry 4.0-related processes [74] has paved the way for more streamlined and efficient production workflows. Additionally, collaborative features within Metaverse applications [7,25,27,30] have improved teamwork and knowledge sharing among manufacturing personnel [43].

From the analysis presented in this paper, the following three major research directions are evident:

1. Use of the Metaverse to actively involve customers and suppliers in the new product development (NPD) process
2. Further development of data transfer protocols and IoT connectivity utilising 5G and emerging 6G standards to combat latency issues in certain Metaverse hardware.
3. Development of new interactive graphical visualisation metaphors for use in Metaverse technologies and research into human cognitive reasoning and duplication of human senses for use in conjunction with collaborative robotics.
4. Training and familiarisation of workers with metaverse technology.

LLM and GPT integration with explainable AI (XAI) are likely to be a future research target to justify the solutions and answers provided by generative AI solutions and mitigate the propensity to provide "hallucinations" based on artificially produced "data". In providing generated scenarios in Metaverse applications such as product concept and design options, the ability to justify a design based on sound data and judgement becomes paramount, especially when envisaging the use of semi-autonomous product customisation, design, and production systems of the medium-to-long term future [98].

In summary, revisiting Yao et al. [84], the Metaverse may well be the human-in-the-loop enabler that allows not just knowledge sharing with artificial systems but also enhanced real-time decision making by human operators and managers of production systems.

6. Conclusions

The practical implications of understanding the evolution path of Metaverse technology in manufacturing are significant. Manufacturers can leverage this knowledge to stay competitive and adapt to the changing landscape. By embracing Industry 4.0 and 5.0 human-in-the-loop advancements, they can sustainably streamline processes, reduce production costs, enhance product quality, and understand and reduce carbon outputs. Understanding the role of Metaverse technology allows manufacturers to invest wisely in systems that align with their specific needs. Additionally, the evolution of the Metaverse offers opportunities for upskilling the workforce through immersive training experiences, thereby increasing overall efficiency.

Recognising the barriers to Metaverse technology adoption is crucial for manufacturers seeking to implement these innovations. Addressing technical challenges like accuracy and latency issues can lead to smoother integration. Overcoming organisational and cultural barriers requires a strategic approach that involves both employee training and change management.

The implications of the findings are substantial and multi-faceted. Manufacturing organisations should consider incorporating Metaverse technology into their operations to harness its transformative potential. However, the varying impact observed across manufacturing areas calls for a strategic approach. For instance, organisations aiming to optimise production flows or enhance assembly tasks should prioritise adopting Metaverse technology. Meanwhile, those focused on quality control or facility inspection may need to explore complementary technologies or strategies. Furthermore, the findings highlight the need for tailored implementation strategies. Not all manufacturing contexts will experience the same degree of impact. Factors such as the complexity of processes, workforce readiness, and Metaverse technology infrastructure availability should inform implementation decisions.

Several limitations are associated with this study. This paper's focus on published research may result in publication bias, as studies with negative or inconclusive findings might not be as widely available. Some industry literature and white papers may have been omitted. While efforts were made to categorise studies by their impact areas, the differing application and utilisation of methodologies, frameworks, and technologies within studied industry sectors may introduce variability in the analysis and interpretation of findings.

Future research will focus on emerging Metaverse technologies and their potential impact on manufacturing processes. This would provide insights into how newer innovations, such as advanced augmented and virtual reality systems along with generative technologies, may further transform manufacturing and the role of the "human in the loop". While this study focused on manufacturing, conducting cross-industry comparative studies could also be valuable. Comparing the adoption and impact of Metaverse technologies in manufacturing with other sectors such as healthcare, education, and entertainment will yield further innovation and insights into the unique challenges and opportunities within manufacturing.

Author Contributions: Conceptualization, V.E., W.G. and C.J.T.; Writing—original draft, V.E.; Writing—review & editing, W.G. and C.J.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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