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Review

Industrial Metaverse: A Comprehensive Review, Environmental Impact, and Challenges

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Abstract: The Industrial Metaverse paradigm can be broadly described as a virtual environment that integrates various technologies such as augmented reality and mixed reality to enhance business operations and processes. It aims to streamline workflows, reduce error rates, improve efficiency, and provide a more engaging experience for employees. The promise of the Industrial Metaverse to drive sustainability and resource efficiency is compelling. Using advanced technologies such as the Industrial Metaverse is vital in an endeavor to have a competitive edge in a rapidly evolving business environment. However, the environmental impact of the technologies underpinning the Industrial Metaverse, like data centers and network infrastructure, should not be overlooked. The ecological footprint of these technologies must be considered in the sustainability equation. Researchers have warned that, by 2025, without sustainable artificial intelligence (AI) practices, AI will consume more energy than the human workforce, significantly offsetting zero carbon gains. As the Metaverse persists in evolving and gaining momentum, it will be necessary for companies to prioritize sustainability and explore new ways to balance technological advancements with environmental stewardship. However, recent studies have conjectured that the Metaverse holds the potential to reduce carbon emissions, as digital replacements for physical goods become more prevalent and physical activities like mobility and construction are reduced. Moreover, the specific extent to which this substitution can alleviate environmental concerns remains an open issue, presenting a knowledge gap in understanding the real-world impact of digital replacements. Thus, the objective of this paper is to provide a comprehensive review of the Industrial Metaverse, as well as explore the environmental impact of the Industrial Metaverse. The integrative literature review design and methodological approach involved multiple sources from the Web of Science and databases such as the ACM library, IEEE Library, and Google Scholar, which were analyzed to provide a comprehensive understanding of the developments in the Industrial Metaverse. Firstly, by considering the Industrial Metaverse's architecture, we elucidate the Industrial Metaverse concept and the associated enabling technologies. Secondly, we performed an exploration through a discussion of the prevalent use cases and the deployment of the emerging Industrial Metaverse. Thirdly, we explored the impact of the Industrial Metaverse on the environment. Lastly, we address novel security and privacy risks, as well as upcoming research challenges, keeping in mind that the Industrial Metaverse is based on a strong data fabric. The results point to the Industrial Metaverse as having both positive and negative environmental effects in terms of energy consumption, e-waste, and pollution. Research, however, indicates that most Industrial Metaverse applications have a positive environmental impact and subsequently trend toward sustainability. Finally, for sustainability in the Industrial Metaverse, enterprises may consider utilizing renewable energy sources and cloud services. Furthermore, we examined the effects of products on the environment, as well as in the creation of a circular economy.

Keywords: industrial; Metaverse; digital twin; deployment; security; environmental impact

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Citation: Nleya, S.M.; Velempini, M. Industrial Metaverse: A Comprehensive Review, Environmental Impact, and Challenges. *Appl. Sci.* **2024**, *14*, 5736. https://doi.org/10.3390/app14135736

Academic Editors: Juan A. Gómez-Pulido and Rui Araújo

Received: 14 February 2024
Revised: 27 March 2024
Accepted: 26 June 2024
Published: 1 July 2024

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1. Introduction

Increasingly, the Metaverse paradigm is being hailed as the next big thing in the history of the Internet. The Metaverse is a collaborative, social, and immersive environment

that blends both the physical and virtual realms to the point that data exchange and interactions become fluid and affect each other [1]. The growing Metaverse paradigm is divided into three distinct industries, including the Consumer Metaverse (CM) for leisure and retail, the Industrial Metaverse (IM), which blends the physical and digital worlds, and the Enterprise Metaverse (EM) for virtual workspaces and office collaboration [2]. One practical application of the IM can be the manufacturing industry [3].

The IM is the application and development of the Metaverse in the industrial field, encompassing the entire process of industrial product development, production, service, and application [4]. According to [5], the IM is an important application area within the Metaverse. It is a new industrial system, economy, and model serving the industrial economy based on core infrastructure and the application concepts of the Metaverse. The IM can achieve holographic display and cross-time–space aggregation of all factors, value chains, and industry chains in virtual worlds. It also incorporates new social and economic models. Through means such as human–machine interaction and digital identities, it collaboratively carries out industrial production and business activities to promote industrial transformation—upgrading and innovative development.

The IM is characterized in [6] as persistent, real time, economic, interoperable, featuring co-creation and -construction, and purposeful. The ability to create lasting, digital representations linked to elements of the real world is what distinguishes the IM [7]. In [8], the IM is portrayed as a persistent 3D platform that is used throughout a value chain, an organization, and the life cycle of a product. It functions as a digital representation of the whole organization in its operational setting. It combines users, machines, materials, and processes in a bidirectional flow between the physical and virtual worlds because of its combinatory nature. The IM is also characterized as real time, which means it is synchronized at any time and kept in real time, which allows everyone to participate in the experiences in real time. Furthermore, the IM has the feature of a fully functional economy, meaning both individuals and enterprises can create, own, and invest in digital assets and work or invest in the IM, and users will obtain the expected income and value. Another characteristic of the IM is that of interoperability, depicting unprecedented interconnection characteristics, including information interoperability, data interoperability, and value interoperability.

There is no data island in the IM. An isolated system is like a closed country, which gradually falls behind and loses its status and eventually cannot exist in the IM. Furthermore, co-creation and co-construction is a feature that allows members to collaboratively create the applications and content of the IM platform, sharing in the rewards in the end. Finally, the IM can also be characterized as purposeful, as it promotes the efficient development of the real industry, and is committed to building a brand-new production and service system that encompasses the whole value chain and industrial chain. The IM has enormous potential to change many different industries. This technology is transforming the way enterprise's operate, from fostering better teamwork and communication in industrial settings to opening up new avenues for training and simulation [9].

1.1. Motivation

According to [10], the IM will provide an Industry 5.0 vision that goes beyond productivity and efficiency as one of the objectives, reaffirming the industry's position in society and enabling human-centered, human-resilient, sustainable, and intelligent solutions to meet experience-driven individual requirements. The promise of the IM to drive sustainability and resource efficiency is compelling. Using advanced technologies like the IM is imperative to maintain competitiveness in the fast-changing economic environment. However, the environmental impact of the technologies underpinning the IM, like data centers and network infrastructure, should not be overlooked. The ecological footprint of these technologies must be considered in the sustainability equation. The report in [11] warns that, if sustainable AI practices are not adopted, by 2025, AI will consume more energy than human labor, thus negating the benefits of achieving the zero carbon objective. As the

Metaverse continues to evolve and gain momentum, it will be necessary for companies to prioritize sustainability and explore new ways to balance technological advancements with environmental stewardship. Thus, as the IM persists in evolving and gaining momentum, it will be necessary for companies to prioritize sustainability and explore new ways to balance technological advancements with environmental stewardship. However, according to recent studies [12], the IM may be able to lower carbon emissions if physical activities like construction and mobility are reduced and digital commodities substitute physical items more frequently. Nonetheless, there is still a lack of research on the precise degree to which this substitution might address environmental concerns, creating a knowledge vacuum about the practical effects of digital substitutes. The objective of this paper is to explore the environmental impact of the IM. To achieve this objective, the methodological approach leveraged an integrative literature review design where multiple sources from the Web of Science and databases such as the ACM library, IEEE Library, and Google Scholar, which were analyzed to provide a comprehensive understanding of the developments in the IM.

1.2. Our Contributions

We give a thorough analysis of the IM and, subsequently, investigate its environmental effects. More specifically, by discussing the numerous issues about the IM, our review offers insights for readers to comprehend the impact of the IM on the environment. To this end, the contributions of this review are four-fold and are summarized as follows:

- Considering the IM architecture, we examined the IM concept and the numerous enabling technologies used to build and experience the IM.
- We explored new and upcoming prevalent use cases of the IM and deployments.
- We explored the impact of the technologies underpinning the IM such as data centers and network infrastructure on the environment.
- We address novel privacy and security risks, as well as outline open research challenges while considering that the IM is based on a strong data fabric.

1.3. Paper Organization

Figure 1 depicts the sections of this review paper, which is structured as follows: Firstly, in Section 2, a concise synopsis of the methodological approach is provided with an emphasis on the scholarly databases that were used, and how the literature was selected and processed. This is followed by an overview of the IM architecture, the roadmap, and the associated driving technologies in Section 3. Prevalent use cases and deployments by enterprises are discussed in Section 4. The IM impact on the environment is discussed in Section 5, focusing on the implications of the deployments of the IM by enterprises. The IM is based on a strong data fabric, and this gives rise to security and privacy issues, which are discussed in Section 6. Future research challenges on the full implementation of the IM are also outlined in Section 7. Finally, the paper is concluded in Section 8.

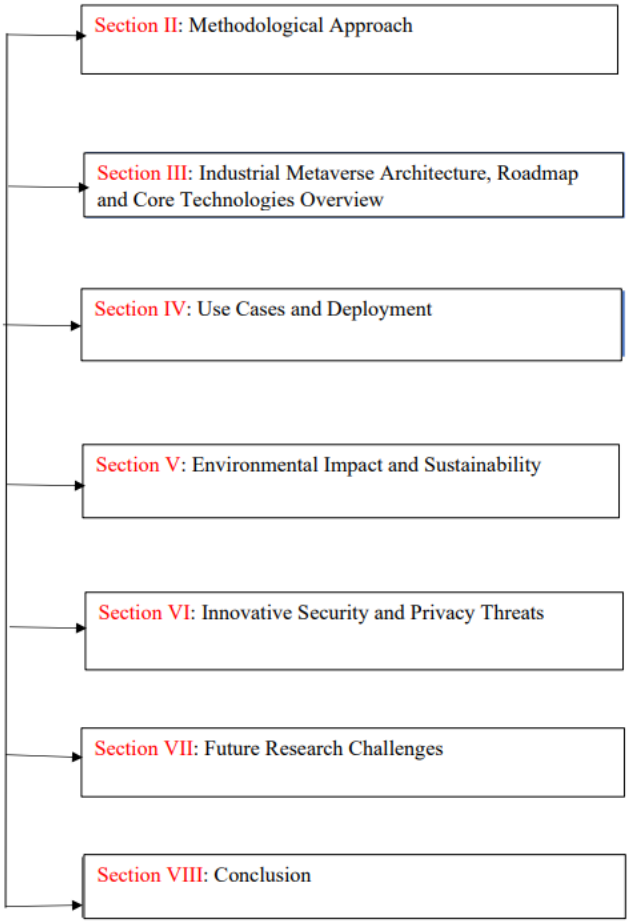


Figure 1. Organization of the structure of this paper.

2. Methodological Approach

The approach utilized in this paper is the integrative literature review [13,14]. This approach synthesizes studies already published on a specific subject to gain a greater understanding of a given subject. Contextually, we strove to achieve an understanding of the IM's development and its impact on the environment. Specifically, this review approach was accomplished in five stages, as depicted in Figure 2. It explains how we selected the articles for our evaluation of the IM, its role, applications, implementation, environmental impact, and challenges.

In the first stage, the problem was identified through the guiding question, "How does the IM paradigm impact the environment?" Our systematic approach involved an extensive literature search including, but not limited to the Web of Science, IEEE Explore, ACM Digital Library, ScienceDirect, Springer Nature, and Google Scholar. These databases are renowned for their provision and coverage of quality academic publications on the IM. The first set of search terms was constructed to yield a wide selection of pertinent publications concerning the problems and uses of the IM. The key search terms we employed included "IM", "Digital twins", "deployment and IM", "security", "Environmental impact and IM", and "challenges of IM" and their variations. To retrieve relevant literature, we made sure that our search included relevant terms. Our preliminary searches yielded a sizable number of articles—about 88 across the various databases. Thereafter, a methodical screening procedure was applied to these publications to remove any duplicate or unnecessary articles. Articles published during the years of 2021 and 2023 met our criteria. These articles, as is customary, concentrated on explaining the IM paradigm in terms of developing technology. The papers also provide an overview of the technology that makes up the IM. There were also additional papers with an emphasis on the implementation challenges and IM use cases. The papers that address the IM's impact on the environment in addition to implementation

were also included. A few publications that go on to discuss the technical and security issues in more detail were also included. Eligible publications ($N = 80$) were examined for definitions, conceptual aspects, technical aspects, implementation, and concerns about the IM during the data analysis stage. Additionally, an analysis of these publications was conducted to determine how the IM affects the environment. The last step that led to the development of this article is the presentation of the results, which concisely and clearly lays out the integrative review together with all the detailed phases, findings, and recommendations.

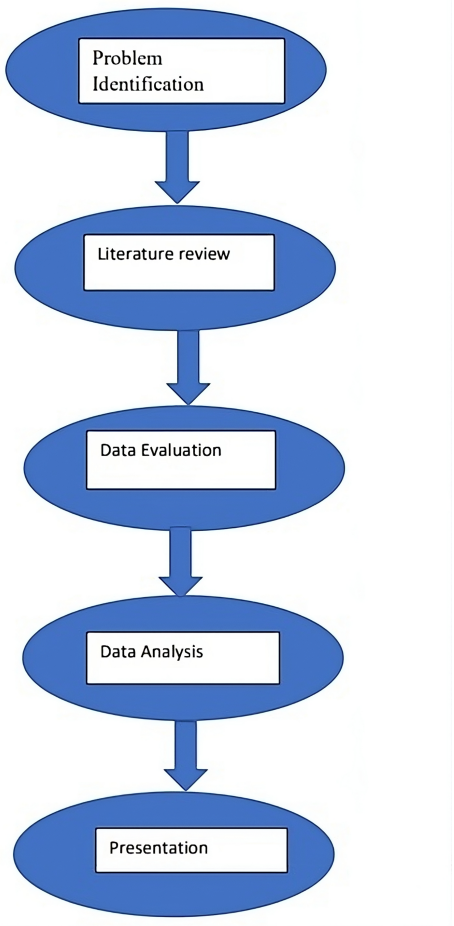


Figure 2. Research design.

3. Industrial Metaverse's Architecture, Roadmap, and Core Technologies Overview

Figure 3 shows the three layers of the IM architecture, which are the infrastructure, core, and application layers [15]. The infrastructure layer underpins the Industrial Internet of Things (IIoT) and guarantees that the IM functions normally. Among the important technologies stored in the core layer are artificial intelligence, blockchain (BC), cloud computing, digital twins, virtualization of industrial production scenarios, modeling and simulation of industrial scenarios, data-driven technologies, and Metaverse engines. Product experience and marketing, operational decision-making centers, safety education and training, improved risk visibility and reminders, and quick and flexible equipment maintenance are all part of the application layer.

The IM is primarily driven by the key technologies depicted in Figure 4. The key technologies of the IIoT, AI, BC, mixed reality (AR/VR), cloud computing, edge computing, digital twins (DTs), and 3D printing and scanning are powering the IM.

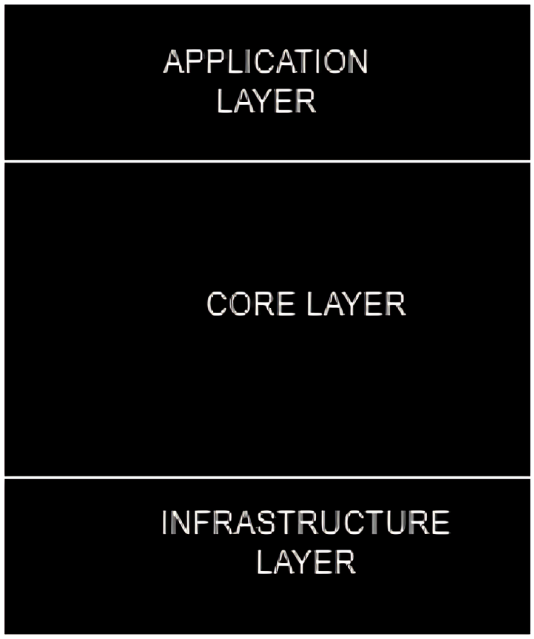


Figure 3. IM's architecture [15].

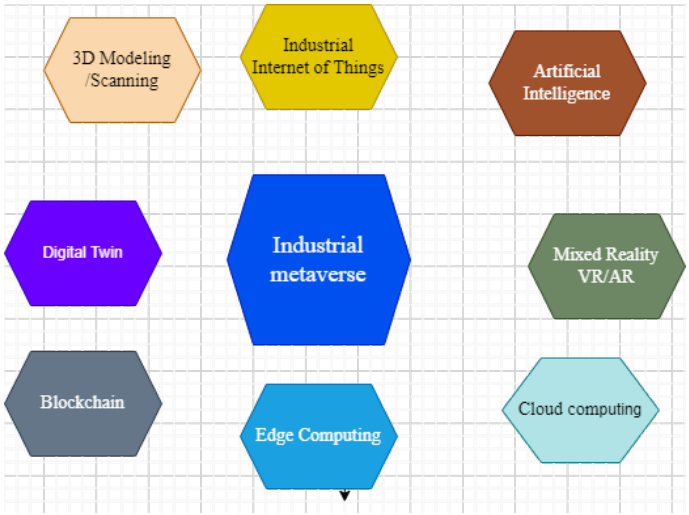


Figure 4. IM's driving technologies.

3.1. Industrial Internet of Things

By automating smart things to sense, gather, process, and communicate real-time events in industrial systems, the IIoT serves as a new paradigm for the IoT in the industrial sector. Formally, this paradigm is described as a system of highly integrated, intelligent industrial components that are used to monitor and control industrial processes, assets, and operating time in real time, thereby achieving a high production rate with lower operational costs [16]. The main objective of the IIoT is to achieve high operational efficiency, increased productivity, and better management of industrial assets and processes through machine health, intelligent monitoring applications for production floor shops, product customization, and predictive and preventive maintenance of industrial equipment [17]. The infrastructure layer, core layer, and application layer are the three levels that make up the IIoT's architecture [15]. The IIoT is applied in various domains [18] ranging from robotics technology, healthcare, emergency response systems, solar-assisted systems, smart grids, disaster management, construction, agriculture, and the automotive sector.

3.2. Artificial Intelligence

For the Metaverse to function based on the creator's principles, AI is a necessary technology [16]. AI has shown how crucial massive data processing is to improving immersion and enabling virtual agents to have an intellect comparable to that of humans [19]. With key functions including content production, security, personalization, maintaining digital identities, immersion, real-time translation, and intelligent Non-Player Characters (NPC), AI has become a crucial element of the Metaverse. AI can assist in the creation of 3D models, textures, and animations, among other types of content for the Metaverse. By automating the process of building and constructing virtual worlds, AI-powered solutions can cut down on the time and expense needed to create content:

- Security: The Metaverse presents a number of security risks, including fraud, identity theft, and cyberattacks. AI can monitor user behavior and identify any questionable activities, such as identity theft or malevolent actions.
- Personalization: AI systems are capable of analyzing user data to provide each user with a customized experience. An AI system, for instance, can be trained to learn user preferences for virtual apparel, virtual accessories, and virtual activities and then provide tailor-made suggestions.
- Creating and managing digital entities: AI is utilized in the Metaverse to generate and manage diverse digital creatures, including chatbots, virtual assistants, and NPCs. These entities can interact with users, offering tailored experiences according to their tastes and actions.
- Immersion: Since AI makes realistic physics, lighting, and sound effects possible, it can aid in the creation of more immersive virtual environments. AI systems, for instance, can mimic the behavior of fire, water, and other natural elements, adding realism to the virtual world.
- Real-time translation: AI has the potential to facilitate real-time language translation in the Metaverse, facilitating international collaboration and communication. This could result in the ability of AI to translate spoken languages in the Metaverse in real time, facilitating international collaboration and communication. This has the potential for the establishment of an entirely worldwide virtual community.
- Intelligent NPCs: NPCs are virtual characters that can communicate with players in the virtual world and are managed by the AI of the game. AI algorithms can make it possible for NPCs to comprehend common language and respond appropriately, adding realism and interest to interactions [20].

3.3. Cross, Virtual, Augmented, and Mixed Reality

The term "extended reality" (XR) refers to a group of immersive technologies, such as electronic and digital environments with projected and represented data. XR integrates virtual reality (VR), mixed reality (MR), and augmented reality (AR) [21]. Virtual reality (VR) is a computer-generated environment that simulates real-world sights and objects, giving the users the impression that they are fully immersed in their surroundings [22]. With VR headsets or other VR devices like the Oculus Quest 2 and HP Reverb, it takes the user experience to the next level. In a realistic setting, the user uses a system to control the simulated environment, making it a self-controlled environment. Thus, sensors, displays, and other characteristics like motion and movement tracking are used in VR to improve a virtual world. VR has wide applications in areas such as military, education, healthcare, entertainment, fashion, heritage, business, engineering, sport, media, visualization, construction, film, and telecommunications. The hardware used for VR includes input devices of numerous categories [23]. Three subcategories focusing on input provision for Head-Mounted Displays (HMDs) exist. Controllers are the main input category, while the second category consists of navigation devices, which allow the user to have a more intuitive moving experience. Navigation devices function as an input source for navigating through a virtual world while giving the users the impression that they are moving through infinite spaces. Body-tracking devices fall into the third group. In this case, posture-estimation tech-

niques take into account both the users' hand gestures and the real posture of their upper or lower body. AR is a cutting-edge technology coupled with 3D technology features, which add a contextual layer of information to the user's sensory experience of the real world. In terms of functionality, an AR-enabled gadget with a camera—such as smart glasses, tablets, or smartphones—parses a video feed in order to recognize a tangible object in the user's surroundings, like a piece of equipment or a warehouse's layout. The link between the physical and virtual worlds is created by a digital twin, which is a 3D digital version of the object stored in the cloud. After that, it gathers data from both digital and physical items. Next, data about the object are downloaded from the cloud via the augmented reality gadget. Using markers or trackers like GPS, accelerometers, orientation, and barometer sensors, it overlays digital data on the object. A hybrid digital and real-world 3D interface is generated as a result. Because products are streaming real-time data to the cloud, users may move about and utilize gestures, voice commands, or touchscreens to interact with objects and environments [24]. MR is a term referring to a live direct or indirect view of a physical, real-world environment whose elements are augmented by computer-generated sensory input, such as sound, graphics, labels, or 3D (animated) models. It creates a new habitat where physical and 3D digital things co-exist and interact in real time by fusing the real and virtual worlds. Unlike VR, MR does not take users out of their natural surroundings. With a different kind of headset (one that does not block the outside world), the generated virtual scenes adapt to the users' actual views and alter them based on where they are [25]. Digital visuals superimposed on top of the real world can be altered thanks to mixed reality (MR). One project that integrates MR at the moment is Microsoft HoloLens2. By incorporating sophisticated tracking techniques, MR makes use of AR tools to continuously track the user's actual views, position, and mobility. MR offers numerous advantages in a number of fields, including engineering, healthcare, entertainment, and education. In the field of education, MR gives students the opportunity to fully engage in a learning environment with interactive 3D simulations and projections, allowing them to comprehend the ideas and systems they are studying on a deeper level. Finally, AR, VR, MR, and everything in between are all included under the umbrella term of extended reality (XR). It establishes a new reality in which the digital and physical realms are combined on various levels to provide improved user experiences and substantial business prospects. It is anticipated that XR will be a major 6G driver [26]. In the future, several wireless XR applications related to industry, education, gaming, and social networking will emerge, advancing the underlying communication infrastructure and technologies.

3.4. Cloud Computing

Although it is still in its early stages, the cloud computing paradigm enables users to access computer resources over the Internet [27]. Cloud computing and cloud storage are combined to provide the services required for the Metaverse. The Metaverse deployer will send all necessary data to cloud storage so that cloud computing services can access it. After that, a specialized cloud computing service will host and provide all the services required for the Metaverse to function flawlessly. The increased computational requirements will also make it challenging for cloud computing to centralize and store all pertinent material. Edge computing allows mobile devices with limited capabilities to assign their work to edge servers for processing by moving cloud computing to the edge of networks [28]. As a result, it will be necessary to disperse and relocate this type of data closer to the point of consumption. By positioning edge devices in remote areas at the network's edge and closer to users, edge computing and IoT devices can cooperate to guarantee that users receive the necessary data instantly without delay [29]. In light of this, prospective advancements and trends that might influence the direction of cloud computing and the Metaverse are enumerated as follows:

- Growing usage of cloud computing and the Metaverse across a range of industries: The Metaverse has the potential to significantly impact numerous industries ranging from retail, gaming, entertainment, and healthcare to education. In order to provide

the infrastructure required to enable these virtual experiences, cloud computing will be crucial. Thus, in the upcoming years, we should anticipate seeing a rise in the use of cloud computing and the Metaverse in these sectors.

- VR/AR technology developments: The Metaverse relies heavily on VR/AR technology, and as this field continues to progress, more lifelike and immersive digital experiences should be possible. As a consequence of these developments, a stable and expandable cloud infrastructure will be necessary to meet the demanding computational needs of VR and AR.
- The expansion of the creative economy: It is possible that the Metaverse will present chances for artists to make money off of their abilities. In order to give content creators the infrastructure they need to produce and market their work globally, cloud computing will be crucial.
- Improved remote collaboration and work: It is anticipated that cloud computing and the Metaverse would enhance distant collaboration and work, making it possible for teams to operate together in virtual settings with ease. This could result in a workforce that is more adaptable and effective, as well as more productive.
- Privacy and ethical issues: Data privacy, ownership, and security are only a few of the ethical and privacy issues brought up by the usage of cloud computing and the Metaverse. It will be crucial to address these issues as the Metaverse and cloud computing develop in order to guarantee that they are used in an ethical and responsible manner.

3.5. Edge-Computing

There has been a rise in the popularity of the edge computing paradigm among academics and professionals. Through its ability to connect cloud computing facilities and services to end users, it serves as a facilitator for several emerging technologies, including the IoT, AR, and Vehicle-to-Vehicle (V2V) Communications. Edge computing can be thought of as an accessible platform close to the edge of the network or the data source. In order to meet user needs ranging from low-latency real-time applications to application optimization and much more, it provides networking, storage, compute, and edge intelligence [30]. With its decentralized architecture, edge computing is a cloud computing extension that offers benefits including reduced costs, lower bandwidth requirements, and lower processing power consumption. Edge computing is characterized in [31,32] by a dense geographical distribution, mobility support, location awareness, proximity, and low latency. A computational resource black hole exists in the Metaverse. The IM will, thus, require higher computational capacity, and mobile users accessing the Metaverse will require considerably minimal latency to deliver real-time, advanced computational capabilities like AR/VR and speech recognition. In the Metaverse, edge computing contributes to low latency, high efficiency, as well as security. The introduction of edge computing in the Metaverse results in fog computing [33]. Given the similarities of the edge computing and fog computing paradigms, computational abilities are provisioned both in the local networks and the cloud, subsequently cutting down on the latency of and load on backbone networks.

3.6. Blockchain

A blockchain is essentially a public ledger wherein all committed transitions are stored in a chain of blocks. Creating a blockchain platform that is user-friendly, scalable, and safe is the Metaverse's objective. The blockchain-based methods range from data collection, data sharing, data storage, and data interoperability to protection of data privacy [34]. Sensitive data, which might include biometrics and bank or credit card information, are gathered during the data-acquisition process. This process can be leveraged by training algorithms exemplified by decision management, product creation, marketing, and recommendation systems. The Metaverse requires enormous data storage, meaning that a new block is generated for each transaction, making the Metaverse's storage unchangeable. The use of BC technology leads to many blocks that contribute to data distribution, which improves

data accessibility for applications such as Metaverse life support. Data sharing facilitates data exchange within the Metaverse. User-specific personalized systems will be developed using the data gathered by AR/VR and IoT devices in the Metaverse. In addition, many application sets, including healthcare and finance, will be able to interact and share data within the Metaverse. The ability to effectively regulate interactions between virtual worlds is a prerequisite for the Metaverse's interoperability. Two facets of the blockchain's privacy protection are content secrecy and user anonymity. The blockchain's privacy-preserving method is primarily built on the following three technologies: Shuffling technology, Zero-knowledge proof, and Ring signature [35].

3.7. Three-Dimensional Modeling/Scanning

Three-dimensional laser scanning in the Industrial Metaverse comprises a shared, digital representation of the physical world that incorporates data from various sources to create an interactive, three-dimensional laser scanning services model [36]. The goal is to provide a platform for users to visualize and interact with data naturally and intuitively to make decisions faster. Three-dimensional laser scanning in the Industrial Metaverse is probably the best option to simulate real-world conditions accurately. A digital twin may be a better choice if one requires a less expensive or more accurate alternative. Digital twins are digitized representations of an object or system that do not include human interaction. However, the Metaverse of 3D scanning services enables dynamic human interaction in environments composed of digital images, such as furniture, cars, and product pictures, without allowing users to alter the physical state of those objects. This convergence offers new possibilities of how humans can interact with digital models and opens up new potential applications for twins and the 3D laser scanning in the Metaverse. For example, humans could use twins to test different scenarios before interacting with their real-life counterparts in the Metaverse. The major companies in 3D scanning technology include Faro, Artec, Hexagon, and Leica Geosystems:

- Faro Technologies: Faro is a leading 3D scanning company. It provides many software tools, laser scanners, and 3D measuring, imaging, and realization technology.
- Artec 3D: Artec 3D, which is well-known for its portable, handheld 3D scanners, offers solutions for businesses in the automotive, aerospace, and entertainment sectors, as well as for independent producers.
- Hexagon: Hexagon provides high-precision 3D scanning and metrology solutions for sectors including automotive, aerospace, and manufacturing, with a strong emphasis on industrial applications.
- Leica Geosystems: Leica, a member of the Hexagon group, is well known for its precise, high-quality 3D scanning solutions for a range of markets, including building, surveying, and mapping sectors. They have cutting-edge laser scanning technology, such as the Leica BLK series, which makes it possible to seamlessly incorporate places and items from the real world into the Metaverse.

3.8. Digital Twins

The Digital Twin (DT) is one of the most promising enabling technologies for Industry 4.0 and smart manufacturing. The seamless integration of the online and physical realm is a defining characteristic of DTs [37]. DTs are defined in [38] as virtual duplicates of any physical object (a physical twin), connected by real-time data exchange. Practically, DTs have a wide range of applications in varying domains including, among other things, designing/planning, optimization, upkeep, safety, decision-making, remote access, and training. For businesses looking to increase their efficiency, productivity, and competitiveness, it can be a very useful tool. These applications are motivated by the advantages of DTs including fast prototyping, as well as product re-designing, cost-effectiveness, predicting problems/System Planning, optimizing solutions and improved maintenance, accessibility, being safer than the physical counterpart, waste reduction, documentation and communication, and training. In general, rapid prototyping is a process that allows de-

signers to quickly transform their concepts into tangible prototypes. Practically, this enables them to validate, test, and refine their ideas while ensuring the best possible product design. Additionally, it opens up the possibility of customizing each product according to the requirements and usage patterns of users. Because the DT is connected to its physical twin throughout its life, it is possible to compare the performance of the product to what was anticipated, which enables engineers and product designers to re-evaluate the assumptions of the design. In terms of cost-effectiveness, enterprises that have leveraged DT technology have reported an average increase of 15% in efficiency and a 13% reduction in maintenance costs. Consequently, with the creation of virtual replicas of their physical systems, these companies are saving time and money while improving their overall performance [39].

DT technology also enables the prediction of issues and mistakes for its physical twin's future situations, giving planners the chance to adjust systems appropriately.

Given the data flowing in real time between the DT and the physical asset, problems can be predicted at various stages of the product lifecycle. Examples in this category include items like automobiles, aircraft, factory equipment, etc., that have complicated structures consisting of several different elements. Ultimately, it becomes more difficult to predict component failures using traditional methods as a product's complexity increases. Another added advantage is that of optimizing solutions and improved maintenance. This is in contrast to classical maintenance methods, which are reactive, rather than proactive due to their reliance on worst case situations and heuristic experience concerning the particular substance, structural layout, and use of a single product. Through the use of several simulations, the DT offers the most optimal solution or maintenance plan, hence simplifying the process of maintaining the system or product. Furthermore, the continuous feedback loop that exists between the DT and its physical equivalent continuously validates and improves the system's operation. Another benefit of a DT is its accessibility, since it allows for remote control and monitoring of the physical device through the DT's usage. Virtual systems, like DTs, are more widely distributed and accessible remotely than physical systems, which are limited by their location. Remote monitoring and control of equipment and systems becomes vital in cases where local access is banned, as was the case during the COVID-19 pandemic, when governments enforced lockdowns and operating remotely or non-contact methods were the only realistic alternative. Furthermore, it is safer than its physical counterpart, particularly when used in dangerous and harsh industries like mining or oil and gas. Because of its predictive nature and ability to access its physical counterpart remotely, the DT can lessen the likelihood of dangerous malfunctions and mishaps. DTs also have the advantage of waste reduction as the simulation and testing of products are performed virtually. Before a product is manufactured, prototype designs can be virtually tested in many conditions to ensure that the final design is good. This reduces development costs and time to market, in addition to preventing material waste. Documentation and communication comprise another advantage, where data that are dispersed throughout several software programs, databases, and hard copies must be synchronized to establish a data dictionary (DT), which makes it easier to retrieve and maintain the data in one location. By improving the comprehension of system responses, the DT makes it possible to record and convey the behavior and workings of the physical twin. The main advantage is realized in training. The DT can be used to create safety training programs that are more effective and instructive than those that follow conventional methods. Operators can be taught to utilize a DT to reduce the risks before working on a high-risk location or hazardous machinery. By exposing and teaching them about various processes or scenarios, they will become more comfortable handling the same problems in person. For instance, the DT can be used to train new staff in the high-risk field of mining on how to operate machinery and handle emergencies. Lastly, the DT can be a very useful tool in bridging the knowledge gap between seasoned and new employees.

High fidelity, dynamic, self-evolving, recognizable, multi-physical, multi-scale, and multidisciplinary are just a few of the attributes that define DTs [40,41]. Firstly, high fidelity means a DT can replicate every detail of its physical twin thanks to an incredibly lifelike dig-

ital model. Computer models with extremely high fidelity are thought to be the foundation of the DT. When DT simulation and prediction tools are presented with a set of alternative actions or scenarios, this level of detail makes them more reliable. Moreover, the DT is also dynamic, meaning it changes with time in tandem with changes in the physical twin. This is achieved by a continuous exchange of data between the physical and virtual worlds. The concerned data can be either dynamic, wherein they vary with time, or static. A DT is also characterized as self-evolving, meaning the changes during its life cycle are in tandem with its physical counterpart. A closed feedback loop is produced when modifications are made to either the physical or digital twin because they are mirrored in each other. Because a DT uses its physical twin's data to gather information in real-time, it can adapt and self-optimize, evolving throughout its lifetime alongside its physical counterpart. Furthermore, the data and information about a product change as it progresses through its lifecycle, and this also applies to the models—which can include functional, manufacturing, usage, and 3D geometric models, among others. The development of such models for DTs enables a DT to be uniquely distinguished from its physical twin or vice versa, anywhere in the world and throughout its life cycle. In digital twin technology, the macroscopic geometric aspects of the physical twin, including the size, form, and tolerance, as well as the microscopic features, like surface roughness, serve as the basis for the virtual model. Since a DT is based on both the physical and material properties of the physical twin—such as stress analysis models, fatigue damage models, and thermodynamic models—as well as the previously mentioned geometric properties, it is also multiphysical. The material properties of the physical twin include stiffness, strength, hardness, and fatigue strength. Lastly, the fact that Industry 4.0 is centered on multiple disciplines makes DTs multidisciplinary. With DTs serving as the foundation for Industry 4.0, a variety of fields are combined, including automation and industrial engineering, computer science, information technology, and communications; mechanical, electrical, electronic, and mechatronic engineering; and system integration physics, to mention a few.

4. Use Cases and Deployment

Business enterprises using the IM's use cases are starting to realize more benefits than those in the planning stage, especially in terms of safety improvement (9%), capital expenditure savings (15%), and sustainability (10%), according to a study by Nokia and EY [42,43]. Industrial use cases are being implemented throughout the value chain to enhance current business processes by providing visualization, data interoperability, and interwoven digital–physical worlds—even though the Metaverse's full potential may yet be undiscovered [44]. A summary of the six IM use cases is provided in Table 1. The first use case focuses on engineering and industrial design, wherein several interconnected design spaces, each generating a distinct experience, are created by Metaverse designers within the meta-design space that constitutes the Metaverse [45]. The macro and micro levels of real-world design are both improved by Metaverse design. At the macro level, designing in the Metaverse may entail working together in real time inside a virtual representation of the inside of large-scale items such as aeroplanes. At the micro level, parts might be tested, changed, and iterated in a matter of seconds as opposed to investing money and effort in constructing or printing a 3D model or prototype. Practically, design engineers can construct detailed industrial designs because of the capabilities of the Metaverse. To view the product in a real-world environment, interact with it, and alter the design, they employ virtual reality. This method allows one to innovate more quickly and cost effectively because it saves time and reduces the cost of physical prototypes. In addition, the Metaverse offers designers and engineers fresh viewpoints and inspiration, enabling them to produce more original and useful creations. IM applications can speed up design and engineering processes and help one launch better goods faster. Logistics and supply chain management make up the second use case. It concentrates on the transparency of the supply chain and insight into how goods are produced, distributed, stored, and sold and will grow because of the Metaverse. Additionally, the Metaverse encourages collaboration along the supply chain,

improving the effectiveness and efficiency of the entire chain [46]. Examples of IM use cases include VeChain and TradeLens. They demonstrate how supply chain processes can be streamlined and optimized using this technology. The TradeLens technology automates and digitizes supply chain activities, minimizing paper-based documentation and manual processes, using smart contracts and digital signatures. VeChain simulates every stage of the supply chain, from raw materials to finished goods, using blockchain technology and the Metaverse. Blockchain technology is used to track each transaction and movement. The third use case centers on manufacturing operations and maintenance. Industrial big data, operational data management, artificial intelligence, robotic process automation and autonomous systems, digital twins, and cloud computing are just a handful of the state-of-the-art technologies that constitute the IM. In the manufacturing industry, the Metaverse enhances efficiency through product design, production, and maintenance:

1. In product design: Product design is the process of making physical or digital products. The Metaverse enables designers to have the full autonomy to create products that never existed. For instance, fashion companies like Nike and Balenciaga have created items that, even if they were available to consumers, they might not necessarily choose to wear in real life, but which help them create or define their virtual personas on this platform. Given the nearly endless innovation, designers have never-before-seen opportunities to push the limits of design [47].
2. Improve the manufacturing and production process: Metaverse simulations provide the capability to test several factory scenarios and gain insights from scaling up or reducing production. The provision of optimization opportunities within the facilities through these simulations can be obtained without affecting the manufacturing that is already taking place. Practically, in a smart factory, operators can use Microsoft Dynamics 365 Guides for real-time instructions overlaid on equipment, while IoT sensors collect data on machine performance, quality metrics, and inventory levels. This renders it possible for operators to quickly identify and solve problems, optimize production settings, and enhance the general effectiveness and quality of manufacturing.
3. Improve quality control: IoT sensors are deployed for the harnessing of data in manufacturing processes. This facilitates the collection of real-time data from the various equipment and machinery. Subsequently, one can examine data from the production procedures to find flaws or problems that require attention [48]. Manufacturing companies can streamline processes and boost efficiency by using Metaverse technologies and applications such as VR and AR. For example, Dynamics 365 Guides and Remote Assist can be leveraged for 3D drawing in a real-world environment. Moreover, front-line workers wearing a HoloLens can also annotate their physical space with digital ink, creating an interactive and immersive experience. In the automotive manufacturing industry, BMW workers wear headsets that overlay digital information onto real-world objects. This allows them to visually inspect and identify defects in the components in real time, reducing the risk of defective products reaching the assembly line or being shipped to customers.
4. Better warehouse and logistics management: AR can be leveraged to streamline logistics and warehousing procedures by utilizing Metaverse technology. A case in point is that of DHL, a global logistics company that is using augmented reality (AR) headsets to provide their workers with real-time information, such as order details, inventory locations, and picking instructions, overlaid onto their field of vision. This allows their workers to work hands-free and efficiently navigate the warehouse, reducing errors and improving order accuracy.

Using "immersive training environments" for training is the focus of the fourth use case. It is necessary to train workers, both seasoned and novice, in Industry 5.0 working settings and from the Operator 5.0 point of view. What is required is more effective and efficient hands-on training, whether it be locally or virtually, and this promotes market demand for these sophisticated cyber–physical training environments. This is so that workers, both experienced and novice, can safely experience and learn from their operational

mistakes and poor decisions. Even though mistakes can be the best teachers in some industrial situations, it may not be practical or safe to use them as a learning tool. The significant costs, hazards, and time-consuming activities that traditional physical or virtual training settings entail for businesses can, thus, be reduced with the use of contemporary IM-based training environments. However, "safe" immersive IM environments can be used where employees can experiment with novel and creative methods of doing things, even using trial-and-error techniques, which may result in process enhancements. A better user experience is one of the most significant advantages of using "Metaverse-based solutions" while training employees. Complete immersion offers both perceptual and cognitive aspects of the entire environment and the issues, as well as a richer user experience [49]. As an example, complex machinery can be practiced on and operated by trainees, who can also receive safety instructions, learn how to perform maintenance and repairs, conduct remote training, and acquire critical soft skills. This promotes staff that is more effective and knowledgeable. Employees and trainees can take advantage of the Dynamics 365 Guides' more sophisticated features, which include pre-join settings for HoloLens users joining Teams calls that let them turn on or off their audio and video before joining the session. During the meeting, users can also change these settings. This allows frontline staff to use the HoloLens as their primary calling device in settings where secrecy is paramount without compromising security. The Dynamics 365 Guides simplify document navigation. Through action steps, this also offers the additional capability of linking straight from one guide to another. One has to click on hyperlinks to get to different online pages, and this enables easy switching between various training materials or manuals. These cutting-edge training techniques provide a secure and monitored environment for practical learning, which boosts productivity, reduces costs, and improves safety in industrial settings. The fifth use case for the IM is sales and marketing for product production. The Metaverse enables one to create virtual product experiences that allow customers to visualize and engage with merchandise within a virtual setting. The Metaverse has opened up many opportunities for businesses to market their goods by organizing virtual product launches using the Metaverse to launch brand-new products. Companies can create virtual launch events where users can virtually experience the new products, learn about their features, and even pre-order them. This creates buzz and anticipation among their customer bases. Virtual factory tours help customers connect with the brand. This allows them to experience the manufacturing process and get an opportunity to view the facilities without physically visiting the factories. Virtual booths at trade shows can showcase products to a global audience. These booths can engage visitors and demonstrate the products using virtual presentations, videos, or interactive demos. Virtual trade shows offer a cost-effective and environmentally friendly way to market products and reach potential customers globally. The sixth use case emphasizes development and research. With its immersive and collaborative features, IM applications have changed the way that industries undertake research and development (R & D). In the end, this results in new inventions, effectiveness, and inventiveness. Classically, physical prototypes have been used to conduct R & D on products that were not only time-consuming, but costly as well. The IM simulates the design of a product or service at a very early stage as a cost-effective design approach. It enables the design team to swiftly change course and select the optimal and most suitable design options. The production of early-stage products employing the Metaverse would be an ideal, "low-hanging fruit" use case for industries [50]. The Ford Motor Company is a typical example. It has been investigating how to leverage the Metaverse for research and development in fields like car design, safety testing, and manufacturing efficiency. They have built virtual prototypes of their vehicles and tested them virtually for performance and safety using VR simulations.

Table 1. IM use cases.

Use Case Scenario	Summary	Ref
Industrial design and engineering	IM apps can help you streamline design and engineering processes and bring better products to market faster	[51,52]
Supply chain and logistics	Optimize the flow of goods, identify potential bottlenecks, and reduce waste	[46,53]
Manufacturing operations and maintenance	Enhance product design, production, manufacturing processes, quality control, warehousing, and logistics management	[54–56]
Training	Remote training, virtual environments, multi-user interaction, and automated supervision	[57–59]
Marketing and sales for manufacturing products	Virtual product launches, factory tours, and virtual booths at trade shows	[60,61]
Research and development	Design, safety testing, and manufacturing optimization	[62–64]

Deployment

The IM is still in its early phases of growth and is gaining momentum to the extent that its large-scale deployment according to industry forecasts will take place in the next few years [65]. There are obstacles to its implementation and eventual popularization [66]. Several prevalent deployment cases [67] have to date been noted, namely Coca-Cola (HBC), General Motors (GM), automotive Original Equipment Manufacturers (OEMs), Vodacom Group, Simulated Training Solutions, FREYR Battery, and Renault IM. It is important to remember that variables like water use, greenhouse gas emissions, and electricity consumption will be taken into account when evaluating IM deployment in this specific setting. Both scholarly and non-scholarly sources are used for this:

(A) Coca-Cola HBC: The beverage behemoth's partner, Coca-Cola HBC, used the IM to improve the supply chain's resilience and sustainability. In order to reduce waste and increase sustainability while improving operational efficiency and lowering the transportation sector's carbon footprint, Coca-Cola HBC collaborated with Microsoft to create an immersive digital replica of its bottling facility in Edelstal, Austria. Additionally, Coca-Cola HBC implemented automated yard management and vision picking, which improved resource and availability checks, as well as directing trucks into loading docks and minimizing errors. By 2040, Coca-Cola HBC wants to have zero carbon emissions. The IM has improved this supply chain, allowing Coca-Cola HBC to meet changing customer wants and expectations while increasing operational efficiency, sustainability, and profitability. Coca-Cola HBS Austria has made investments in new machinery and systems at its Edelstal site to lower its usage of resources including energy and water. The new high-speed bottling process can fill 45,000 glass bottles an hour. This has enabled Coca-Cola HBC Austria in Edelstal to cut its carbon dioxide emissions by 50% from 2010 to 17.5 g per liter of beverage produced in 2019 [68]. In addition, the compressed-air network's six high-pressure compressors will be added to the current energy management system. PET bottles are formed from blanks using the 36 bars of air that these compressors produce. Ultimately, this reduces machine maintenance time and aligns the compressors in closer proportion to demand. Consequently, these six units account for roughly twenty percent of the plant energy consumption. Furthermore, Coca-Cola HBC has striven to use water more efficiently. According to Figure 5, in the year 2004, 2.7 L of water was utilized to make 1 L of beverage. However, at the end of 2017, it took 1.92 L of water to make 1 L of Coca-Cola. In 2020, the amount of water to produce a liter of Coke had dropped to 1.7 L of water [69].

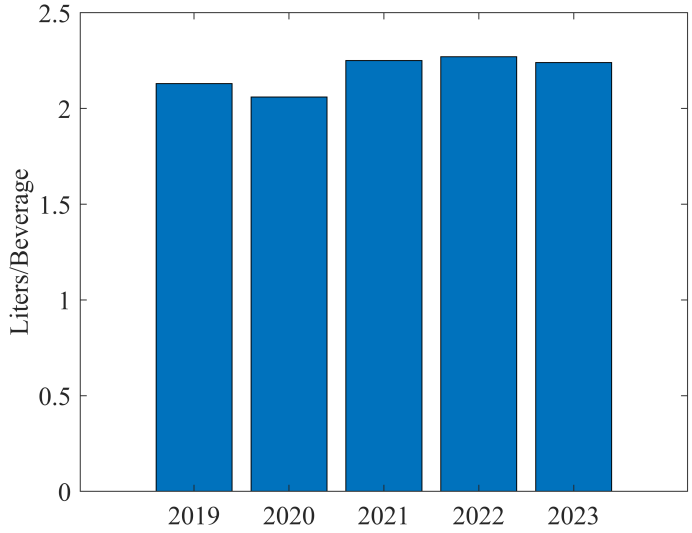


Figure 5. Liters per beverage.

According to Mission Target 2025 [70], the liter per beverage is predicted to drop to 1.53, and this is inline with the Sustainable Development Goals (SDGs) and the targets set forth by the United Nations.

(B) General Motors (GM): GM has used Siemens' Process Simulate to quickly design an ergonomically sound production line. To account for modifications to the designs of current vehicles and the manufacturing of new ones, General Motors must periodically upgrade its production line. Engineers use a virtual reality headset to work remotely and fully immerse themselves in the designs in order to maximize efficiency. It facilitates comprehension of operator movements, hand clearances, manual assembly, and line of sight. With this knowledge, engineers may spot issues early and address them before the final product is created. With Process Simulate, the GM team is making the most of motion capture technology by having a line design engineer don a suit and carry out tasks that an operator would typically undertake. The engineer can better comprehend uncomfortable postures and how long an operator should stay in them by using the motions that were collected. Engineers can minimize health issues related to work and optimize the manufacturing line ergonomically. To this end, GM's advances in other areas with IM are as follows:

I. Biomechanics—the study of how the bones, muscles, tendons, and ligaments interact and affect an operator's fatigue—will be applied to all the motions recorded. Subsequent software will replicate the biomechanics of an individual operator carrying out prolonged duties. Health problems can be precisely detected through simulation, and the operator can be fit with personalized protective equipment or bespoke exosuits.

II. A digital twin can be created from each operator's 3D model, allowing for the simulation of authentic factories. Given GM's massive production staff and the amount of robots in the line, it is critical to determine whether the robots are not impeding operator movements. Before starting the production line, General Motors can ensure that the robots and workers are operating in perfect harmony.

III. In real time, simulate and monitor the operator tasks: Precautionary steps can be performed before any work-related illness or accident arises by tracking biomechanics in real time. Businesses may protect the well-being and security of their most valuable asset—humans—with the aid of the IM.

According to [71], GM's energy intensity climbed progressively beginning in 2020 and peaked between 2021 and 2022 during the COVID era. The quantity of energy required in a GM factory to build a vehicle is known as the energy intensity. There

was an estimated 1.32% decrease in energy intensity between 2021 and 2022, which means that less energy was needed to build the same car as before. GM wants to reach an energy efficiency of 1.5 MWH per vehicle by 2040, according to [72]. This indicates that, by 2040, GM wants to be carbon-neutral. Switching from internal combustion engines to electric vehicles is an obvious step for GM to take in order to achieve carbon neutrality [73]. Over 75% of GM's carbon emissions, according to the company, are from conventional gas-powered vehicles. The emission levels of various vehicle kinds are shown in Figure 6; it can be observed that pickups emit more carbon dioxide than other vehicle types. Their production facilities account for the remaining 25%, which the company intends to remove through the use of solar and wind power. GM stated that, between 2030 and 2035, it will power all of its locations in the United States exclusively with renewable energy. Nonetheless, as Figure 7 illustrates, there has been a consistent decrease in industrial energy usage for the French automaker Renault [74] between the years 2021 and 2023. Another metric used in assessing data centers is water consumption.

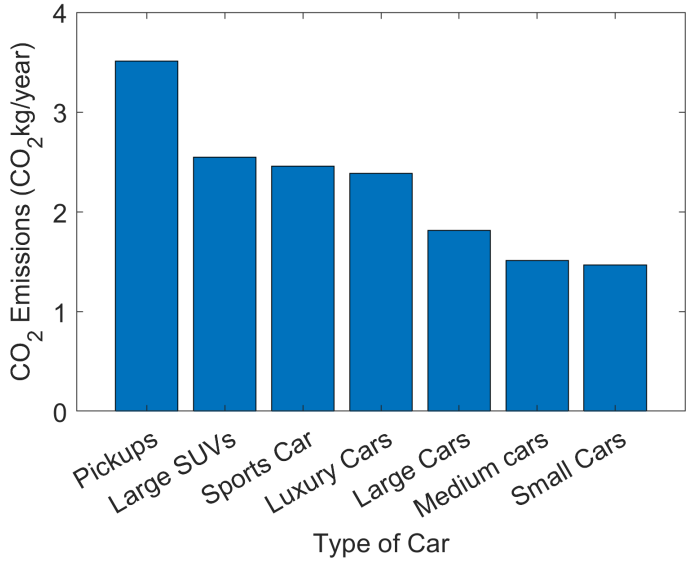


Figure 6. CO_2 emission levels [75].

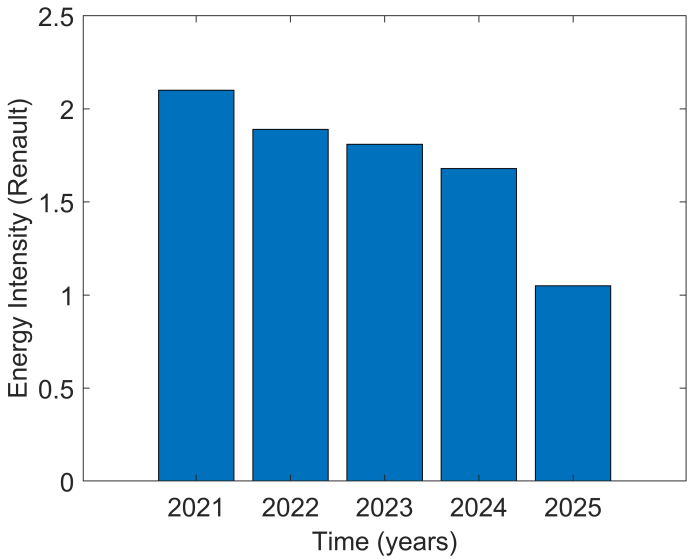


Figure 7. Renault energy intensity [74].

(C) Automotive Original Equipment Manufacturers (OEMs): Virtual reality and other digital technologies have long been used by businesses to optimize manufacturing and enhance designs. Because it can precisely replicate an entire manufacturing line and can eventually aid in essentially planning entire factories before a single brick is constructed, the digital twin of planning is significant. One OEM set out to establish a setting in which the digital twin of planning was grounded in accurate, real-time, and lifelike measurements from the factory shop floor, rather than in human experience, manual calculation, or trial and error. Virtual simulation data and actual production data are collected and analyzed simultaneously while any non-conformities are being observed. In order to facilitate collaborative and integrated simulation and visualization, an IM architecture was created, making sure that all authoring tools (as data sources) were connected to layers. A data management layer, together with the layers for authoring tools, simulation, and visualization, provides the foundation of these linkages. The OEM lowers the risk of new technology introductions, has stricter adherence to ramp-up curves, earlier concept validations, and overall, a more stable production process and a better understanding of the behavioral model of a factory thanks to its ability to simulate entire productions before any real undertakings. Additionally, the digital twin of planning and IM architecture promote more flexible, modular production where it is possible to automatically choose the best plant at the touch of a button to produce a specific part or model. This lower energy consumption promotes sustainability. The car manufacturer might expand even farther and build a digital twin of operations, which might enhance simulations by adding functions like predictive maintenance and real-time digital control.

Significant variations in the energy usage per car for the Volkswagen Group between 2019 and 2023 are reported by the authors in [76]. In 2023, the energy consumption per car was less than 2000 kilowatt-hours per vehicle manufactured, which is a significant reduction over the previous year when a vehicle needed approximately 2200 kilowatt-hours to be produced. The breakdown of energy usage in a Renault company bodywork assembly unit is shown as components in Figure 8. Paint, machining/assembly, compressed air, building heating, and other processes are among the energy components [77]. Compressed air seems to be used at the lowest proportion and paint shop at the highest percentage.

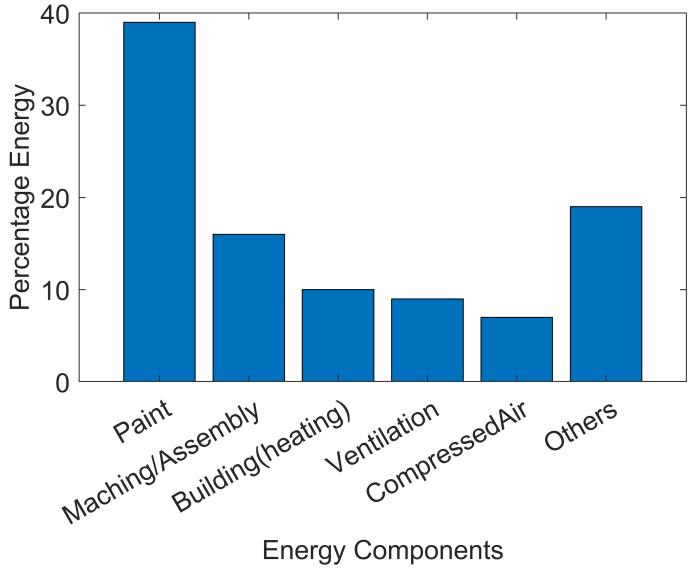


Figure 8. Analysis of energy components [77].

Water is heavily consumed by the worldwide automotive industry for a variety of industrial processes. A car's production is estimated to require more than 39,000 gallons of water, although estimates differ on whether or not tire production is included [78]. The overall amount of water used in the production of cars has been able to be reduced by 51.4% between 2005 and 2022 thanks to long-term efforts for lowering water consumption [79].

(D) AI and digital twins for network administration (Vodacom Group): Vodacom Group teamed up with the American chip manufacturer Nvidia to enhance its tower management skills in Cape Town through the use of AI and simulation techniques. The research runs several different network configurations in real time using a digital twin of Vodacom's Cape Town network. The operator has observed the digital twin to be helpful; unfortunately, the virtual version of its network requires much processing power. The project cannot be expanded to other cities due to the cost involved, and this challenge is discussed in Section 7.

(E) STS3D—VR and AR for training simulations in mining: A Pretoria-based business called Simulated Training Solutions (STS3D) makes use of immersive technology including virtual reality (VR) and AR to create virtual underground mining environments for staff training on many subjects like drilling, blasting, and operating heavy machinery underground in an endeavor to promote health and safety. The simulations recreate environments that are otherwise impossible to replicate in real life, making it difficult for trainees to acquire real-world experience without the use of IM technology.

(F) FREYR Battery: This demonstration is a part of FREYR's first Gigafactory, which they are currently building. In response to the rapidly expanding global market for affordable, high-density battery cells for electric vehicles, marine applications, and stationary energy storage (ESS), the firm provides a clean, Nordic solution. Through a business strategy designed to enhance long-term value creation and unlock sustainable and superior returns for their stakeholders, they aim to produce battery cells that are more ecologically friendly. The center of Northern Norway's process industry, Mo Industrial Park, produces the metals and minerals that the world needs. It employs 2500 people, has roughly 100 businesses, and uses as much energy overall as three Alta power stations. A water plant with a delivery capacity of 2700 L per second is also present. Mo Industrial Park has made great strides in the circular economy and energy recovery. Approximately 400 GWh of recycled energy is produced in the park each year, which is equivalent to the yearly energy demand of nearly 24,000 families. High-temperature flue gas is utilized for district heating; co-gas is used for heating; the heated cooling water is used to produce smolt. The ambitious ambitions for the future include activities linked to aquaculture and hydroponics, biocarbon and battery technologies, and the production of hydrogen [80]. Furthermore, about half [81] of Giga Arctic's capacity will be leased to long-term offtake partners, according to the business. It has also secured conditional offtake agreements for an additional 100 GWh of cells from 2024 to 2028 and an offtake arrangement for 25 GWh of cells with a European energy technology customer.

(G) Renault IM: Four dimensions make up the Renault IM, which is a comprehensive, ongoing, and real-time IM. These dimensions are massive data collection, process digital twins, supply chain ecosystem connectivity, and several cutting-edge technologies. A 60% reduction in vehicle delivery time, a 50% reduction in the carbon footprint of vehicle manufacturing, an extra EUR 260 million in inventory savings, and a contribution to the Group's goal of a 60% reduction in warranty costs are all anticipated benefits of the Metaverse. The Renault Group has launched the first IM as part of its rapid digitalization efforts. Currently, 8500 pieces of equipment make up 100% of the connected production lines, 90% of supply flows are continuously observed, and the entirety of the supply chain data is stored inside the Renault

Group Metaverse, a real-time, authentic duplicate of the real world. Since 2016, digital technology has resulted in EUR 780 million in savings as part of Industry 4.0. It will achieve EUR 320 million in various savings by 2025, of which EUR 260 million will be inventory savings, 60% less time spent on vehicle delivery, 50% less carbon emissions throughout the vehicle production process, a large decrease in innovation cycles, and a contribution to the Group's objective of 60% less warranty expenses:

I. Massive data collection: Renault Group has created a platform for gathering large amounts of data to feed the IM, a special data capture and standardization solution, and levers that enable the production process to be performed in real-time while gathering data from all industrial sites. Massive data collection will benefit from dynamic spectrum technologies works in [82–84], and this may perhaps will be extended to smart farming [85] and cultural heritage [86,87].
II. Digital twins of processes: The utilization of DTs is enhanced by supplier data, sales forecasts, quality data, and exogenous data like weather and traffic patterns, among other things. Artificial intelligence also makes it possible to create predictive scenarios.
III. Connecting the supply chain ecosystem: Supplier data, sales forecasts, quality data, as well as external data like traffic or weather improve the use of digital twins. Artificial intelligence also makes it possible to create predictive scenarios.
IV. Ensemble of advanced technologies: Advanced technologies (big data, real time, 3D, cloud, etc.) are converging to speed up this digital transition. In light of the technologies' convergence required to manage the digital twins and their ecosystems in a resilient manner, the Renault Group has created a special platform [88].

5. Environmental Impact and Sustainable Development

Although the IM brings amazing changes to industrial areas, this technology is still in its infancy and has a significant environmental impact. Any change in the quality of the environment, whether positive or negative, alters a system's natural flow of processes and constitutes an environmental impact [89,90]. To achieve sustainable development, this event must be evaluated. End-to-end complex industrial system control is becoming increasingly important due to sustainability imperatives. The majority of developed nations aim to achieve net zero by 2040–2060. This implies that businesses must overcome the challenge of maintaining economic growth while achieving net-zero environmental impact. The IM is having an impact on the environment in many ways. This includes energy consumption, e-waste, virtual economies, blockchain technology, the elimination of activities that generate pollution, the reduction in the pollution caused by activities, a decrease in the consumption of physical objects, accurate assessment of the pollution generated, and enhanced enforcement and reward systems. An explanation of each way the environment is impacted is provided below:

I. Energy consumption: It is anticipated that the servers and data centers needed to support the IM's development will consume a substantial amount of energy. This might result in a considerable rise in energy usage, especially if the Metaverse is widely deployed as predicted [91]. Figure 9 shows the global data centers wherein the number of data centers in a country is depicted. The U.S. has the highest number of data centers amounting to 2710, and the lowest number of data centers are found in Italy.
Figure 10 shows the energy usage in terms of the power usage effectiveness (PUE). Global PUE has continued to decrease from the year 2006 when it was 2.5 until 2022 when it was 1.57.

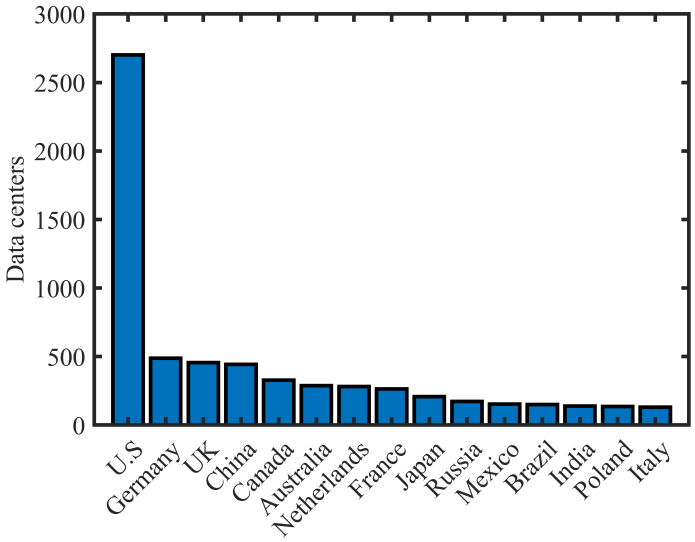


Figure 9. Global data centers [92].

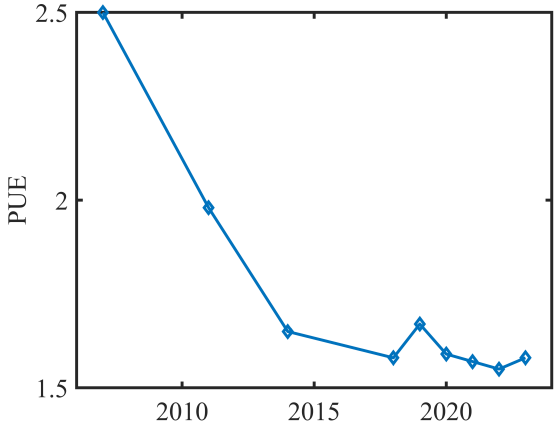


Figure 10. Global PUE.

Although the Metaverse can reduce carbon emissions associated with travel, building, and maintaining infrastructure, the servers and data centers that power the Metaverse can also consume significant energy. Given the IM's early stages, the impact of energy consumption still needs further investigation. However, cloud computing and data centers are the main tools of the IM data centers, which are large groups of connected enterprise servers frequently used to store, process, or transmit large quantities of data. This means data centers use a large amount of electricity, which leads to several environmental issues. In one of the few major cases, the amount of energy consumed over the years was examined using the TRUBA dataset. This dataset includes the daily energy consumption of supercomputers, storage, and networking devices. TRUBA's forecast results point to a reduction in energy consumption in the future. Furthermore, the same study also shows that the energy consumption of TRUBA is decreasing, but it must be noted that the usage of cloud servers for deep learning tasks is increasing [93]. Ensuring that the underlying infrastructure supporting the Metaverse is powered by renewable energy sources is key to achieving overall net zero.

II. e-Waste: Electronic waste (e-waste) has significantly increased because of the growing need for the latest technology, posing an environmental threat. A case in point is the innovation in cellular phones that has adopted the digital part IM. Innovation is an expensive endeavor that requires much trial and error and produces waste in various forms. The digital part industry can reduce waste, conserve resources, and accelerate

innovation cycles by moving the innovation process to the Internet of Medical Things. Faster innovation does, however, result in shorter product lifetimes, which increases waste and obsolescence. Consider the smartphone market, which is expected to sell more than 1.7 billion units by 2021. Since most of these cell phones have replaced older models in this (almost) mature market, there are now over 1.5 billion cell phones worth of e-waste. Innovation is a cause of this replacement as new, eye-catching models were introduced. Innovation must coexist with recycling and reuse because it is essential for business and beneficial to users. The IM, which spans all layers, can play a crucial role in innovation and e-waste management [94]. This unorganized sector often deprives e-waste of its most advantageous components, exacerbating the real threats posed by e-waste. All electronic waste contains hazardous elements like lead, cadmium, beryllium, mercury, and brominated flame retardants. Incorrect disposal of gadgets and devices increases the risk of these hazardous compounds leaking into water bodies, poisoning the air, and increasing the risk of contamination. Unmanaged e-waste directly affects people's health and the environment, claims [95]. As a result of improper e-waste disposal, 45 million kg of polymers containing brominated flame retardants and 58 thousand kg of mercury are currently released into the environment annually. The increasing demand for electronics increases the quantity of outdated and abandoned electronics. Approximately 50 million tonnes of e-waste are produced annually, which is greater than the mass of all commercial aircraft ever manufactured. Rather, considering these factors, it can be inferred that the Metaverse will have a greater negative impact on the environment than a positive one [96]. However, according to [97], globally, only 17.4% of electronic waste is recycled, which worsens environmental and health problems, especially in developing nations. An estimated USD 57 billion is lost every year as a result of electronic waste being disposed of, including important raw materials like iron, copper, and gold. By implementing circular models, businesses can reduce their environmental impact and explore new opportunities to address e-waste issues. On the positive, it is important to note that, according to [95], 52 billion kg of CO_2-equivalent emissions were avoided and 900 billion kg of ore were not dug during primary mining as a result of the creation of secondary raw material from e-waste recycling.

III. Virtual economies and blockchain: The IM's virtual economies, which are supported by blockchain technologies such as non-fungible tokens (NFTs) and cryptocurrencies, have significant energy needs. Blockchain networks' energy usage is a major concern [98,99], particularly for those that employ proof-of-work consensus techniques. According to research, mining Bitcoin uses as much energy as small nations, which results in a large carbon footprint approximated to 475 g per kilowatt-hour (gCO_2/kWh) [99]. Furthermore, Ref. [100] estimates that 127 terawatt-hours (TWh) are consumed annually by Bitcoin alone, which is more than several nations combined, including Norway. In the U.S., the cryptocurrency industry emits between 25 and 50 million tons of CO_2 annually, which is comparable to the emissions from U.S. railroads' diesel fuel usage. It is recommended that GameFi platforms look into eco-friendly options, such as proof-of-stake consensus algorithms, to reduce their carbon footprint and enable the gaming industry to promote sustainable expansion [101].

IV. Elimination of pollution-generating activities: Increasingly, with the adoption of the IM, numerous pollution-generating activities are avoided. These activities range from commuting, face-to-face meetings, off-site work events, and transport. Virtual meeting space Gather.Town has over four million users who prefer a virtual space platform that provides a novel approach to organizing online conferences, events, and meetings. Users can engage each other in real time in a 2D environment on the platform virtually as if they were in the same physical space [102,103].

V. Reduction in pollution generated by activities: To evaluate the effects of various scenarios on an entity's energy consumption, such as a city or factory, one can use the Metaverse. To evaluate the effects of various scenarios on energy usage, an entity

like a factory can be created using the IM. For instance, the IM's digital twins can be used to replicate real-world performance conditions cost effectively and safely. Microsoft's implementation of IM capabilities for Hellenic, one of the biggest Coca-Cola bottlers, is an example. With over 55 locations in Europe, Hellenic services 29 local markets. Ninety thousand Coca-Cola bottles are produced per hour on a single production line in Greece. Microsoft used sensor data to create digital twins that allowed factory workers to immerse themselves in the models. The factory reportedly reduced its energy consumption by more than 9% percent in 12 weeks. Furthermore, physical objects like diesel generators account for CO_2 emissions, amounting to 1,091,618 kg/yr of pollutants [104], and this is costly to mitigate.

VI. Reduction in the consumption of physical objects: It is important to think about the possible challenges of virtual consumption and how the environment might be affected. Although virtual environments have the potential to be more environmentally friendly than real ones, it is still unclear how this will impact energy consumption and carbon emissions [105]. Realizing the possibility of much less materialistic consumption can be facilitated by the IM. It is stated that 21% of consumers expressed their willingness to engage in digital activities in the future, which is expected to reduce the need for physical items [106].

VII. Precise assessment of pollution generated and improvement in reward and enforcement: Finding out how much pollution a company produces can help with processes related to rewards and enforcement, as well as encouraging the adoption of eco-friendly practices. While tracking carbon in the real world is difficult, it can be done in the Metaverse by using blockchain technology to create fungible digital assets. Tokenization makes it easier to transfer carbon credits and establishes a market for voluntary carbon credit exchange. The credits might be used to offset emissions that have been reduced as a result of conservation efforts in the forestry industry and participation in carbon sequestration initiatives like improved soil and altered land use planning. This is exemplified by Reseed company's platform, which utilizes blockchain technology to ensure the validity of carbon stock management, from registration through validation and verification, enabling farmers to receive additional income while providing a potential return to investors [107]. To be ready for sustainability within the IM, enterprises may consider utilizing renewable energy sources and cloud services, in addition to developing a culture of examining the effects of products on the environment, as well as creating a circular economy.

6. Innovative Security and Privacy Threats

The IM is not a utopian digital environment. It constitutes digital representations of real industrial environments, systems, assets, and spaces that users can control, communicate with, and interact with. This leads to many security and privacy challenges. It is a physical–digital fusion and human augmentation for industrial applications. Instead of being a closed platform run by a single corporate entity, it is an integrated ecosystem of businesses and consumers, which results in many security and privacy issues [108]:

- Data security and cybersecurity risks: With the increased reliance on interconnected systems and data sharing, the IM raises concerns about data security and cybersecurity risks. To this end, more and more devices, as well as platforms are increasingly becoming interconnected. Practically, this increases the risk of cyber threats and data breaches. Safeguarding sensitive data is, thus, imperative to protect enterprises, governments, and individuals.
- Privacy implications and regulatory compliance: The IM also brings to the fore challenges with regulatory compliance and privacy issues. Thus, with companies collecting and analyzing huge amounts of data, there is a need to ensure that the privacy of individuals is respected and protected. Optimizing innovation and privacy is a challenge that needs to be addressed.

- Avatar authentication issue: Increasingly, digital avatars such as faces, videos, and voices are employed in the virtual world, which is a form of Metaverse, where user authentication and verification are common in comparison to the real world. Realistically, attackers can make identical sounds and movies by mimicking the appearance of the real user using sophisticated AR and VR tools and devices coupled with AI bots. Consequently, the security and privacy of avatars remain a major concern.

7. Future Research Challenges

A full realization of the IM is constrained by challenges ranging from emerging disputes, regulatory regimes, interoperability, and cybersecurity [109]. Since the IM is an integration of numerous new-generation information technologies, it has grown to be a focus of growing interest for researchers [62]. We focus on cybersecurity where the existence of an IM (as opposed to merely a digital twin) denotes the presence of an additional level of connectivity, either with the Internet or an internal network. IMs use significant amounts of personal data, making them easy targets for hackers. To prevent unauthorized access, businesses must carefully consider how they handle data processing and storage within the IM and ensure that they have stringent security measures in place:

1. Security by design: The robust datasets linked to digital twins are useful for both businesses and hackers. Digital twins are vulnerable to manipulation by hackers who could use them to harvest identities, encrypt data, extort businesses, or spy on corporate [110] secrets. A case in point is the deployment of fake digital twins, which enable hackers to create virtual versions of users or entire environments using compromised data for criminal intents. A deep flake scenario could, as an example, pose as a dishonest executive member of a company in a Metaverse virtual conference room to trick the victim into disclosing sensitive information. Data Poisoning is another aspect where data from the underlying AI and ML learning systems may be altered. This compromises the insights businesses derive from their simulations and, in the worst case scenario, may result in disastrous business decisions based on inaccurate data. Companies run the risk of allocating funds to unproductive channels in the belief that they are acting based on reliable projections from their digital twins if, for instance, demographic data or action profiles of the modeled target groups are fabricated. Consequently, security and user privacy must be foundational design components that should be considered when creating any Metaverse applications rather than being added on later [111].
2. Communications and protocol design: Immersive IM experiences will require high download speeds, low latency, and large capacity to facilitate heterogeneous interconnected devices to communicate with the virtual model at the requisite level. In industrial settings, this will require 5G and possibly also 6G networks [109]. To this end, a change in paradigm for the communication protocol will be required that is goal-oriented and semantically aware. A seamless instant messaging experience must be taken into account when designing a communication protocol. In the end, a model design will be needed to standardize the IM's communication protocols, so that it can be accessed from various virtual worlds' heterogeneous communication systems.
3. Energy-efficient and Green IM: The IM market is now projected to be worth between USD 100 and USD 150 billion, with a conservative 2030 forecast of about USD 400 billion, but with a potential of increasing to more than USD 1 trillion [48]. The IM is creating more opportunities for companies and workers and increasing the adoption of greener practices and renewable energy [112].
4. Limitations of VR and AR technologies: The current limitations in the capabilities and dependability of VR and AR technologies present a significant obstacle to the implementation of the IM in mining. To produce precise and practical digital twins of mines and supply the situational awareness required for increased safety, these technologies may be enhanced.

5. High-cost implementation: The newest gear and software for virtual reality and augmented reality is expensive. To decide if these technologies are feasible for their operations, miners must assess the costs and potential benefits.
6. Human factors and ergonomics: It is critical to protect the health and safety of employees on the IM. This entails reducing the possibility of accidents, making sure employees are properly trained, and offering help when needed. Furthermore, using the IM for an extended period may harm one's health.
7. Training and adoption: The workforce in the mining sector is diverse, and not every employee may be familiar with the newest technological advancements. Some may oppose the changes engineered by the use of new instruments. Mining businesses must engage in thorough and customized training and change management programs that are especially geared to suit the needs of their employees to ensure the successful adoption and usage of these tools.

8. Conclusions

The IM is a virtual space that is used in industrial sectors to create a virtual interconnected network of real-life hardware, processes, and systems with their digital replica. It offers a realistic perspective on how manufacturers can use the Metaverse by recreating actual events in a virtual environment. The IM is driven by a variety of emerging technologies such as the Industrial Internet of Things, artificial intelligence, mixed reality (AR/VR), blockchain, cloud computing, edge computing, digital twins, as well as 3D printing and scanning. Several use cases range from industrial design and engineering, supply chain management and logistics, and manufacturing operations and maintenance, training, to research and development. Though it is still in its early phases, the IM has been deployed in many real-world scenarios by businesses like GM, HBC, and auto OEMs. The business is impacted by the IM deployments in both positive and negative ways such as energy consumption, the creation of e-waste, and pollution in certain cases. Research shows that most IM applications have a positive impact on the environment and are sustainable. Through the use of the IM, we can conduct tasks that would typically require a physical presence in the real world—such as traveling to conventions and concerts, going to work, and attending international congresses in a fully virtual setting from the comfort of one's home or office. This significantly reduces greenhouse gas emissions from cars, trains, or aeroplanes. Furthermore, GM has been utilizing Siemens' Process Simulate to quickly design an ergonomically sound production line. To account for modifications to the designs of current vehicles and the manufacturing of new ones, General Motors must periodically upgrade its production line. Engineers use virtual reality gear to immerse themselves in the designs while working remotely in order to maximize efficiency. This facilitates the comprehension of operator movements, hand clearances, manual assembly, and line of sight. Engineers can use this information to detect issues early on and find solutions before they become problems in the real world. Additionally, the IM's ability to connect users with real-time energy consumption data can improve their understanding of patterns in energy usage and empower them to make wise decisions about their energy use. The majority of use case scenarios involving the IM's deployment have resulted in privacy and security concerns. These encompass data security, privacy implications, and regulatory compliance.

Author Contributions: S.M.N.: conceptualization, methodology, investigation, writing—original draft, visualization. M.V.: conceptualization, methodology, writing—original draft, writing—review and editing, supervision, project administration, funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: The authors gratefully acknowledge the financial support from the National Research Foundation of South Africa (Grant Number 141918).

Data Availability Statement: No data were used for the research described in the article.

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

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