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Entry

The Metaverse in Industry 5.0: A Human-Centric Approach towards Personalized Value Creation

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Definition: In the context of Industry 5.0, the concept of the Metaverse aligns with the vision of Web 4.0, representing a digital ecosystem where individuals and organizations collaborate in a human-centric approach to create personalized value. This virtual universe connects multiple interconnected worlds, enabling real-time interactions between users and computer-generated environments. By integrating technologies like artificial intelligence (AI), virtual reality (VR), and the Internet of Things (IoT), the Metaverse within Industry 5.0 aims to foster innovation and enhance productivity, efficiency, and overall well-being through tailored and value-driven solutions. Therefore, this entry explores the concept of the Metaverse in the context of Industry 5.0, highlighting its definition, evolution, advantages, and disadvantages. It also discusses the pillars of technological advancement, challenges, and opportunities, including its integration into manufacturing. The entry concludes with a proposal for a conceptual framework for integrating the human-centric Metaverse into manufacturing.

Keywords: Metaverse; Industry 5.0; Web 4.0; human-centricity

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1. Introduction

The Metaverse is another revolution of the Internet [1], which provides users an immersive experience through the support of communication channels between the real and virtual world [2]. It is a multi-dimensional (including the three dimensions of space and the dimension of time, among others) virtual space within which users can interact through their virtual replicas [3]. Consequently, implementation of the Metaverse facilitates the generation of a replica of the real/physical world, which can both interact with and affect certain aspects bidirectionally. Further to that, it facilitates everyday tasks such as trading, socialization, and work [4,5]. As a result, the design of new products will become an indispensable part of the Metaverse. Users will be capable of remotely collaborating with product developers, and knowledge can be transferred in a more robust way.

1.1. World Wide Web (WWW): From Web 1.0 to Web 3.0

Among technological advances and advancements, the creation and evolution of the WWW is of utmost importance. It began as a simple communication tool back in the 90s, and since then it has become a driving force for the communication of the world, the exchange of information and assets, the remote execution of tasks, and the collaboration of groups [6].

Web 3.0, also known as the Semantic Web, was introduced by Tim Berners-Lee et al. in their research [7]. What is worth noting is the vision of the authors for the structure of the Internet (see Figure 1), which amplifies the level of comprehension of the machines with the integration of ontology-based frameworks.

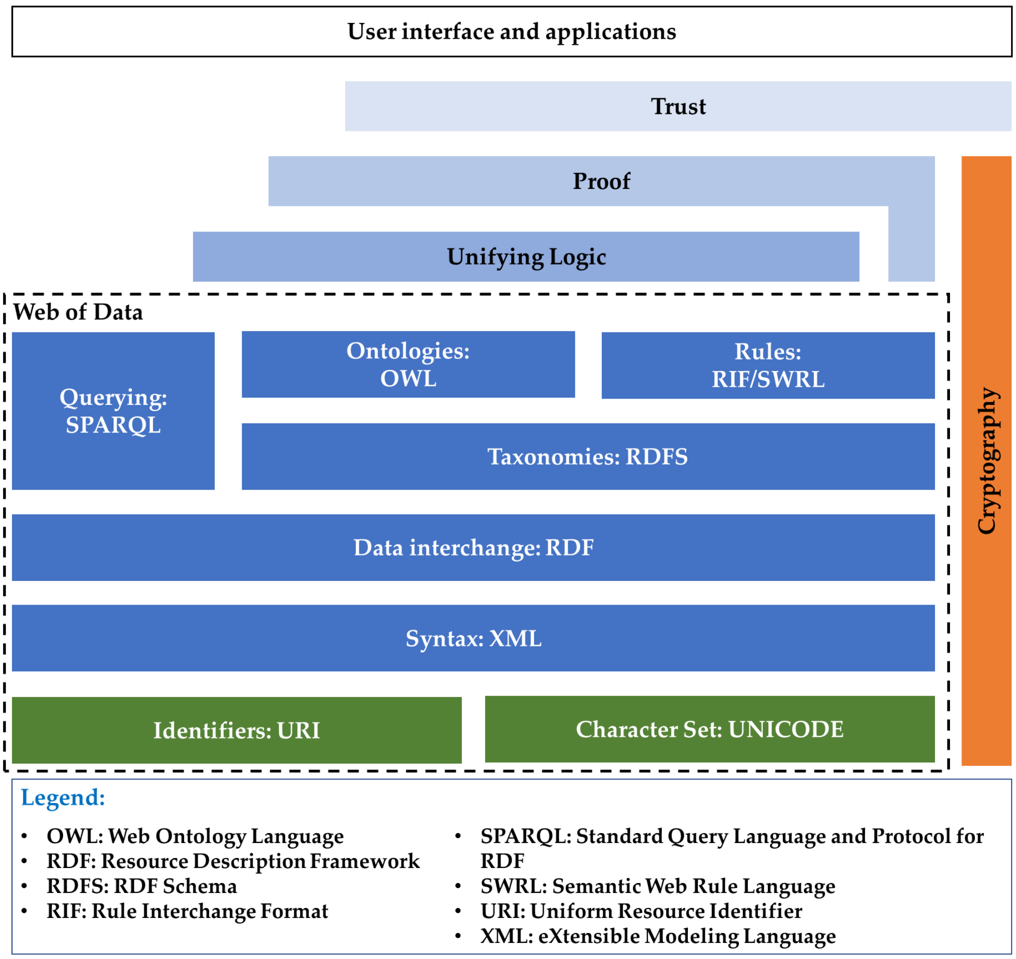

Figure 1. Web 3.0 stacked layer architecture (developed by the author).

1.2. Web 4.0 and the Metaverse

Web 4.0 currently has not been discussed adequately; however, it can be realized as the symbiotic web. Web 4.0, recognized as the fourth generation of the World Wide Web, is envisioned by the European Union executive to integrate artificial and ambient intelligence, Internet of Things devices, trusted blockchain transactions, virtual worlds, and extended reality. Web 4.0 envisions a harmonious interaction between humans and machines, leading to advanced interfaces like brain–computer interfaces (BCIs). It emphasizes efficient web content comprehension and execution for faster, superior website performance. This concept involves achieving a critical mass of network participation for global transparency and collaboration across sectors. Web 4.0, or webOS, resembles an operating system, facilitating highly intelligent interactions similar to the human brain [8]. While the concept of virtual worlds, commonly referred to as the Metaverse, is not novel, recent advancements in technology and improved connectivity infrastructure have prompted significant investments from companies like Meta. However, the outcomes of these investments have been met with uncertainty [9].

The objective of Web 4.0 is to enhance the inclusivity of the internet, specifically targeting individuals with disabilities who will benefit from the utilization of assistive technologies for improved access to web content. Web 4.0 is presently in its nascent phase, yet it has already exerted significant influence on our internet usage patterns. Anticipated advancements in the future are expected to further optimize user-friendliness and interactivity on the web, surpassing current standards. More specifically, in the era of Web 4.0, the convergence of the Metaverse and advanced BCIs promises to seamlessly merge virtual experiences with cognitive capabilities, leading to a new era of interconnected digital landscapes. A technological pillar to achieve that will be BCIs that facilitate human–computer interaction through the utilization of neural signals generated by the user's thoughts. By detecting and translating brain activity into computer-readable commands, BCIs have the potential to revolutionize our interactions with technology. While still at an early stage of development, BCIs exhibit immense promise for diverse applications, ranging from communication and control of prosthetic devices to entertainment. The transformative impact of BCIs extends beyond aiding individuals with disabilities, offering broader advancements in human–computer interaction as a whole [10].

In light of this projection, commissioner Thierry Breton introduced a non-legislative initiative concerning the Metaverse last year. The strategy emphasizes that virtual worlds are persistent and immersive environments, leveraging technologies such as 3D and extended reality (XR) to seamlessly blend the physical and digital realms in real time, serving diverse purposes [11]. In financial terms, the Metaverse is growing, indicating a potential investment opportunity beyond the hype. Concretely, in 2022, worldwide revenue for the Metaverse was rated at 65.51 billion US dollars. The corresponding projections for 2023 are 82.02 billion US dollars, and, most importantly, it is estimated that by the end of 2030 the market size of the Metaverse will have grown by more than ten times reaching a value of 936.57 billion US dollars [12].

1.3. Web 4.0 and the Metaverse Need

In the rapidly evolving technological landscape, Web 4.0 emerges as the latest trend, necessitating our awareness and adaptation to remain at the forefront [13]. In summary, Web 4.0 is characterized by most of the technological pillars of Industry 4.0 (Figure 2) and the following properties [14]:

- The online environment has to be consistently connected, enabling constant interaction. Users can connect with one another;
- The emerging web functions as a unified Web OS, where information seamlessly transfers between various points within the system;
- Background processes involve self-learning AI systems that strive to comprehend users, mimicking human communication patterns;
- It engages users through interpersonal communication methods, much like human interactions;
- It embodies an intelligent, interconnected, and open web structure;
- The speed and dependability of Web 4.0 exceed previous standards;
- It necessitates ubiquity, identity, and connectivity as fundamental prerequisites.

Figure 2. Web 4.0 and the Metaverse, common technologies (developed by the author).

Based on the above, the following summarizing and comparative Table 1 has been created.

Table 1. From Web 1.0 to Web 4.0—Technical Details (Developed by the Author).

Web Version	Description	Technical Aspects	Application Examples	Reference
Web 1.0	Static, read-only web content	Basic HyperText Markup Language (HTML) and Cascade Styling Sheet (CSS) for layout;	Early websites, online encyclopedias	[15]
Web 2.0	Interactive, user-generated content	Asynchronous JavaScript and XM (AJAX) for real-time interactivity	Social media platforms, Wikipedia, YouTube	[16]
Web 3.0	Semantic web, machine-understandable data	Resource Description Framework (RDF), ontologies, metadata for semantic understanding	Linked data projects, semantic search engines	[17]
Web 4.0	AI-driven, immersive and personalized experiences	Artificial intelligence (AI), Internet of Things (IoT) integration, virtual reality, blockchain potential	AI virtual assistants, mixed reality applications	[13]

1.4. Human-Centric Metaverse Challenges

The creation of the Metaverse poses a crucial challenge requiring a solution. As per the literature [6], the development and viability of the Metaverse are fundamentally centered around humans. Consequently, significant consideration must be given to human experience [18]. Furthermore, the Metaverse's operations necessitate the organization and involvement of human agents. Safeguarding human rights and combatting criminal activities within the Metaverse are also critical challenges that require attention [6]. Thus, by the time the conception of the Metaverse originated by humans, the Metaverse has to follow the principle of "placing the human operator/user first".

1.5. Contribution of the Paper

The EU's economic forecast for the period beyond 2030 [19] emphasizes digitalization as a primary driver, with Web 4.0 representing a significant technological shift leading to a seamlessly interconnected, intelligent, and immersive global environment. The virtual worlds market is projected to expand from €27 billion in 2022 to over €800 billion by 2030, indicating substantial growth [20]. Virtual worlds are set to impact societal dynamics, presenting both opportunities and challenges that require attention. The new strategy aims to align Web 4.0 and the Metaverse with EU values and principles, ensuring the full application of individuals' rights and fostering a conducive environment for European businesses. The strategy aligns with the Digital Decade policy's 2030 objectives [21], emphasizing skills, business, and public services in digitalization. Infrastructural aspects are covered through the Commission's connectivity package and broader initiatives, while addressing openness and global governance in virtual worlds and Web 4.0. The key strategy pillars are as follows: (1) empowering people and reinforcing skills; (2) business—supporting a European Web 4.0 industrial ecosystem; (3) government—supporting societal progress and virtual public services; and (4) shaping global standards for open and interoperable virtual worlds and Web 4.0.

Thus, this research explores the key intersection of cutting-edge technology and human-centered innovation, emphasizing how the Web-4.0-based industrial Metaverse can revolutionize Industry 5.0 by empowering individuals to actively shape and personalize value creation within the industrial landscape.

1.6. Manuscript Structure

The rest of the manuscript is structured as follows. In Section 2, an exploration of Cyber-Physical Systems (CPS) and their role in facilitating personalized value creation within the industrial Metaverse is presented. Then, in Section 3, a framework specifically designed for personalized value creation in the Metaverse, providing insights into its implementation and application, is discussed. Section 4 delves into the challenges faced in developing an industrial human-centric Metaverse and its relationship with Web 4.0. Finally, the concluding remarks summarize the key findings and contributions of the paper. The review methodology of this entry is analyzed in a detailed manner in the Supplementary Material, in which Figure S1 is used in order to indicate the most pertinent areas of research as well as their interconnections in the context of Metaverse and personalized value creation.

2. Pertinent Literature

Cyber-Physical Systems for Personalized Value Creation in the Industrial Metaverse

The understanding of evolving components of Industry 5.0 relies on advanced Cyber-Physical Systems (CPS) architecture that aligns with industry standards. Traditional CPS architectures fall short in incorporating the vertical and horizontal diversification of human, physical, and cyber components [22]:

- **3C (Connection, Conversion, Cyber) architecture:** The integration of computation, communication, and control in 3C CPS architecture enables the realization of smart industries by incorporating human, physical, and cyber components [23];
- **5C (Connection, Conversion, Cyber, Cognition, and Configuration) architecture:** The architectural framework of the 5C Cyber-Physical System (CPS) encompasses five distinct levels: smart connection, conversion, cyber, cognition, and configuration. This structure seamlessly integrates several components, including sensors, actuators, cognitive modules, and advanced automation mechanisms. Its primary objective lies in facilitating and enhancing intelligent decision-making processes within the intricate production environment [3];
- **Key protocols:** Implementations such as Profibus/Profinet, Open Platform Communications—Unified Architecture (OPC-UA), Fieldbus, and Ethernet Powerlink play crucial roles within the 5C CPS architectures [24];
- **Self-adaptiveness**: Self-adaptive CPS architectures exhibit the ability to operate in dynamic and uncertain environments, employing adaptation logic to adjust to adverse circumstances and uncertainties [25];
- **Fog computing:** Fog gateways in industrial CPS leverage fog computing to process samples efficiently and enable rapid evaluation, integrating predictive models with intelligent machinery [26];
- **Reference Architecture Models:** Reference Architectural Model Industrie 4.0 (RAMI 4.0) and International Industrial Relations Association (IIRA) serve as reference architecture models for Industry 4.0 and the industrial internet, respectively, facilitating standardization, information sharing, and interoperability among technologies in smart industries [27].

In the year 2020, a notable shift occurred in the progression of spatial computing. In this context, software platforms play a pivotal role as the fundamental technology facilitating the creation and execution of application programs [28]. In terms of literature, a restricted number of published works that delve into software platform complications pertinent to the Metaverse have been published. Notably, a study based on extended reality (XR) software platforms designed for the Metaverse can be found in [29]. These layers are as follows: (1) enabling platforms; (2) content platforms; (3) human-centered platforms; (4) utility platforms; and (5) platforms for applications. These layers, constituting a structural foundation, consist of the following components:

- **Enabling Platforms:** These form the bedrock of the Metaverse ecosystem, serving as the fundamental architecture that enables the intricate interplay between the virtual and real world. Within this layer, crucial information and communication technology (ICT) components are harnessed to provide the necessary backbone for seamless connectivity and data exchange.

- **Content Platforms**: At the heart of the Metaverse, content platforms facilitate the creation, distribution, and consumption of diverse digital content. This layer incorporates advanced technologies like immersive media production tools, enabling the realization of rich and engaging virtual experiences.
- **Human-Centered Platforms:** Focused on user interaction and experience, this layer emphasizes the harmonious integration of humans and technology within the Metaverse. It encompasses innovative user interface (UI) paradigms, responsive interactions, and sensory feedback mechanisms, all of which aim to provide a user-centric and immersive digital environment.
- **Utility Platforms:** This layer underpins the practical functionality of the Metaverse by integrating Internet of Things (IoT) devices and associated protocols. It empowers real-time data acquisition and communication, enabling dynamic interaction between the physical and virtual realms.
- **Platforms for Applications:** Situated on top of the preceding layers, this layer provides the canvas upon which several application scenarios are developed and executed, such as healthcare, education, entertainment, and manufacturing.
- **Communication Protocols Layer:** In the context of the proposed industrial Metaverse framework, robust and efficient communication protocols play an indispensable role in ensuring seamless and secure data exchange across the interconnected fabric of virtual and physical environments. These protocols act as the digital highways that enable real-time interactions between Internet of Things (IoT) devices, smart sensors, immersive interfaces, and backend systems. By adhering to standardized communication protocols, such as MQTT (Message-Queuing Telemetry Transport) and CoAP (Constrained Application Protocol), the industrial Metaverse can facilitate rapid and reliable information flow, enabling predictive maintenance, real-time monitoring, and collaborative production. These protocols also contribute to optimizing bandwidth usage, enhancing latency management, and bolstering cybersecurity measures, thereby laying a robust foundation for the industrial Metaverse's transformative potential in shaping the factories of the future.

Similarly, a framework of the Metaverse as a mediating design space between high-value-added case studies and technology trends in society and business is discussed in [30]. Based on the above, a technical framework for the industrial Metaverse including key information and communication technology (ICT) infrastructure and key Metaverse technologies is presented in Figure 3.

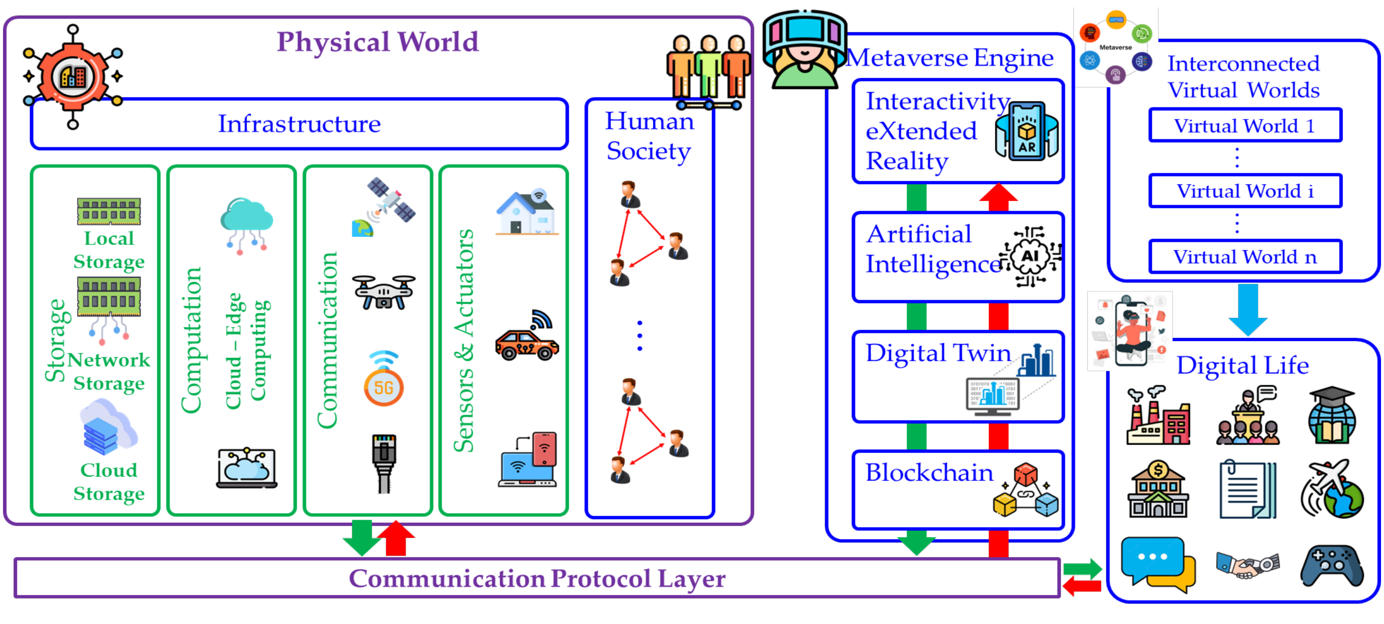

Figure 3. Technical framework for the industrial Metaverse (developed by the author).

3. A framework for Personalized Value Creation in the Metaverse

The virtual environment provided by the Metaverse offers an innovative design experience, unrestricted by physical limitations, thanks to augmented reality, virtual reality technologies [31] and blockchains [32]. Designers can explore their emotional and functional design concepts and evaluate their solutions in a digital space, enabling creativity across various domains, such as avatar customization, education, architecture, and entertainment [33]. This immersive and interactive environment enhances interactions between designers and users, facilitating human-centered design and blending the boundaries between the real and virtual worlds [34]. However, the full potential of interactivity in the Metaverse remains untapped, as the connection between the digital and physical realms is not yet seamless. To unlock this potential, a design system that links digital and real spaces is crucial for human-centric Metaverse interaction. Existing digital tools, while offering technical support, have limitations, due to their separate development for specific design stages and the incomplete integration of design knowledge [35]. To overcome these limitations, an interactive personalized design system for the Metaverse should extract and utilize design knowledge, providing computational models that empower designers to seamlessly transition from the digital environment to real-world manufacturing. By optimizing human–product interactions in the digital and physical domains, the application potential of the Metaverse can be expanded, surpassing previous design systems in its advancements. The key sections of the proposed framework include the development of an interactive knowledge-based design system for the Metaverse, the application of the Design–Display–Evaluation–Adjustment process within the system, and the innovative use of a fuzzy transformer method for computational modeling. These models serve as fundamental tools for capturing design-related knowledge. The structure of the proposed system includes the real-world environment, the Metaverse's virtual environment, and their interactions, facilitated by the system. The system bridges the gap between the digital and physical realms, enabling the generation, display, evaluation, and adjustment of virtual products. Design knowledge is stored in a design knowledge base, which contains different types of design knowledge expressed through perceptual cognition computational models. These models simulate the relationship between design perception (the style of a product) and product components (the form of a product). Users interact with the system using avatars in the Metaverse, input their design demands, and receive design results displayed in the virtual environment. The evaluation procedure allows users to provide feedback, and, based on the evaluation results, the system outputs the final design or enters an adjustment phase where unsatisfactory product components can be modified. The iterative process continues until a satisfactory design result is achieved. The proposed system (Figure 4) emphasizes the utilization of design knowledge and computational models to enable seamless transitions between the digital and real worlds, enhancing human–product interactions within the Metaverse.

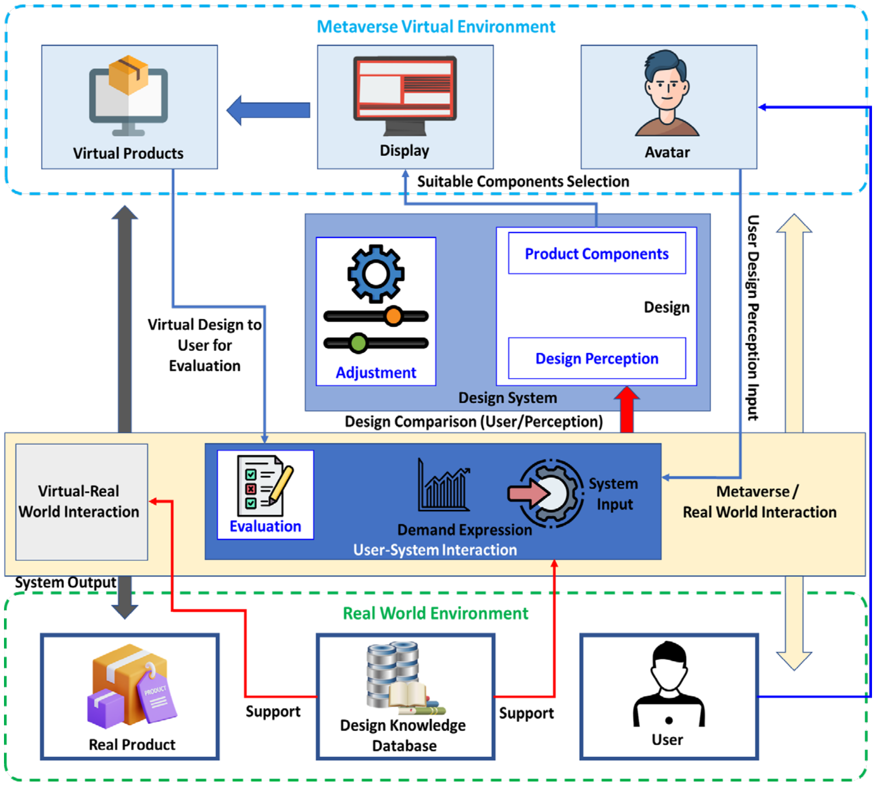

Figure 4. Human-centric framework for personalized product design (developed by the author).

4. Applications of the Human-Centric Metaverse (HCM) in Industry 5.0

The impact of the pandemic shifted work and living from physical to virtual spaces. The Metaverse integrates virtual and real realms. It complements real life, forging new online–offline relationships and energizing the actual economy. This is at an early stage, with vast applications. However, it has to be stressed that the Metaverse, while not a replacement for real-life experiences, represents a novel amalgamation of virtual and real dimensions. The Metaverse is currently in its infancy, but it offers a variety of potential applications, especially under the human-centric pillar of Industry 5.0 [6].

4.1. Education Metaverse

The Metaverse employs extended reality (XR) technologies to enhance the virtual classroom, providing students with immersive experiences. A notable example is discussed in [28], which allows students to explore the internal workings of the human body, akin to in an anatomy room. Moreover, through the integration of virtual world technology, students can participate in online classes without the need to physically attend. Platforms like Zoom, Teams, and the 3D classroom map in [36] play significant roles as virtual classrooms in the post-epidemic era, enabling remote and non-face-to-face teaching [37,38]. Emphasizing a human-centric approach, the Metaverse leverages augmented reality, artificial intelligence, and other cutting-edge technologies to enhance learning by making it more engaging, convenient, and comprehensive. Learners are provided with increased opportunities to experience, explore, learn, teach, collaborate, and interact with others within this novel virtual domain. An Edu-Metaverse Framework for PSS Collaborative Assembly is presented in Figure 5.

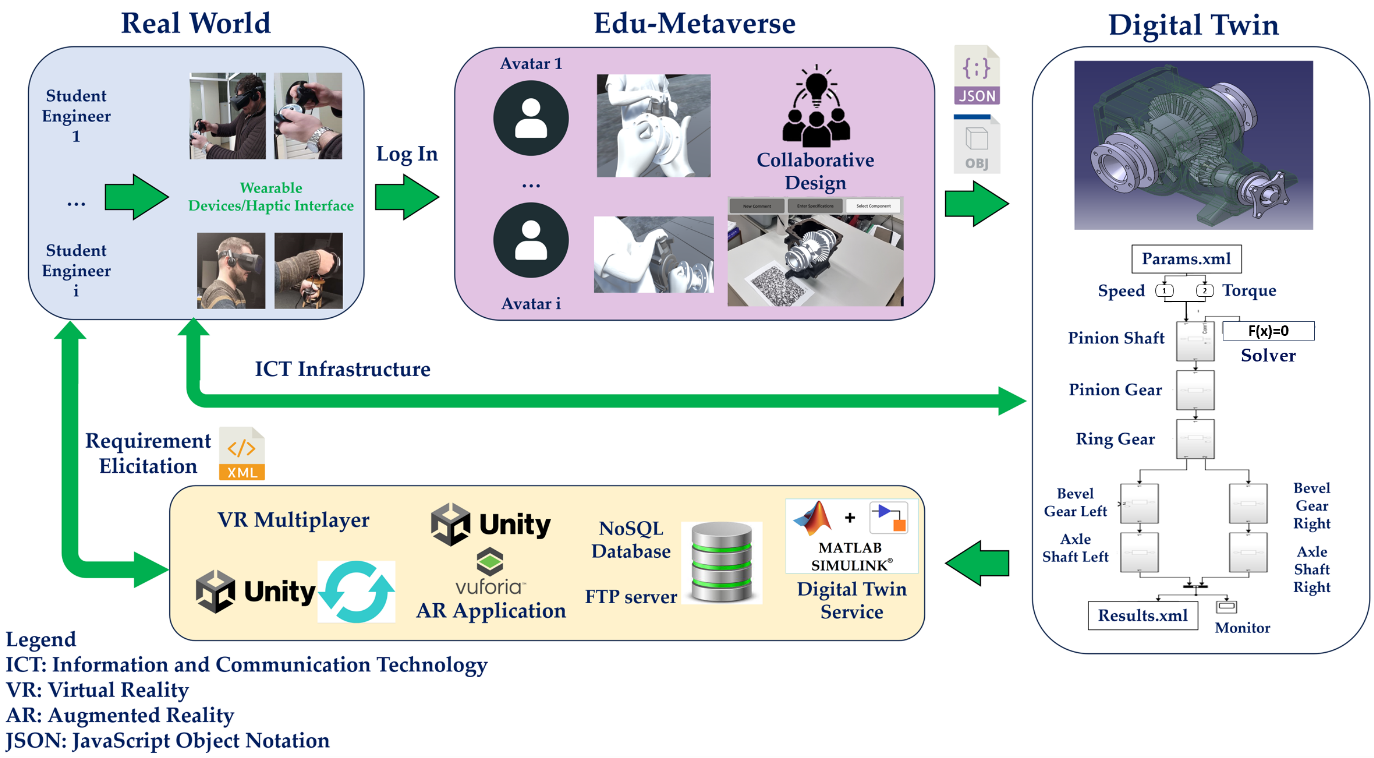

Figure 5. The Edu-Metaverse framework for product–service system (PSS) collaborative assembly (developed by the author).

4.2. Healthcare Metaverse

In the field of clinical medicine, the Metaverse allows experts to engage in real-time remote guidance during surgical procedures through virtual platforms [39] or visualize patients' clinical health data with AR technology [40] (Figure 6). This immersive environment effectively transcends the limitations of time and space, facilitating collaboration among global experts as they collectively address challenges and find solutions. Leveraging Internet of Things technology and embedded devices that seamlessly integrate information and physical objects, the Metaverse exhibits remarkable promise in advancing medical care [41,42].

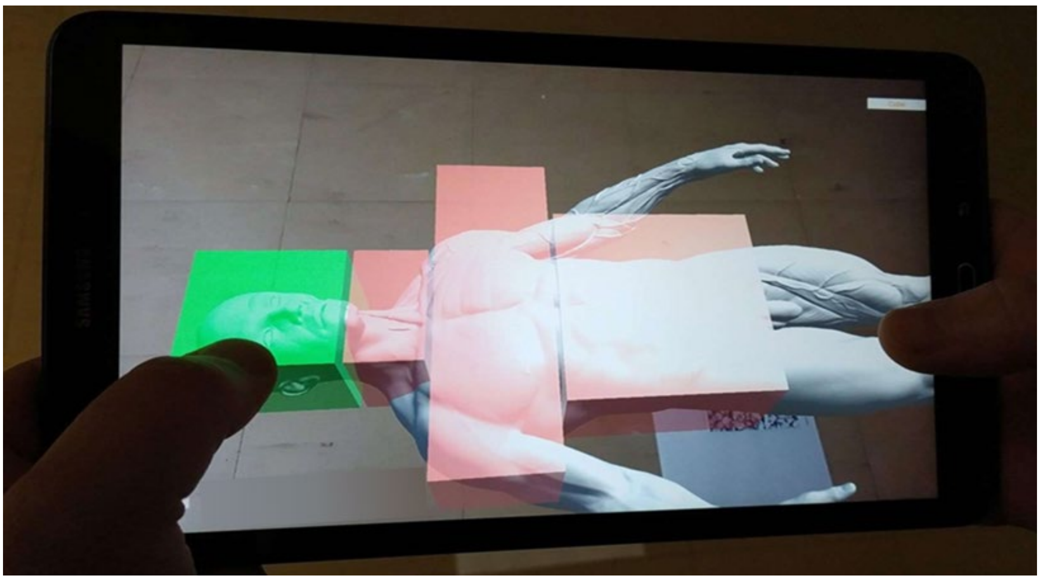

Figure 6. AR visualization of the segmented human body (Android tablet), adapted from [40].

4.3. The Metaverse in Tourism and Archaeology

The popularity of the Metaverse has catalyzed changes within the tourism sector, giving rise to a novel concept known as "smart tourism" [43]. Smart tourism revolves around placing tourists at the focal point of the experience, allowing them to enjoy the delights of travel without leaving the comfort of their homes. This is made possible through the integration of artificial intelligence, big data, and other related technologies from the Metaverse. An exemplary application of this concept is observed in the domain of scenic spots and historic sites, where augmented reality (AR) and mixed reality (MR) experiences are employed to enrich cultural heritage sites. This augmentation enhances overall user participation and satisfaction, especially when tailored to individual preferences and interactions with historical artifacts in the physical world [44]. By leveraging these technological capabilities, smart tourism offers immersive and personalized experiences to tourists.

4.4. Blockchain Integration in Industrial Metaverse

Blockchains and non-fungible tokens (NFTs) are distinct but interconnected components of decentralized digital systems and platforms such as the industrial Metaverse. On the one hand, a blockchain can serve as a backbone technology, providing secure, transparent, and immutable transaction records [45]. On the other hand, NFTs use blockchains' capabilities to create unique and indivisible digital assets [46]. Unlike fungible cryptocurrencies, NFTs represent singular items or creative works, establishing ownership, scarcity, and provenance in the digital space. While blockchain ensures the integrity of transactions across various applications, NFTs specifically cater to the authentication and monetization of one-of-a-kind digital content, from artwork to collectibles and beyond. Based on the above, the industrial Metaverse aims to establish a scalable and secure blockchain platform, emphasizing digital asset creation and smart contracts. Users are equipped with tools, known as the Metaverse Digital Asset System, enabling them to generate and distribute digital assets. The integration of smart contracts facilitates secure and efficient digital asset transfers within Metaverse. The decentralized nature of blockchains complements the Metaverse's virtual economy, where utility tokens and NFTs play a significant role in safeguarding digital assets. While NFTs enhance asset security, the challenge of double spending requires resolution for seamless blockchain integration [47].

In addition to motivating network security, the reward functions of blockchains in an industrial Metaverse environment can also be used to improve other sectors such as education and healthcare (as already discussed in Sections 4.1 and 4.2). For example, using a virtual wallet, students can earn tokens for their academic achievements, which they can use in order to gain access to more educational resources, such as e-books or exam preparation materials. Similarly, in healthcare, patients can earn tokens by maintaining a healthy lifestyle and achieving certain health goals, such as maintaining their body weight or completing a health assessment. These tokens could be exchanged for discounts on medical treatments, gym memberships or other wellness-related services. The key benefit of blockchain integration in the above-mentioned scenarios is the creation of a secure and proven record of user activities, which is also accompanied by increased transparency (due to the fact that the blockchain remains visible to the participants) and improved security for all parties involved (due to the fact that each transaction is recorded in the distributed ledger only after the participants have reached a consensus) [32].

Originating as a bridge between the virtual and physical realms, the Metaverse faces the task of enabling irreplaceable token trading and investment with real-world currency. A conceptual framework for blockchain integration in the industrial Metaverse is presented in Figure 7 [32].

4.5. Industrial Metaverse

The emergence of the industrial Metaverse dates back to the convergence of the industrial internet, which seamlessly combines physical equipment with information technology [41]. Unlike the industrial internet, the industrial Metaverse goes a step further by integrating the Metaverse with the industrial sector, creating a close interaction between the real physical world and the virtual digital realm. This integration is based on the Metaverse's distinctive hyper-spatio-temporal characteristics to enable virtual verification, design, and optimization of manufacturing processes throughout the product life cycle. Additionally, the industrial Metaverse emphasizes promoting collaboration between virtual and real spaces. It facilitates mapping and broadening of the operations conducted in the physical industry within the virtual space, empowering industrial enterprises to achieve cost reduction, enhance production efficiency, and foster efficient collaboration both within and between companies [29].

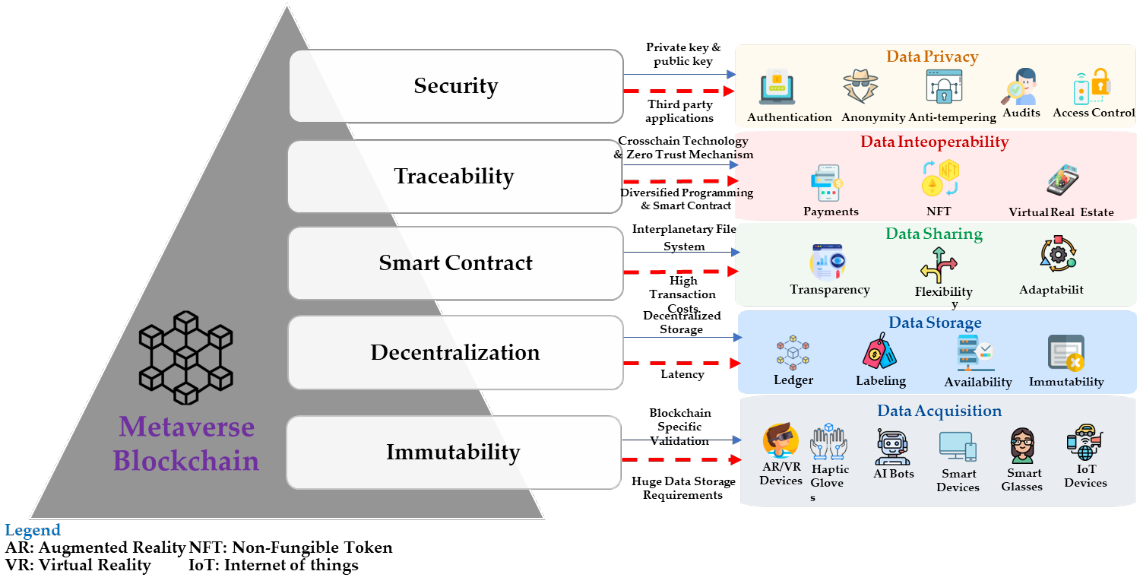

Figure 7. A blockchain framework for the industrial Metaverse, adapted from [32].

Three main entities are at the core of the industrial Metaverse: (1) products, (2) businesses, and (3) consumers. By embracing a human-centric approach, the industrial Metaverse propels the industry forward through comprehensive digitalization, supported by blockchain production relations, immersive communication, and the pervasive influence of AI technologies [29]. Beyond that, the core of the Metaverse lies in the integration of extended reality technologies, which offer the opportunity to present new information to the user's physical environment in a more pleasing manner, as well as applications that can be developed following a step-by-step approach towards the guidance, training, and education of users. As a result, gamification could be considered an inherent property of the Metaverse. For example, in industrial settings, gamification could be utilized in order to engage employees in participating in training activities and provide rewards for completing milestones or achieving certain goals [48]. Similarly, a logistics company could create a virtual reality game in which players must optimize supply chain operations to transport goods as efficiently as possible [49]. By incorporating gamification into Industry 5.0, companies can improve workforce engagement, increase productivity, and foster a culture of continuous learning and improvement. As a result, a conceptual framework presenting a Metaverse as a service (MaaS) model for service-oriented DTs towards Industry 5.0. is presented in Figure 8.

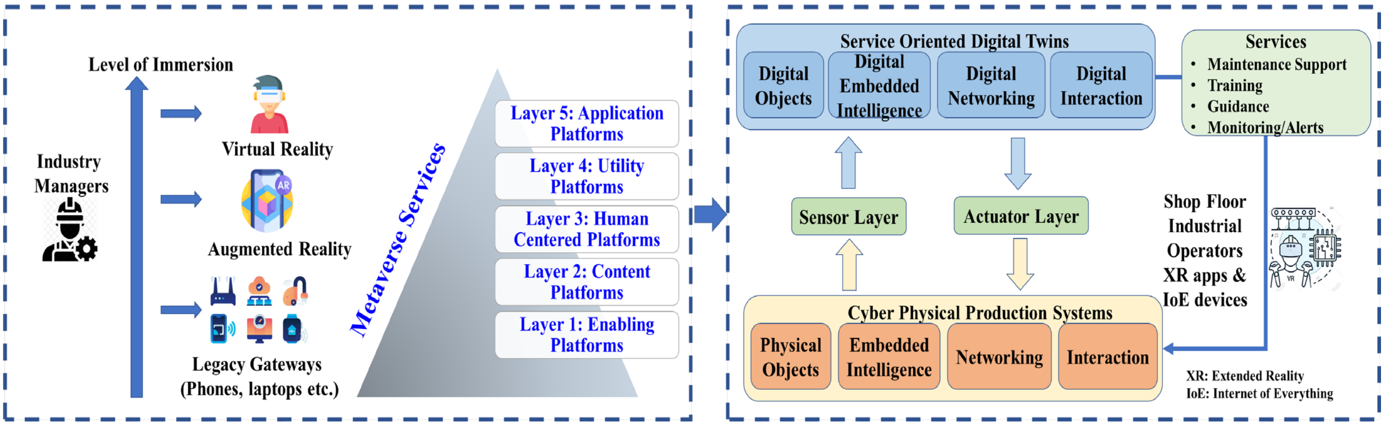

Figure 8. A Metaverse as a service (MaaS) model for service-oriented DTs towards Industry 5.0, adapted from [29].

5. Discussion and Outlook: Challenges for the Industrial Human-Centric Metaverse and Web 4.0

Web 4.0 brings forth a host of exciting possibilities, but it also poses unique challenges that need to be addressed. As the digital landscape evolves, several key challenges emerge for Web 4.0 and the Metaverse as well. These include ensuring data privacy and security in an increasingly interconnected environment, managing the complexity of vast amounts of user-generated content, fostering inclusive and accessible web experiences, navigating ethical considerations surrounding emerging technologies, and addressing the potential digital divide that may arise from uneven access and skills. Meeting these challenges will be vital for the successful implementation and adoption of Web 4.0.

5.1. Wisdom Manufacturing, the Industrial Metaverse, and the Social-Driven Web

The term "wisdom manufacturing" (WM) was initially introduced in 2014 through the combination of four networks: (1) the Internet of Things (IoT), (2) the Internet of Services (IoS), (3) the Internet By and for People (IbfP/IoP), and (4) the Internet of Contents and Knowledge (IoCK) with the manufacturing domain [50]. Subsequently, it evolved into a socio-technical system, denoted the Social-Cyber-Physical Production System (SCPPS), for in-depth investigation [51]. The evolution of WM has followed advancements in new-generation information and communication technologies (ICT) and artificial intelligence (AI) [52], finding applications in proactive manufacturing driven by big data [53] and autonomous smart manufacturing [54]. Therefore, WM constitutes a hypernetwork combining a physical network (IoT), a virtual network (IoS), a social network (IoP), and an interlinking network (IoCK) [55]. As such, WM can be integrated into the industrial Metaverse, enabling the seamless flow of knowledge, insights, and intelligent decision-making across interconnected virtual and physical manufacturing ecosystems.

5.2. Industrial Metaverse Sustainability

The emergence of Industry 5.0 underscores the necessity of responsible technology adoption within the industrial Metaverse, which is a critical consideration amplified by its potential impact on human empowerment and societal well-being. Industry 5.0 is built on human-centric manufacturing, resilience, and sustainability practices. Thus, it necessitates a detailed examination of its principles for businesses, policymakers, and academics to collaboratively foster an equitable and sustainable future. However, existing literature highlights the multifaceted challenges posed by digital technologies, including robotics, big data, and Industry 4.0, encompassing concerns such as shifting labor dynamics, heightened energy consumption, and environmental consequences. Similarly, the Metaverse presents an opportunity to reduce carbon emissions through decreased mobility alongside potential social implications linked to reduced interpersonal interactions. Aligning with the concept of responsible digitalization, the authors in [56] advocate for an Industry-5.0-aligned Metaverse, emphasizing human rights, environmental conservation, and social integration, thereby offering a holistic perspective for navigating the complex landscape of technology-driven advancements while prioritizing sustainable development. The available empirical data indicate that the utilization of big datasets necessitates data centers to annually consume approximately 200 terawatt hours of energy, surpassing the energy consumption of certain countries, like Argentina [57]. This consumption equates to half of the global electricity utilized for transportation and represents around 1% of the total global electricity demand. Currently, data centers contribute about 0.3% of overall carbon emissions, while the ICT sector is responsible for over 2% of the world's emissions [58]. Furthermore, the implementation of Industry 4.0 technologies seeks to enhance productivity across supply chains. However, the existence of outdated production and logistic systems can lead to heightened emissions and pollution, significantly impacting the environment. As a result, the adoption of Industry 4.0-driven digital transformation might necessitate disruptive changes in supply chains, including environmentally conscious investments in products, processes, and supply chain networks, which could potentially compromise the efficiency of processes and workflows [49].

5.3. Industrial Human-Centric Metaverse Challenges

The human-centric Metaverse faces a multitude of challenges that necessitate careful consideration and effective solutions. Privacy and security emerge as significant concerns due to the vast amount of personal information shared, demanding robust measures to safeguard data and protect against unauthorized access or misuse [59]. Ethical considerations pose another critical challenge, encompassing dilemmas such as consent, digital rights, and the potential impact of immersive experiences on mental health and well-being [60]. Inclusivity and accessibility demand careful design and implementation to ensure equitable access and inclusive experiences for individuals with disabilities, diverse cultural backgrounds, and varying digital literacy levels [61]. Striking a balance between user empowerment and control, while preventing manipulation or exploitation, is a critical challenge in building a human-centric Metaverse [62]. Establishing trust and safety measures, including protection against harassment, cyberbullying, and fraudulent activities, is essential to foster positive and secure user interactions and experiences within the Metaverse [63].

Furthermore, it has to be mentioned that the industrial Metaverse, driven by the integration of physical industries with the virtual realm, can leverage generative AI's capabilities to optimize manufacturing processes and enhance collaborative operations, marking a significant advancement in industrial innovation. When revolutionary AI tools like OpenAI's ChatGPT and Google's Bard emerged, users were impressed by their capabilities, but soon, concerns arose about their potential impact in a world where AI can handle diverse tasks. Similarly, the Metaverse also provoked concerns [64]. On the one hand, virtual interactions and entities can offer novelty and convenience, but poorly designed implementations risk dehumanization and adverse effects on well-being. On the other hand, safety concerns are becoming central to discussions surrounding the Metaverse, as evidenced by India's Digital India Act, which explicitly addresses investigating crimes in the virtual realm, such as dissemination of misinformation and incitement of violence [65]. As generative AI and the Metaverse shape the next evolution of the internet, a critical question emerges [66]:

- Will this transformation prioritize efficiency and incentives at the expense of authenticity, diversity, and safety?
- Ensuring alignment with our values, identities, and self-worth becomes paramount, aiming to amplify and enhance human endeavors.

Addressing these challenges is pivotal for the development of a human-centric Metaverse that upholds privacy, ethics, inclusivity, user empowerment, and trust to provide meaningful and safe virtual environments.

6. Concluding Remarks

This entry explores the applications of the human-centric Metaverse in Industry 5.0, highlighting its potential implications and benefits for the education, healthcare, tourism and archaeology, blockchain, and industrial sectors. In conclusion, this entry not only highlights the potential of the Metaverse within Industry 5.0, taking into consideration the digital agenda of the EU beyond 2030, but also contributes a conceptual framework for a Metaverse interactive design system based on human perceptual cognition computational modeling. This system expands the possibilities of the Metaverse, enabling its application in diverse product design system development. Future research directions will involve exploring the integration of the system with real-world smart factories and incorporating product technical parameter modeling to enhance the capabilities of the proposed system. These endeavors will further advance the utilization of the Metaverse in Industry 5.0 and its value creation potential.

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