The Korean Institute of Communications and Information Sciences

Available online at www.sciencedirect.com

ScienceDirect

ICT Express 10 (2024) 233–255

www.elsevier.com/locate/icte

Metaverse in advanced manufacturing: Background, applications, limitations, open issues & future directions

Gabriel Chukwunonso Amaizu, Judith Nkechinyere Njoku, Jae-Min Lee, Dong-Seong Kim*

Department of IT Convergence Engineering, Kumoh National Institute of Technology, Republic of Korea

Received 18 March 2022; received in revised form 26 November 2023; accepted 22 February 2024
Available online 27 February 2024

Abstract

The metaverse promises to revolutionize the internet by introducing a new era of three-dimensional objects. The advancements in artificial intelligence and immersive technologies have made the metaverse a trending topic in various industries, including manufacturing. This study aims to provide a comprehensive understanding of the metaverse, its underlying technologies, and the current trends shaping its development. By delving into the concept and potential applications of the metaverse in manufacturing, we seek to uncover its transformative benefits for the industry. Through an exploration of existing use cases, we aim to highlight the practical implications of the metaverse. Recognizing the need for further research, this study also addresses the limitations, privacy concerns, and security implications associated with the metaverse. By examining these aspects, we hope to motivate further investigation and contribute to the ongoing discourse surrounding this emerging paradigm.

Keywords: AI; AR; Automation; Manufacturing; Metaverse; MR; VR; XR

1. Introduction

The Metaverse is by far the most trending topic today in the technology industry. It is made up of the words “meta” and “Verse” which means “Transcend” and “Universe” respectively. With the metaverse, humans envision creating a universe that runs simultaneously with the real world [1]. The term “metaverse” first came to be in a 1992 science fiction novel titled “Snow Crash” by Neal Stephenson [2]. Although it can be argued that the metaverse has come a long way since then. A more recent depiction can be found in Zak Penn and Ernest Cline’s “Ready Player One”, another dystopic science fiction released in 2018. Nonetheless, the metaverse is more than just a dystopic science fiction movie.

According to Microsoft, a metaverse is a digital space inhabited by the digital representations of people and things. The internet as we know it is evolving and taking on a new face as the metaverse is seen as the vision of the internet. The internet is often seen as a place where communication, sharing, and work take place. Hence the metaverse can be said to be an internet we can interact with like we would with a physical world [3]. The metaverse opens an abundance of opportunities, no longer a vision, now a reality. Members of a team can join a meeting from anywhere, real-time translations allow people from diverse cultures to collaborate in real-time, walking on a factory floor from the comfort of their home. All of these are the endless possibilities of the metaverse. It stretches us beyond the physical limitations of this world.

The early adopters of the metaverse were the gaming, entertainment, and more recently, the social media industries. However, the metaverse is much more than that. There has been and still is ongoing research in other industries, such as health, and energy on the applications of a metaverse in those fields. The manufacturing industry, however, is yet to exploit the full benefits of the metaverse.

The novel COVID-19 virus, first reported in late 2019, did harm to the manufacturing industry. Supply chains were disrupted, and factories were closed. This did impact the rate and scale of production of personal protection equipment as recommended by the World Health Organization (WHO) [4]. Before the outbreak, there had been a series of research and development on manufacturing automation with researchers looking for and devising ways to make production autonomous [5,6]. This was further aided by the boom of Industry 4.0 with cloud

* Corresponding author.
E-mail address: dskim@kumoh.ac.kr (D.-S. Kim).
Peer review under responsibility of The Korean Institute of Communications and Information Sciences (KICS).

https://doi.org/10.1016/j.icte.2024.02.010

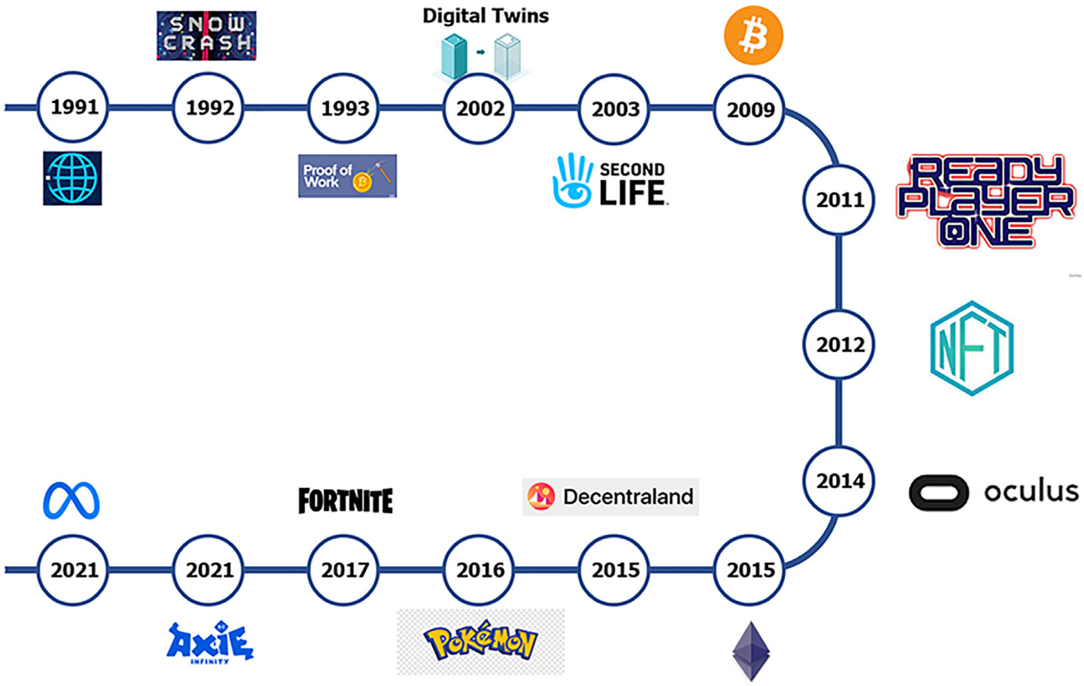


Fig. 1. Metaverse development timeline between 1991 and 2021 depicting major events from the advent of the internet to Facebook's renaming to Meta.

manufacturing, cyber–physical systems (CPS), and the Internet of Things (IoT) playing prominent roles [7,8]. However, as COVID-19 has shown in the last couple of years, the manufacturing industry still has some ways to go to achieve this feat.

While manufacturing industries were taking heavy hits during the pandemic, tech companies were seeing their shares rise to record levels. As physical meetups and activities became increasingly difficult and rare, virtual activities took center stage. Activities ranging from online meetings to concerts began to make waves. Industries that seemed prepared (e.g., the entertainment industries) began taking full advantage of this new virtual platform/world. The popularity of the metaverse was not just down to the pandemic; the proliferation of related technologies has led to this surge. Advancements in virtual reality (VR), augmented reality (AR), mixed reality (MR), extended reality (XR), artificial intelligence (AI), Blockchain, non-fungible tokens (NFTs), and digital twins (DT) are of essential importance to the acceleration and realization of the metaverse.

The metaverse project is thriving, and this has resulted in many technological giants investing and betting big on the project. In 2016, Microsoft introduced the HoloLens and HoloLens 2 in 2019, which are both MR smart glasses. By 2021 the Microsoft mesh which is a platform that would further the development of immersive and interactive experiences within MR applications together with holoportation was rolled out. The mesh is an MR platform, and together with the holoportation, a user can bring their actual person instead of an avatar into a mixed reality environment. There was also the 70 billion United States Dollar (USD) takeover (their biggest deal ever) of Activision Blizzard in January 2022, showing their intent to stick with the metaverse project.

Facebook CEO Mark Zuckerberg gave a glimpse of the metaverse while announcing the company's new name, "Meta". The glimpse included a group of friends hanging out in real-time in a virtual space with their avatars. The company, to date, has spent more than 10 billion USD in the development and acquisition of hardware and software which would be used within the metaverse. With the acquisition of Oculus, Meta aspires to give users more immersive experiences, especially with the rollout of the Quest 2 VR headsets.

Other major players in immersive technology development (and by extension, the metaverse) include the likes of Google, whose main interest lies in AR (at least for now), Unity, Nvidia, and Qualcomm. In Fig. 1. a timeline of the metaverse development can be seen. It depicts the major events that have taken place for the metaverse to be where it is from 1991 to 2021. The developments started with the advent of the Internet in 1991, then in 1992 the science fiction novel "Snow Crash" that coined the term "metaverse was released" [2]. The concept of proof of work (PoW) was invented by Noar and Cynthia Dwork in 1993 as a mechanism to prevent denial of service attacks (DDoS). PoW presents a cryptographic proof where a party (prover) has to prove to others (verifiers) that an amount of specific computational effort has been expended and the verifier can further confirm this using minimal effort. 2002 saw the emergence of digital representation of real-world objects, this is now known as DT. Linden Lab launched Second Life in 2003, a platform that allowed users to create their own avatars and interact with other users and user-created content within a virtual world [9]. The Blockchain revolution started in 2009 when the now famous Satoshi Nakamoto published the bitcoin white paper detailing a peer-to-peer electronic cash system using hash-based PoF [10]. Another dystopian science fiction novel "Ready Player One", which was basically a worldwide

Table 1
List of abbreviations and their meanings.

Acronym	Meaning
3D	Three-Dimension
AI	Artificial Intelligence
AM	Additive Manufacturing
AR	Augmented Reality
CPS	Cyber–Physical System
DDoS	Distributed Denial of Service
DL	Deep Learning
DT	Digital Twin
HMD	Head Mounted Display
IAI	Industrial Artificial Intelligence
IoT	Internet of Things
KAIST	Korea Advanced Institute of Science and Technology
ML	Machine Learning
MR	Mixed Reality
NDA	Non-disclosure Agreement
NFT	Non-Fungible Token
NIST	National Institute of Standards and Technology
PoW	Proof of Works
RUL	Remaining Useful Life
USD	United States Dollar
VR	Virtual Reality
WHO	World Health Organization
XR	Extended Reality

virtual reality game in a novel was released in 2011. NFTs became a thing in 2012 [11] while Oculus launched their first VR headset in 2012. Ethereum was launched and its white paper was published by Vitalik Buterin in 2015 [12]. A series of VR games were released in the subsequent years after. Decentraland in 2015, Pokemon Go in 2016, Fortnite in 2017, and Axie in 2018. Some of these VR games were Ethereum-based and incorporated NFTs. Finally, in 2021, Mark Zuckerberg announced a direction change in Facebook by renaming it Meta. All of these companies are betting billions on the metaverse in one form or another. Metaverse, however, has been known to have limitations that could arise from devices or software. There are also age-old issues of privacy and security, all of which are addressed in this study. Full definitions of abbreviations used in this study can be found in Table 1.

1.1. Motivations

In the dynamic realm of technology, the fusion of AI and immersive technologies has birthed the metaverse, ushering in new 3D experiences. This subsection succinctly outlines our technical motivations, emphasizing the interplay between technological advancements, the manufacturing sector, and the inherent challenges. Thus the three main motivations of this paper include:

- **Technological Advancements in AI and Immersive Technologies:** Explore the transformative potential of the metaverse in response to significant advancements in artificial intelligence and immersive technologies, aiming to understand how these technical developments contribute to the emergence of 3D objects within the metaverse.
- **Application of the Metaverse in Manufacturing:** Investigate the specific applications of the metaverse within the manufacturing industry, providing a comprehensive understanding of how the integration of the metaverse can revolutionize processes, and enhance efficiency in manufacturing.
- **Addressing Practical Implications and Limitations:** Analyze existing use cases to highlight practical implications of metaverse implementation in manufacturing, while also addressing inherent limitations, privacy concerns, and security implications. This technical examination aims to inform industry practitioners and researchers about both the potential benefits and challenges associated with adopting the metaverse.

1.2. Contributions

Manufacturing simply put is the process of creating or producing goods with aid of machines humans or biological processes. This field has been explored by many scholars and has undergone a series of changes over the years. These changes often involve more efficient ways of manufacturing as manufacturers continuously compete globally in an ever-evolving and dynamic marketplace. Production agility, innovativeness, and high product quality are attributes that would gradually be ushered in by the digitalization of the manufacturing process [13]. On the other hand, the metaverse is a three-dimensional representation of a virtual world where the digital and real worlds co-exist together. In this paper, we take a first look (to the author's best knowledge) at the background, applications, limitations, and open issues on what we will refer to as Industrial Metaverse (i.e the application of metaverse in manufacturing). The major contributions of this paper are presented thus:

- Defining the concept "Metaverse", its origin, timelines of major events with regard to its development, as well as major players in the industry. This article goes further to introduce the various elements of metaverse such as AR, VR, XR, and DT, and how they relate to manufacturing where possible. We also discussed some of the characteristics of the metaverse like immersiveness, economy, and interoperability.
- As a way of getting acquainted with the current state of manufacturing, this study covers some of the recent trends pertaining to the manufacturing industry. We looked at technologies such as additive manufacturing (AM), AI, big data, and Blockchain, how they have contributed to smart manufacturing and some of the methodologies associated with each of these technologies as related to the manufacturing process.
- By use of a scenario-based approach, this study explores the various possible future application of the metaverse in manufacturing. We look at the prospectives metaverse would bring to areas of manufacturing like prototyping/product design, remote collaboration/communication, real-time monitoring, immersive training, etc.

- We presented two case studies of Metaverse applications in manufacturing. First is BMW's factory of the future and then the Korea Advanced Institute of Science and Technology (KAIST) Metaverse factory experience center. This study presents their workings and key attributes.
- Finally, the limitations, and future works with regard to Metaverse applicability in manufacturing are presented.

In this paper, several contributions have been put forward. Firstly, we present the general concept of the metaverse. Then the background of the metaverse, where we highlighted the driving technologies behind the growth of the metaverse and later proceeded to the unique characteristics of the metaverse. In order to be able to understand how the metaverse could be incorporated into manufacturing, we have also introduced, some of the current trends in manufacturing today while also highlighting some of their limitations. In addition, we have also presented the possible scenarios where and how metaverse could be applied in the manufacturing industry while exploring the benefits of such applications. Although the concept of a metaverse in manufacturing is still at its infant stage, we are still able to present some of the few use cases and will later go on to present some perceived limitations as well as security and privacy challenges that this new world will be faced with.

1.3. Roadmap

The remainder of this study is organized as follows: Section 2 consists of some theoretical background about the metaverse. In Section 3, we introduce the recent trends in the manufacturing industry, while Section 4 dives into some proposed applications of a metaverse in the manufacturing industry. Case studies of a metaverse in manufacturing are covered in Section 5, and current metaverse issues are addressed in Section 6. In Section 7, the future works arising from current issues are presented. This study is then concluded in Section 7. The paper organization is further presented pictorially in Fig. 2. This study incorporates a form of scoping review by providing an overview of metaverse in manufacturing, identifying key concepts, technologies, use cases, and gaps in the literature.

2. Metaverse background

This section starts by introducing the elements of the metaverse and previous works that have incorporated these elements and manufacturing, then we discuss the characteristics of the metaverse.

2.1. Elements of metaverse

The metaverse is comprised of various elements. Here we explore those elements, which include immersive technologies, avatars, digital twins, and the metaverse itself. Some of these elements are depicted in Fig. 3.

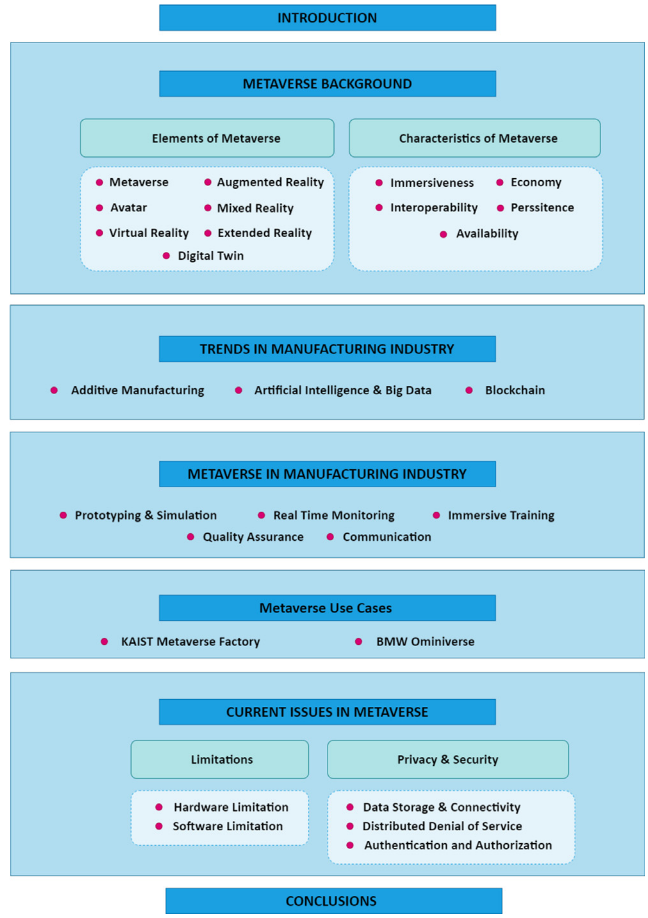


Fig. 2. Organization of paper.

2.1.1. Metaverse

A metaverse is an immersive three-dimensional (3D) representation of a virtual world. In this virtual world, users can interact with objects, virtual spaces, and other users using their digital selves or an avatar. The metaverse is growing and has had various definitions and applications. It has also been dubbed as the next generation of the internet in recent years. The technologies driving this innovation are mainly VR/AR headsets and other wearables.

2.1.2. Avatar

The word "Avatar" comes from a Sanskrit word and means "descent". It is used to refer to the descent of a deity on earth. In the metaverse, avatars are digital representations of users. An avatar in the metaverse can interact with virtual objects and spaces, can own virtual items too, and carry out a varying number of activities in the metaverse [14].

2.1.3. Virtual Reality (VR)

VR makes use of a VR headset or a head-mounted display (HMD) to immerse users in a digitally simulated environment [15]. It deceives the brain into believing (to some extent), that what the user is seeing is real. The devices used (VR headset & HMD) present users with a 360-degree view of the virtual world [16]. The virtual world can be a simulated real

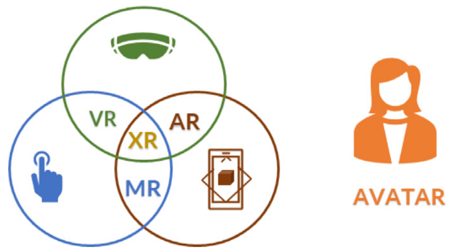


Fig. 3. Elements of Metaverse showing how the various immersive technologies relate to each other.

world or imagined. This gives VR developers the freedom to create whatever they want thereby availing the benefits of VR to all industries as opposed to the entertainment and gaming industries, which were the first adopters. In manufacturing, VR has been used for activities such as the inspection process for collision detection [17] and accuracy [18], it is also used (to an extent) in training employees, and simulation [19,20] albeit to a lesser degree.

2.1.4. Augmented Reality (AR)

On the other hand, AR overlaps the real world with virtual objects. A user can avail of this experience by making use of devices such as glasses, smartphones, or most screen devices. Since AR merges the real world with a virtual one, users need not be removed from the real world entirely, meaning they can interact simultaneously with both worlds [16,21]. A well-rounded example of AR is the Pokemon GO game. AR performs similar roles with VR in manufacturing albeit to a slightly higher degree [22]. Two commonly employed areas of AR in manufacturing are warehouse logistics and supply chain management [23]. Authors in [24] detailed a series of applications of AR within the warehouse. Also, a systematic review was given in [25] detailing the integration of AR for quality control, while a plethora of applications of AR in manufacturing is presented in [26].

2.1.5. Mixed Reality (MR)

Mixed reality integrates the concepts of AR and VR. In MR, virtual and real-world objects interact in real-time. Sometimes called hybrid reality, MR allows users to overlay digital objects such as videos, 3D models, etc., into the real world and interact with such objects as they would a physical one [27]. An example of MR is Microsoft's HoloLens. MR has advanced a lot over the years most especially as a technology and its use cases. The advent of MR has greatly reduced the efforts and money spent on learning or training of factory workers [28]. Aside from learning, the current iterations and applications of MR in manufacturing range from mapping for manual operations [29], floor layout planning [30], fault diagnosis [31], and design patterns planning [32].

2.1.6. Extended Reality (XR)

Extended reality (XR) is an all-embracing term covering technologies such as VR, AR, MR, and everything in between. Together, these technologies are revolutionizing the future and have been termed "immersive technologies" as they immerse users in a digital environment with applications in different domains [33]. XR includes all technology that can integrate the physical and virtual and make them one. In Table 2, a summary of the objects and environments of VR, AR, and MR is shown.

Table 2
How VR, AR & MR interacts with objects and their environments.

	Objects	Environment
VR	Virtual	Virtual
AR	Virtual	Real
MR	Virtual & Real	Virtual

2.1.7. Digital Twin (DT)

A digital twin is a virtual or digital copy of physical assets, products, or processes [34]. DTs are designed in such a way that it works or perform in harmony or synchronicity with the real-world asset it is modeled on [35]. Recently DT has become a mainstay in manufacturing. As it keeps getting deserved attention in manufacturing, the number of research articles keeps increasing. DTs used in manufacturing can be built for a variety of dissimilar purposes: DT for monitoring the production processes. This can be achieved by creating a system architecture that uses a virtual manufacturing machine to interface with third-party applications [36], product parameters monitoring during production [37], monitoring a machine tool as proposed by [38]. DT can also be applied for maintenance purposes [39,40]. Lastly DT has been deployed for support machine lifecycle [41,42]. [43,44] give a detailed review of DT in manufacturing.

2.1.8. Non-Fungible Token (NFT)

NFT is derived from Ethereum's smart contracts [12] and is a type of cryptocurrency [45], although it defers from classical cryptocurrencies such as Bitcoin [10]. Bitcoin is a type of classical coin that has all its coins equivalent and indistinguishable [10]. On the other hand, NFT is unique and a like-for-like exchange of NFT is not possible, hence the name "non-fungible". With NFT it becomes pretty easy for creators in a virtual world to not only prove the existence of a digital asset but also prove its ownership in videos, images, or art-like forms [46]. Industries and scientific communities have shown a great interest in NFT in recent years, and its adoption is remarkably high. Verified market research valued NFT market size at 11.32 Billion USD in 2021 and estimated that figure to reach 321.98 Billion in 2030 which is a 33.7% compound annual growth rate over a period of eight years. The report cited NFTs individually, distinctiveness, and transparency among other attributes as reasons for the increase in NFT demand [47]. Research on NFT applicability for industrial purposes is scarce however, a few articles have exploited and proposed mechanisms whereby NFT could be used in 3D creation and AM [48,49].

2.1.9. Wearable technologies

The term wearable technologies is an all-encompassing term used in describing a series of devices either worn directly or loosely attached to a person [50]. These devices allow for the continuous monitoring of human activities as well as behaviors. Before now, wearable technologies have mainly been used in medicine and healthcare [51] for physical activity, mental status, and weight monitoring. Roughly, wearable technologies can be classified into three types: wearable health technologies, wearable textile technology, and wearable consumer electronics [52].

Till this point, we have covered a variety of technologies individually including AR, VR, XR, DT MR, etc. as elements of the metaverse. These elements altogether contribute to bridging the gap between the physical and real world, and collectively they all make up the metaverse [33]. They play various roles and offer various levels of immersion. The visual world (in this case metaverse) cannot be accessed without them.

2.2. Characteristics of metaverse

2.2.1. Immersiveness

The metaverse is both immersive and pervasive as users will have access to 3D virtual spaces. This feature of the metaverse is driven by the rapid advancement of AR and VR technologies. So far, users have been able to enter and immerse themselves in the metaverse as avatars. However, this will likely change in the future with the development of high-end wearable sensors, which will help in bringing the virtual and real-world tighter together by sending data into the metaverse and giving users sensory responses [1].

According to Harvard Business Review, there are at least three primary ways, the metaverse may assist in putting customers in control: (1) by inventing new ways to discover and explore products, (2) by assisting in the more meaningful integration of physical and virtual product experiences, and (3) by reestablishing connections between people and brands via AI-powered bots known as “digital humans” that can interact with users in virtual environments [53]. By leveraging immersive experiences within the metaverse, brands can create memorable and engaging interactions with their customers, fostering deeper connections and leaving a lasting impact. In the metaverse, brands can create virtual spaces that reflect their identity, values, and products/services. Users can enter these environments and interact with brand experiences. For instance, a clothing brand could offer virtual try-on using AR, enabling customers to visualize themselves in different outfits and make informed purchasing decisions.

2.2.2. Interoperability

Metaverse can be seen as a platform that hosts a variety of applications and services immersed in it. Applications and services are interconnected together, and many experts believe that there will not be one dominating metaverse. Consequently, interoperability is one important characteristic of the metaverse. This can manifest in various forms in the metaverse; one form could be users’ being able to potentially use several applications simultaneously in the metaverse, just as it is now with smartphones. Due to its interconnectivity, the metaverse will also possess the ability of users, rather than platforms, to own virtual objects. Such a scenario will enable users to use virtual items purchased or acquired on one platform on a variety of platforms [33].

2.2.3. Economy

There will be a fully functioning economy in the metaverse to facilitate the buying and selling of digital objects as well as investing. Since the metaverse is interoperable, digital assets bought in one platform could easily be used on different platforms. In this regard, NFTs, cryptocurrencies, or other forms of tokens (present or in the future) are going to play a considerable role in the metaverse. For this, smart contracts and distributed ledger technologies based on blockchain architecture will very certainly be used [33,54].

Other characteristics of the metaverse include:

- Persistence: The ability of the metaverse to exist irrespective of time and place.
- Availability: This means that the metaverse will be open to everyone to use concurrently.

3. Trends in the manufacturing industry

The advent of the fourth industrial revolution brought about a shift from intelligent manufacturing to smart manufacturing, with smart technologies taking center stage in manufacturing [55]. It is called “smart” because, in the entire manufacturing cycle, data is generated and used in the decision-making process. In this section, we present recent groundbreaking technological trends that have been successfully incorporated into the manufacturing industry. These technological trends played and continue to play a pivotal role in the advancement of the manufacturing industry.

3.1. Additive manufacturing

Additive manufacturing (AM), sometimes referred to as 3D printing, involves the making of objects from a 3D model by adding materials layer by layer. AM will play an important role in the manufacturing industry, both now and in the future, as it enables users the ease and flexibility of creating interesting and complex parts. With the application of AM in manufacturing, it opens the possibility of fabricating parts as a single piece rather than coupling several pieces together, as is the case with subtractive processes [57]. Some benefits of incorporating AM into manufacturing include:

1. AM reduces costs since it is an additive process and does not generate much waste.
2. AM leaves a lower carbon footprint.
3. With AM, it is easy to modify a product with less time. [58].

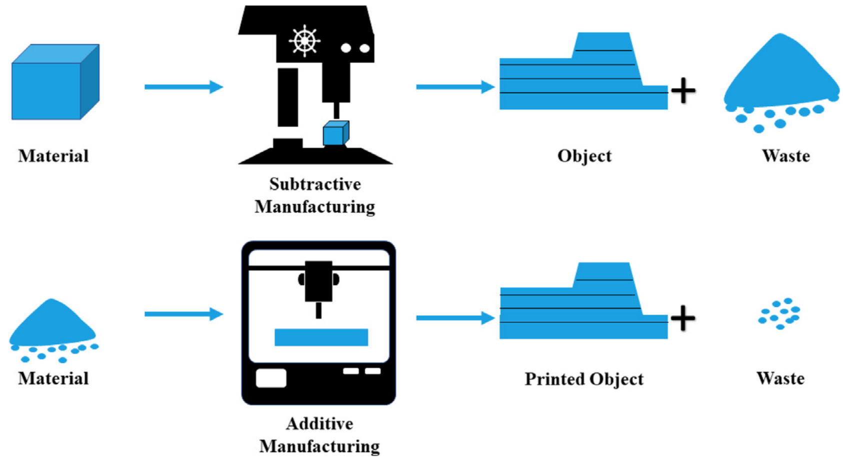


Fig. 4. Comparison between subtractive and additive manufacturing process. Additive manufacturing makes use of less material and produces less waste. *Source:* Reproduced from Adriano et al. [56]., 3D-printing technologies for electrochemical applications.

In Fig. 4, a comparison between AM and its counterpart (subtractive manufacturing (SM)) is presented. As is seen, AM makes use of fewer materials in printing a shape as opposed to the quantity of material needed by subtractive manufacturing to produce the same shape. It can also be seen that at the end of printing and production for both processes, AM produces less waste.

Despite its numerous advantages, institutions have found it difficult to increase the role of AM since its inception in the mid-1980s. This is mainly due to some of the challenges experienced with the technology, one of which is fabricating parts that meet industrial requirements in terms of density, tensile, and hardness. There is still the issue of design patterns, printing errors, and a shortage of qualified personnel [59,60]. AM has a long way to go before it can reach its ideal state, However, in this study, we will be looking at possible ways of addressing some of these issues using the metaverse.

3.2. Artificial intelligence

The introduction of AI technologies into industrial manufacturing has been one of the chief trends that are boosting smart manufacturing. This trend will come to be known as "industrial AI" (IAI). Advancements in branches of AI such as machine learning (ML), deep learning (DL), transfer learning, and computer vision have made it possible to incorporate AI into production processes with great results [61]. So far, AI has been applied in various areas of manufacturing, such as fault diagnosis, quality inspection, remaining useful life (RUL) prediction, and intelligent decision-making and control [62].

Fault diagnosis is the continuous monitoring of a production process or equipment to identify when a fault has occurred and at what part in the production process the fault occurred. The earliest use of AI in manufacturing was the adoption of ML methods for fault diagnosis [63]. The sole aim of fault diagnosis is the prevention of accidents resulting from abnormalities in equipment or manufacturing processes, hence adding safety to industrial manufacturing [64,65]. Various ML and DL methods have been put forward for real-time fault identification [66–69].

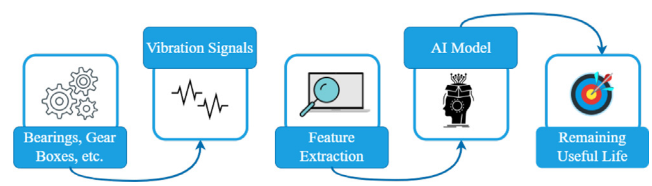


Fig. 5. Predicting remaining useful life of a manufacturing machine using an AI model. The process starts by collecting signals from machine parts and extracting meaningful features which are fed into the AI for prediction [70].

RUL is used to give the lifespan of a component. It is the estimation of when a machine will exceed its useful life and will no longer be able to function properly. One purpose of RUL is to prevent catastrophic failures in manufacturing, which can lead to high costs of maintenance or repair, a setback in the production timeline, or accidents. In Fig. 5, the control flow of RUL is depicted. Sensors placed in bearings, gears, boxes, etc. collect vibration signals. These signals are then processed by extracting useful and valuable features which are later fed into an AI model for RUL prediction. The use of AI has advanced the predictive accuracy of RUL techniques over the years [71–73].

Quality inspection is another field that has been greatly improved by AI. With the aid of AI, it is possible to monitor multistage manufacturing systems and detect quality aberrations early on in the manufacturing process, thereby maintaining the desired standard for a product. Several semi-supervised, unsupervised, and supervised ML algorithms have already been implemented in this regard [74–76]. An agile quality inspection system will invariably lead to a reduction in the wastage of production resources and a reduction in production costs while also speeding up the rate of production [77].

Decision-making and control in the manufacturing process could be in the form of maintenance, resource allocation, or job scheduling. The manufacturing process involves making use of manufacturing resources and knowledge, both of which are affected or influenced by external factors such as demand, and this stipulates the quantity to be produced and the type of

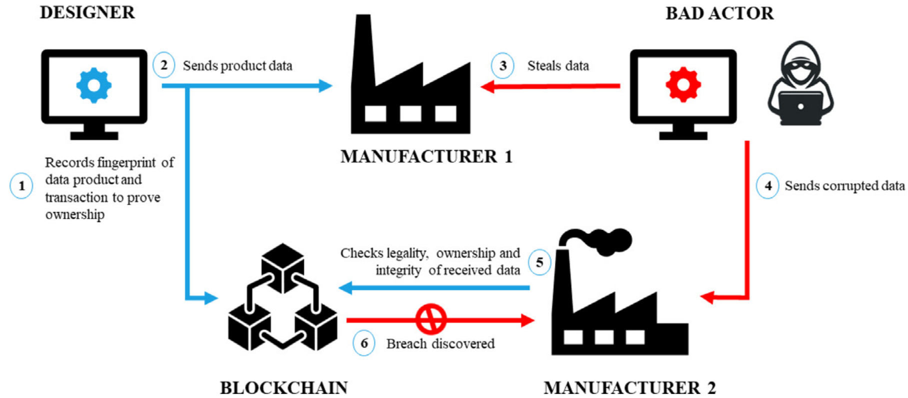


Fig. 6. Using Blockchain to verify messages between a designer and two manufacturers. A bad actor steals and corrupts the file sent to manufacturer 2 from manufacturer 1, but manufacturer 2 can detect the breach.
Source: Adapted from [80] with modifications made to enhance clarity.

resources that need to be used [78]. The reinforcement learning algorithm is widely considered for tackling scheduling problems [79].

For training and learning, AI models are heavily reliant on data. Data has always been employed in the manufacturing process. However, its use in the early times was minimal due to its scarcity. In recent times, the proliferation of IT has resulted in the creation of a colossal amount of data, often referred to as “Big Data”. [81]. Big data is defined not only by the volume of data, but also by velocity, variety, value, and veracity (also known as the 5Vs) [82,83]. Smart sensors have made the process of data collection less strenuous. However, understanding and analyzing this data has become a problem. For example, to get a reliable RUL prediction using any of the AI techniques, the data has to be useful in modeling the AI, and data is not useful unless it is properly processed [84]. Manufacturing systems typically consist of various machines and processes, each of which produces different data. Before such data can be used in any of the AI models, it must be processed with care [85]. The use of AI in robotics has made robots more autonomous. However, to accomplish some difficult tasks, these robots have to be trained with lots of data for a longer period, a process that would be made simpler in the metaverse.

3.3. Blockchain

Several engineering applications and information systems must exchange and share digital product data in order to achieve smart manufacturing [86]. However, this data exchange has been a target of bad actors who want to either steal key production or hack for ransom. This creates the need for a more efficient way to authenticate, authorize, and trace product data [87].

Generally, a Blockchain is a chained data structure that provides a chronological record of blocks of data and information and records the blocks in encrypted form as a distributed ledger that cannot be manipulated or forged [88]. In [89] the American National Institute of Standards and Technology (NIST) uses the Blockchain ledger through a product life cycle to pinpoint violations of non-disclosure agreements (NDAs) and data breaches. By identifying and recording all data transactions without exception, the integrity, legality, and ownership of the received data can be checked just like the manufacturer in Fig. 6. Production tracing typically refers to the path of a product from its origin, while tracking refers to the path from raw material to final product [90].

Blockchain has recently been used to propose solutions to tackle traceability and product tracking in supply chains. In [91] a Blockchain-based ontology promoting provenance in supply chains has been presented. The authors made use of the Solidity smart contract to implement a solution that provides support for some regularly carried out supply chain operations like consuming and producing. In order to obtain a digital representation of physical goods and still maintain supply chain traceability. Authors in [92] proposed a way of using tokens to provide authenticity and use the tokens to link the physical goods and their digital representation. Blockchain has mainly been used to facilitate secure and effective collaboration between companies [93]. However, in [94] a Blockchain solution is proposed to address the problem of individual service integration into the global market; This was achieved by having a huge socioeconomic network and connecting each provider and consumer into the network. In Table 3, we present various sectors along with their corresponding AI and Blockchain applications in manufacturing.

Blockchain, AI, and AM are some of the recent trends in manufacturing. These three technologies are used simultaneously in building more robust, smart, and autonomous factories and production lines [110–112]. These disruptive technologies are also predicted to have a massive impact on the metaverse, especially Blockchain and AI. Currently, NFTs are been used to represent digital assets owned by a user in the metaverse. In the next two sections, we explore aspects of manufacturing where metaverse in combination with some of these technologies can be used to further improve the manufacturing industry.

4. Metaverse in the manufacturing industry

The concept of Metaverse is complex and there is a great amount of uncertainty about how or when it will fully reach its

Table 3
Sectors, AI, and Blockchain applications in manufacturing.

Sector	AI applications	Blockchain applications
Automotive Industry	Quality inspection, fault diagnosis, predictive maintenance, optimization of production processes, robotic automation [95,96].	Vehicle maintenance history tracking, authentication of spare parts, secure payments, peer-to-peer car-sharing [97].
Electronics Industry	Quality control, defect detection, product testing, analysis of complex components and circuit boards.	Supply chain transparency, counterfeit prevention, secure transactions, intellectual property protection [98].
Aerospace and Aviation Industry	Predictive maintenance, real-time monitoring of aircraft systems, quality assurance, optimization of fuel consumption [99].	Improved supply chain management, traceability of components and materials [100].
Pharmaceuticals and Healthcare Industry	Quality control, process optimization, drug discovery, medical imaging analysis, personalized medicine [101].	Drug supply chain traceability, prevention of counterfeit drugs, supply chain integrity [102].
Consumer Goods Industry	Quality inspection, packaging optimization, demand forecasting, supply chain management [103,104].	Product origin and certification tracking, ethical sourcing, recall management [105].
Energy and Utilities Industry	Predictive maintenance, optimization of energy distribution and consumption, anomaly detection in power grids [106].	Peer-to-peer energy trading, tracking renewable energy generation and consumption, secure energy transactions [107].
Food and Beverage Industry	Quality control, food safety monitoring, optimization of production processes [108].	Food traceability, origin verification, prevention of food fraud, recall management [109].

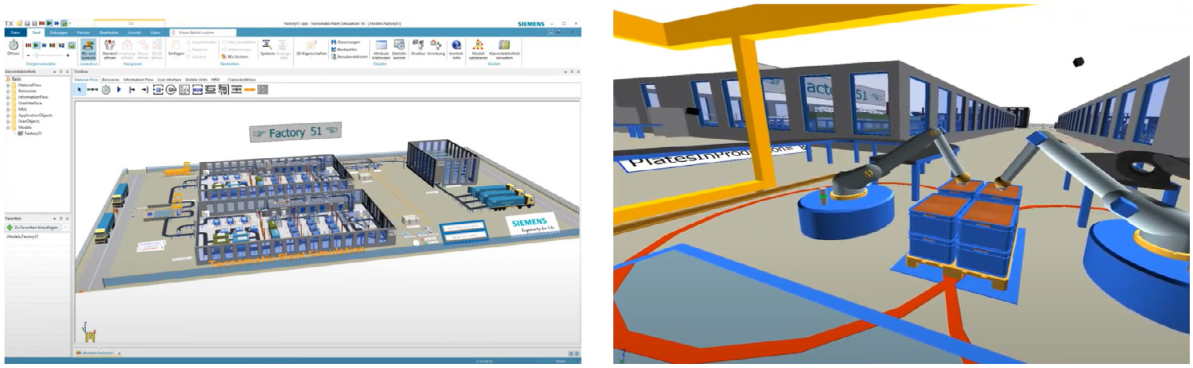
potential, especially in the manufacturing industry. However, we know the technologies that are promoting its rise, and how they have been integrated individually into various manufacturing phases [113,114]. Having said this, in this section, we shall be using a scenario-based approach by exploring possible future applications of a metaverse in the manufacturing industry.

4.1. Prototyping & simulation

There has been an era-long debate on whether prototyping or simulation should be favored in manufacturing. Whichever the industry decides to use more, the incorporation of a metaverse in manufacturing could see both methods highly improved and sophisticated. In AM, for instance, creating a prototype of a part that is to be printed would be easier in the metaverse. By having a part prototype in the metaverse, it becomes easy to interact with such parts and make final decisions or modifications. MR technologies that allow for interaction with overlaid virtual objects could be used in the metaverse to achieve this. Prototyping in AM does not only apply to parts to be printed. A prototype of various design patterns could be made in the metaverse as this will enable a manufacturer to decide on and integrate the right design patterns, especially when they are transitioning from conventional manufacturing to AM.

Simulation typically refers to technologies that model reality. This is another aspect of manufacturing where the metaverse could have a huge positive impact, as some of its elements, such as DT, AR, and VR, have already been used to great effect. VR factory layout simulation (FLS) has been extensively used for solving factory layout planning (FLP) tasks, [115–117]. Fig. 7 showcases the VR factory simulation conducted by Siemens, leveraging their proprietary VR plant simulator called "Tecnomatix". This powerful software enables users to seamlessly model, simulate, visualize, and analyze production systems and logistics processes. The sample depicted in Fig. 7(a) exemplifies a plant simulation created using Tecnomatix. Moreover, the software offers the capability to generate graphical outputs for resource utilization analysis, throughput evaluation, and bottleneck detection. Fig. 7(b) provides a captivating view of the plant from the perspective of a user immersed in the simulation using a VR headset walking inside the virtual plant. In addition, users have the ability to navigate the virtual plant and engage with the system, allowing them to identify areas for potential improvements. By exploring the simulated environment and interacting with various components, users can gain valuable insights into the system's performance and identify optimization opportunities. This immersive experience empowers users to make informed decisions regarding process enhancements and efficiency enhancements.

Although there exist AR solutions [118,119] for FLP tasks, they are outperformed by current VR solutions [120]. With



(a) Plant simulation view (b) VR View

Fig. 7. Tecnomatix VR factory layout simulator made by Siemens [121]. (a) The entire simulation view of the factory using the software. (b) Completed virtual factory as seen from the VR headset.

the metaverse, simulations can get real, as organizations can create DTs of their systems and processes along with a digital user in the metaverse. The metaverse is a virtual world in this case housing the DT and digital user. It has its own economy, digital assets can be bought and sold to create all components of the DT giving it the same look and feel as the physical asset. The digital user or avatar can interact as well as analyze the simulated process or system in real-time, thereby getting an in-depth understanding of the entire chain. A wide variety of scenarios can be simulated based on different options/choices that are available to decision-makers. The ability to simulate multiple scenarios will give an organization enough information which will lead to better decision-making and, invariably, growth of the organization.

There is also the possibility of automated simulations in the metaverse, making use of the real-time data fed into the metaverse and AI. Multiple autonomous simulations could be run in the metaverse and the best scenario implemented. This would be useful when robots are needed to be trained with AI models to carry out varying tasks. A digital replica of the robot could be built in the metaverse and trained simultaneously with different AI models while trying to perform said tasks in the metaverse. The use of AI to train robots in a virtual world is demonstrated in one of our case studies below. The metaverse will also significantly improve the ease of carrying out FLP tasks, applying changes easily on the fly, hence having an optimized production line while bringing production time to the bare minimum.

4.2. Quality assurance

In AM, manufacturers always point to the inconsistency in quality noticed in 3D printed parts. Some of this is a result of a change in temperature [60]. Such issues can be addressed by incorporating metaverse into AM as it will give insight into a real-time temperature reading. Operators can be able to visualize the heat distributions of various parts being printed and can interact with such parts by either increasing or decreasing the temperature. A well-regulated temperature setting will enable the printed part to maintain its quality from start to finish. This concept of visualizing and maintaining heat distribution can also be useful in conventional manufacturing as it affords operators the ease of turning up or down the temperature in a factory shop remotely or physically as the case may be.

4.3. Real-time monitoring & maintenance

The metaverse is an important instrument for real-time monitoring of dynamic conditions in the physical environment [122]. Printing defects caused by printing errors happen now and then, and this always leads to wastage of printing materials, loss of time, and possibly customer dissatisfaction [123]. Metaverse technology can assist in avoiding printing defects by providing real-time monitoring of the entire printing process. This could also be achieved by having a digital version of the process. Monitoring here could give a user information about the material usage, answering questions like, “Is there enough material to complete the printing of a part?” If there is a difference between the part being printed and the final product, it could also be reported to an operator. Getting all this information will enable printing defects to be identified on time and corrected without wasting printing materials. In [124], authors introduced a DT-enabled 3D printer fault detection. They combined a lightweight CNN and DT for monitoring defects in a printer. Similarly, authors in [125] created a DT architecture for the FDM printer. Their DT platform can simulate print results depending on slicer parameter values, allowing the user to fine-tune the parameter if the printed output is likely faulty.

Metaverse real-time monitoring in manufacturing is not limited to just AM. Conventional manufacturing processes can also be greatly revolutionized. Metaverse real-time monitoring in a conventional manufacturing system can enable decision-makers to have an idea of the state of a system even if they are not physically there. Pointing out an area that needs immediate attention could be much easier as the manager can have a view of all systems at the same time and have access to the sensor readings from each area.

Maintenance of various systems can be greatly improved in the metaverse by the real-time influx of data. Technicians or supervisors can be able to see at a glance what maintenance

Fig. 8. A Thyssenkrupp maintenance staff member getting real-time help from a senior staff using Hololens while carrying out a maintenance task [126,127].

has been done on certain parts and when the next maintenance is due just by looking at the part with, say, an MR headset. Repairs can also be carried out with ease since it would be easy to pinpoint a faulty part. With immersive technologies like VR, AR, and MR, remote repair and maintenance will be possible as data can be overlaid in the real world, giving operators real-time data in an industrial environment. An experienced technician will be able to remotely guide a less experienced technician who is in the field without obstructing the technician's views, as is seen in Fig. 8. Researchers over the years have proposed maintenance systems based on AR and VR technologies. Authors in [128] proposed the use of an AR-based infrared marker system for equipment maintenance. The system comprises an infrared filter camera and about six infrared markers. Hence the infrared markers are invisible to the naked eye, so there is no visual obstruction or disturbance. In their use case, they presented the maintenance of a milling machine gearbox where the system presented a technician with overlaid gear model images indicating the function of the gearbox and actions to be performed by the technician as animated 3D models. In [129], an online authoring for AR remote maintenance was proposed. The system allows an experienced operator to develop intuitive, robust, and step-by-step instructions using AR for a less experienced operator to make use of. Authors [130,131] proposed an opportunistic control model for maintenance which reduced task completion time considerably. The design and implementation of a VR and AR-based metaverse for real-time monitoring and maintenance of complex systems will lead to operational efficiency and reduced downtime [132]

4.4. Communication

One of the key characteristics of the metaverse is interoperability. Users can make use of virtual items in different applications, and interact with several applications at the same time [14]. The metaverse can interconnect everything that is embedded within it, and communication between these applications or items becomes increasingly seamless [1]. Putting forth this interoperability and interconnectivity of metaverse into the manufacturing industry could easily bring about better communication amongst processes [133]. For instance, in additive manufacturing, communication between connected printers could enable the drag and drop of 3D models. This becomes important when one printer is sitting idle while another has a couple of tasks in its queue. An operator could easily drag one task from the queue and drop it onto the idle printer. The system could also be programmed to automatically perform the dropping of a task to an idle printer making the entire process autonomous.

Communication can also occur among processes in a factory shop. Since the metaverse connects processes, a factory shop in the metaverse could be built to have its processes share information [133]. Different processes within the factory shop can access and exchange relevant data, such as production schedules, quality metrics, and inventory levels, in a centralized virtual environment. This shared information promotes transparency, enables better planning, and facilitates synchronized operations across different departments or workstations. For instance, consider two processes, A and B, where B can only start after A has completed its task. With communication in the metaverse, all process B needs to do is wait till process A sends a report on its status (complete or incomplete). Based on such a report, process B can either fire up or call another process for debugging (in the case of an incomplete status from process A). All this can be achieved without the presence of an operator. Communication in the metaverse through the help of various devices (VR/AR/MR), and/or sensors will create a future for fully autonomous manufacturing.

4.4.1. Communication for better collaboration

Human-centered communication has come a long way and will play a pivotal role in the metaverse and its application in manufacturing [134,135]. It would allow workers to work together while in different locations [135]. With metaverse, product designers, factory floor planners, and a series of other workers can comfortably work on the same project while staying in different locations. This unique attribute will be seen in the next section when we take a look at the BMW factory of the future. However, for this to happen there needs to be a major breakthrough in human-centered communication. For example, [136], the authors use 3D simulation technology to create a system called "Avatar to Person", which is aimed to repair virtual faces and provide a simulated voice for the disabled. It ultimately allows humans to interact properly.

4.5. Immersive training

Manufacturing industries make use of complex processes and machinery. Getting and training workers to be able to operate the machines and perform the processes is often challenging. The immersive nature of the metaverse can be used in addressing these problems, as staff could be placed in a fully immersive experience of their roles. Immersive technologies and digital twins have already been used to achieve similar results. With a digital twin, a replica of a factory could be made in the metaverse, allowing personnel to be properly

Fig. 9. With the help of Hololens the technician is able to project overlaid step-by-step instructions while carrying out repair on a generator [126,127].

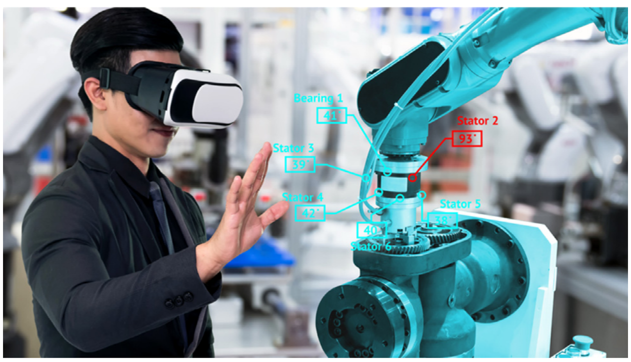


Fig. 10. VR training in an industrial environment [theintellify.com].

trained. This can lead to a very significant reduction in training injuries, especially for exercises that involve dangerous machines or substances. Immersive training will no doubt be of huge benefit in AM as workers can easily be properly trained giving rise to an increase in skilled personnel. On the financial implications of immersive training, this will surely cost less in the long run as trainees will not be required to learn with raw materials or physical machines [137,138].

As always, XR technologies are at the heart of immersive training in the metaverse. So far, we have witnessed many companies from various industries incorporate VR training into their training processes. Walmart, for instance, makes use of VR to assess and train its workforce. AST, a pioneer in digital safety training, now offers all its training (practical and theoretical) using VR technologies. Porsche created a VR training experience to teach their employees the various components of an electric vehicle. In the metaverse, training can also happen while working, with technologies like AR and MR that do not obstruct the view of a user. As shown in Figs. 9 and 10, training videos could be overlaid as virtual objects, and a technician could easily follow the video step-by-step while performing repairs or an employee learning a new product flow while working.

A summary of the benefits that will arise from immersive training in the metaverse includes but is not limited to:-

1. Hands-on learning by direct engagement.
2. Reduce the possibility of injury in dangerous jobs.
3. Cost-cutting in training
4. Remote and continuous learning. All that is needed are wearable devices.
5. Simulate complex processes that rarely occur in production.
6. Continuous improvements.

A summary of the few prospective economic benefits the metaverse will bring to manufacturing include:

1. The integration of the metaverse in factory operations has the potential to create optimal factory floors, resulting in higher production output. By leveraging metaverse technologies, factories can design and simulate virtual factory layouts that are optimized for efficiency, productivity, and streamlined workflows [139,140].
2. The incorporation of the metaverse in digital product design offers significant cost and time savings by eliminating the need for physical mockups. With virtual modeling and simulation capabilities, designers can create detailed and realistic representations of products, allowing for accurate visualization and evaluation before physical production begins. By digitally iterating and refining designs in the metaverse, manufacturers can identify and address potential flaws or design challenges early in the process [141,142].
3. The implementation of immersive training for factory workers in the metaverse has the potential to significantly reduce training costs. By leveraging metaverse components, immersive training provides a realistic and interactive learning environment that closely replicates real-world factory scenarios. Moreover, immersive training in the metaverse often incorporates performance tracking and analytics capabilities which trainers can to monitor trainee progress, identify areas needing improvement, and provide targeted feedback for individual learners [137,138].
4. Through constant monitoring and effective maintenance enabled by the metaverse, machine downtime can be significantly minimized. The real-time monitoring and data analysis capabilities of the metaverse allow for proactive maintenance, identifying potential issues before they result in significant disruptions to production. This ensures smooth operations, increased productivity, and optimized equipment utilization [141].

In general, the metaverse hype will continue to expand, but just like John Burton, CEO of UrsaLeo said, “experimentation is the key” for companies if we are to move beyond the limitations of the “real world”. From this, it is fair to say that the continuous exploration of innovative approaches and integration methods will persist in the metaverse until the optimal ideas and methods are realized. Moreover, with the rapid proliferation of wearables and related technologies, the ease of implementing and using the metaverse for manufacturing will be greatly improved. Moreover, with the rapid proliferation of wearables and related technologies, the ease of implementing and using the metaverse for manufacturing will be greatly

Table 4
Comparison of potential benefits: Existing manufacturing processes vs. Metaverse in manufacturing.

Aspect	Existing manufacturing processes	Metaverse in manufacturing
Design and Prototyping	Physical prototypes often required for testing.	Virtual prototypes for quick and cost-effective testing.
	Limited collaboration in the design phase.	Collaborative design sessions in a virtual environment.
Simulation and Training	Training often involves physical equipment.	Immersive virtual training simulations.
	Limited access to real-world scenarios for training.	Realistic training scenarios in virtual environments.
Maintenance and Troubleshooting	On-site maintenance and troubleshooting.	Remote troubleshooting using AR/VR for virtual equipment.
	Downtime during maintenance activities.	Reduced downtime through remote maintenance.
Supply Chain Management	Limited real-time visibility in the supply chain.	Comprehensive real-time visualization of the supply chain.
	Reactive responses to supply chain disruptions.	Proactive response to changes through virtual monitoring.
Collaboration	Traditional communication tools for collaboration.	Virtual collaborative spaces for global teamwork.
	Challenges in coordinating teams across locations.	Improved coordination and decision-making in real-time.
Quality Control	Physical inspections and quality control measures.	Virtual replicas for thorough quality control inspections.
	Time-consuming manual inspection processes.	Efficient and automated quality control in virtual space.
Customization and Personalization	Limited options for customization in mass production.	Virtual interaction for personalized product customization.
	Tailoring products often involves manual adjustments.	Efficient production of customized items based on virtual specs.
Data Analysis and Optimization	Limited data analytics for process optimization.	Integration with advanced analytics tools for optimization.
	Reactive approach to addressing inefficiencies.	Proactive optimization based on real-time data analysis.
Smart Factories	Limited connectivity among machines and systems.	Integration with IoT for smart, interconnected factories.
	Manual monitoring and control of production processes.	Real-time monitoring and control of processes through connectivity.

improved. Table 4 depicts a comparison between the potential benefits of integrating the metaverse into manufacturing and existing manufacturing processes

5. Metaverse use cases

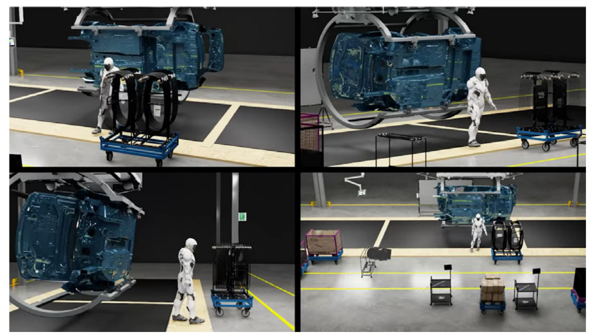
The automobile giant BMW recently teamed up with the chipmaker Nvidia to produce what it calls the "factory of the future". By making use of Nvidia Omniverse [144] and Nvidia AI, BMW was able to create a digital twin of their Regensburg factory. The details of this factory were released at the Nvidia GTC conference held in November 2021. According to Nvidia's vice president, Omniverse is a platform that allows for simulation and collaboration. People can bring in their existing workflows to create virtual worlds while also connecting to those virtual worlds.

This virtual factory [143] is BMW's idea of simulating their entire planning processes, as depicted in Fig. 11. In their presentation, they showed two planning experts located in two different parts of the world testing a newline design in Omniverse. While one expert wormhole into an assembly simulation with a motion capture suit recording task movements, the other expert adjust the line design in real time. Both experts were seen working together to optimize the production line as well as workers' ergonomics and safety. However, this process is still time-consuming and energy-intensive. In order to achieve this process in scale and in simulation, BMW made use of Nvidia Digital Human for simulation. Digital humans are trained with data from real experts. Using digital humans, thousands of simulations can be run to test new workflows for worker ergonomics and efficiency.

(a) Digital human simulation for better worker ergonomics.

(b) Digital human simulation for better worker ergonomics inside of a virtual factory.

(c) Virtual factory simulation depicting humans and robots working together.



(d) Two BMW planning experts are designing and testing a new production line in Omniverse. Both experts are in different places.

Fig. 11. BMW and Nvidia presentation of BMW factory of the future using Nvidia Omniverse and digital humans at the Nvidia GTC 2021 conference [143].

Fig. 11(a) & 11(b) depicts how workers' ergonomics is been simulated and studied in the Omniverse. The first involved simulating workers' picking up (invincible) objects from various heights while. Data collected from this process enables the factory floor planners to determine the height placements of objects in the factory. In the second image, the humans are placed in the virtual factory picking and moving objects. The object heights and placement were a result of the simulation done in the first image. Fig. 11(c) shows the finished virtual factory with humans and robots working side-by-side. Lastly, Fig. 11(d) gives a view of the factory planners, both of who are in different locations but are able to use the Omniverse in working together to plan and test the new production line.

Omniverse has helped BMW create a futuristic virtual factory where an entire production line can be simulated. The production process can be visualized from beginning to end. It also has AI simulations of workers in the form of avatars moving around the factory, handling parts, and interacting with robots to improve productivity and ergonomics.

5.1. KAIST metaverse factory experience center

The Korea Advanced Institute of Science and Technology (KAIST) recently inaugurated an immersive metaverse factory experience center dedicated to manufacturing AI seen in Fig. 12. This cutting-edge facility aims to offer visitors an unparalleled real-life experience in the analysis of manufacturing data. Through the convergence of artificial intelligence (AI) and the metaverse, users have the unique opportunity to engage directly with the aggregation, analysis, and utilization of manufacturing data. At the metaverse factory experience center, participants can delve into a virtual factory environment specifically designed for plastic manufacturing. By leveraging advanced AI technologies and the immersive capabilities of the metaverse, visitors can explore and interact with a digital representation of a factory. This virtual factory enables users to gain a comprehensive understanding of the intricacies involved in analyzing manufacturing data [145].

The virtual factory is a plastic production factory, and it combines AI and the metaverse. Users can access the factory from any location by using either AR, VR, or XR equipment and a metaverse solution. The virtual factory makes it easy to run simulations of products to be produced. There is also the capability of collecting parameters such as temperature, pressure, and speed during production. With these parameters, the metaverse factory can detect and analyze defects and their causes. It can also give a detailed analysis of production, suggest ways of improvement, and improve the quality of the product at each step in the production cycle.

6. Current issues in metaverse

The majority of this study so far has been dedicated to understanding the metaverse, its main concept, and the technologies driving this innovation. Also, in the previous section, probable applications of a metaverse in industrial manufacturing were explored to give an early insight into how a metaverse could revolutionize the manufacturing industry. Although it adopts some current technologies, the metaverse presents a

Table 5
Characteristics and limitations of batteries in wearable devices.

Battery type	Characteristics	Limitations in wearable devices
Lithium Coin	Small and lightweight. Long shelf life. Low self-discharge rate.	Limited energy density for extended use in power-hungry wearables.
Lithium Ion	High energy density. Lightweight. Rechargeable.	Limited flexibility and form factor for certain wearable designs. Risk of thermal runaway in some conditions.
Lithium Polymer	Thin and flexible. High energy density. Rechargeable.	Susceptible to aging, affecting overall lifespan. Potential for swelling and gas buildup.
Graphene	Lightweight. High conductivity. Flexible. Fast charging.	Limited commercial availability and high production costs. Challenges in scalable manufacturing.

Fig. 12. A plastic manufacturing metaverse factory experience center. To the right is a plastic bolt manufactured at the metaverse factory.

near-total shift from previous paradigms. Adopting current technologies makes the metaverse open to the (cyber) threats faced by each of those technologies, and being a new paradigm means that it also has some threats and limitations that have not yet been explored. Moreover, these technologies are being adopted at a much faster pace than the study of their risks. Put all these factors together and it becomes obvious that the metaverse is vulnerable to (possibly) an unprecedented number of threats that might slow down its adoption, especially in critical sectors such as manufacturing. In this section, the possible threats and limitations facing the metaverse generally are discussed.

6.1. Limitations

6.1.1. Hardware limitations

Hardware in the metaverse will typically be in the form of wearable devices. Wearable devices (or wearables for short) have been vital to the success of immersive technologies, and they will no doubt play a tremendous role in the metaverse. Wearables are usually fitted with sensors that collect data and send feedback to the operator.

Availability & Durability: These devices are limited in supply as the research is young and still ongoing. Companies like Meta are working on Oculus Quest 2 and reskin (a wearable skin), while HaptX just released the DK2 gloves and is furthering its research on haptic gloves. The continuous research and development into wearables mean the metaverse future looks good. However as it stands today, advanced wearables are limited and the gap between real and virtual worlds can only be bridged by advancements in wearables. Ensuring durability in manufacturing wearables is vital for sustained functionality. Evaluating construction materials like reinforced polymers or impact-resistant alloys is crucial for resilience in harsh industrial conditions. Balancing durability with ergonomic design is key, as research indicates a well-designed wearable enhances reliability in industrial settings [146].

Battery Life: Another critical issue that has not attracted much attention is the battery life of wearables. The functions performed by wearables are consistently increasing thus leading to an increase in power consumption [147]. HMDs rely on Lithium-based batteries, with examples including the custom-built lithium-ion (Li-ion) battery in Microsoft's HoloLens 1 and the enhanced 36.25 watt-hour (Wh) Li-ion battery in HoloLens 2. In contrast, the Oculus Rift, designed as a tethered PC-based headset, draws power directly from the connected computer and lacks an integrated battery. The Oculus Quest and Oculus Quest 2, designed for standalone use, incorporate Li-ion batteries, with the Oculus Quest 2 featuring a built-in 13.14 Wh capacity. The now-discontinued Google Glass employed a non-removable lithium polymer battery with a reported 570 mAh capacity. In contexts such as industrial manufacturing, where uninterrupted access to the metaverse is crucial, ensuring prolonged battery life is imperative.

Lithium remains the predominant element in batteries due to its status as the lightest metal, making it a prevalent choice for wearable devices. Table 5 provides an overview of different wearable battery types, outlining their respective characteristics and limitations. Despite substantial efforts in advancing battery technologies, they continue to pose a significant limitation to the progress of wearable technology. The development of battery technology has not kept pace with the rapid advancements in wearable technology. As a result, alternative solutions such as energy-efficient sensing [148] and energy harvesting [149] are being actively explored to address these constraints. [150]

6.1.2. Software limitations

AR/VR/MR developers at the moment are in short supply, so developing for the metaverse is difficult. Even when these developers are available, most of the time they lack the skills needed to create applications for the metaverse, and the materials to learn those skills are not readily available. This can lead to applications where the underlining software is prone to attacks as the proper cybersecurity measures were not followed by the developers. Care must be taken in the future to have cybersecurity measures taken at the onset when developing applications to be used in the metaverse.

6.2. Privacy & security

There is already a massive amount of data generated today from the internet, especially since the proliferation of the industrial internet of things [7]. Metaverse although still in its infant days will undoubtedly generate a sheer amount of data through applications and wearable devices [151]. Lawmakers are yet to understand the current social media platforms. One can only imagine how long it would take for them to fully grab the concept of the metaverse and come up with adequate policies to protect the general public. Privacy and Security, an age-long problem to the internet is perceived as the greatest concern of the metaverse.

The pervasive nature of immersive technologies (especially AR and MR) means that metaverse applications will have access to a plethora of users' information (including confidential data) like never before. This unprecedented generation and access to data raise a few security challenges. How does a metaverse application company use and store such data? How is the data secured by these companies? Do third-party applications have access to such data, and if they do, to what extent? What happens when a device is stolen or hacked by an attacker? All of these are security questions that need to be answered to guarantee safety and security in the metaverse [152]. In the rest of this section, some scenarios where privacy and security will be targeted in the metaverse are explored.

6.2.1. Data storage & connectivity

It is no secret that companies rely on third-party libraries for fast development and the cloud for both connectivity and data storage. Hence the cloud architecture and other third-party libraries (especially those used by cloud platforms) become potential targets for adversaries. The man-in-the-middle attack is a very common form of attack on Web 2.0 and will be carried over to the metaverse. An adversary could gain access to a user's information by intercepting data moving between the metaverse and the cloud. This form of attack can be passive or active as the attacker might have enough skills to alter the data [153]. Furthermore, because the data will be stored in the cloud, a breach in cloud security will expose a massive amount of confidential information to an adversary and disrupt metaverse application(s) that use such cloud services.

Wearables can access the metaverse because of the interconnectivity made available by the metaverse. This opens the possibility of an adversary hacking a wearable device for malicious purposes. For a secure metaverse, adequate care needs to be taken in securing third-party servers and cloud platforms, especially as they will be used for processing and storing confidential information. Also important is the physical protection of wearables by operators so they do not fall into the wrong hands.

Concerning manufacturing industries and adopting the metaverse, the importance of securing and storing data cannot be overemphasized. Companies would want to be guaranteed that their product designs, production processes, and other intellectual properties used during manufacturing do not get into the hands of rivals or adversaries looking for ransom. Safety is an important issue in the manufacturing industry, where a hacked device might operate a dangerous machine, which might lead to physical injuries or even death.

6.2.2. Distributed denial of service

Distributed denial of service (DDoS) occurs when a server is flooded with a continuous large amount of traffic, rendering such a server incapable of responding to legitimate traffic. This type of attack has been around for a while [154] and could be a potential problem for the metaverse. Communication and connection are two important aspects of the metaverse, and a DDoS attack will make both unattainable when successfully carried out.

Consider a technician using AR technologies to get real-time help, and that technician gets cut off from that service as a result of a DDoS attack. In such a situation, the technician would be unable to carry out the repair or maintenance, which then leads to a slowdown in production. For immersive learning with metaverse, a DDoS attack will cause a delay in training as trainees will not be able to access the training platform or application, and hence will not be able to learn the needed skills on time to carry out their tasks.

6.2.3. Authentication and authorization

Authentication and authorization of online content and users continue to be a problem, one that will only be exacerbated by the metaverse. Bot detection algorithms have been demonstrated to be ineffective at distinguishing between bots and humans online [155]. Moreover, the steady and rapid advancements in AI have made it easy for automated accounts to be created indistinguishable from humans [156]. AI and ML technologies have now been used by adversaries in creating "deepfakes", which are digital replicas of people.

Motion tracking devices can only make creating deepfakes easier if an adversary gets access to such a device [157], resulting in identity thefts. There is also the possibility of obtaining users' passwords using data stolen from finger-tracking applications in the metaverse if such applications are used to enter a user's password. For example, in 2022, the accounts of 17 Opensea NFT marketplace customers were hacked owing to smart contract issues and phishing assaults, resulting in a $1.7 million loss [158]. Over the past few years, hackers have managed to seize NFTs worth more than $600 million [159]. There needs to be a more robust way of verifying that a user is who they say they are in the metaverse before they can avail of its services and applications. Aside from the issues listed here, the metaverse also poses a list of social problems, some of which can be confronted by effective legislation [160].

Table 6
Common security and privacy challenges in the metaverse along with their potential solutions.

Security and privacy issue	Solution
DDoS Attacks	Employ a combination of ML-based detection models, rate limiting, traffic filtering, and CDN services for a comprehensive DDoS protection strategy.
Authentication & Authorization	Implement blockchain for secure and decentralized identity management. Utilize multi-factor authentication, including token-based methods, and biometric authentication. Consider factors like secure session management and the principle of least privilege.
Data Leakage/Privacy	Mitigate data leakage through Federated Learning, which enables model training without centralized data. Utilize advanced cryptographic techniques such as differential privacy or secure multiparty computation to enhance privacy.
Biometric Leakage	Employ homomorphic encryption to process biometric data without exposing raw information during computation. This ensures a higher level of privacy for sensitive biometric information.

6.2.4. Mitigation strategies

Privacy and security have been an age-old problem, one that will only get more complicated in the metaverse. There is a need for cybersecurity experts to be at the forefront when it comes to developing metaverse applications [54]. In addition, lawmakers have to pass meaningful and precise laws to safeguard the metaverse and its users.

Blockchain [161], AI [162], cryptography, homomorphic encryption, differential privacy [163], and two or three-factor authentication [164] are some of the key technologies that will play pivotal roles in securing the metaverse. In Table 6, some common security and privacy challenges in the metaverse along with their potential solutions are presented.

6.3. Metaverse scalability

The expansion of the metaverse is anticipated to persist alongside the increase in user influx and data generation. Consequently, scalability emerges as a notable concern. The metaverse's inherent interoperability renders it particularly amenable to scalability, given its dependence on pre-existing technologies [54]. Here, we delve into two such technologies and their potential contributions to scaling the metaverse.

Blockchain scalability: The scalability of the metaverse using blockchain can be achieved through the implementation of decentralized protocols and smart contracts that enable interoperability across virtual worlds and applications. Blockchain's distributed ledger technology ensures transparency, security, and immutability of assets, fostering a seamless and trustless environment within the metaverse. By leveraging scalable blockchain solutions, such as layer 2 solutions or sharding, the metaverse can accommodate a large number of users and transactions while maintaining efficiency. Additionally, blockchain-based decentralized finance (DeFi) mechanisms can facilitate a robust virtual economy, allowing users to securely trade, buy, and sell virtual assets across different metaverse platforms, further contributing to the scalability and sustainability of the metaverse ecosystem.

Network Technology: The scalability of the metaverse can be significantly enhanced through the integration of advanced network technologies like 6th-Generation Networks (6G). The ultra-fast and low-latency capabilities of 6G networks enable seamless real-time interactions and high-quality, immersive experiences within the metaverse. Increased data transfer speeds and improved network reliability contribute to a more responsive and dynamic virtual environment, accommodating a growing user base and complex virtual interactions. The integration of 6G technologies can also support the efficient deployment of edge computing, reducing latency and enhancing the overall performance of metaverse applications. This convergence of the metaverse and cutting-edge network technologies fosters a more scalable, interconnected, and immersive digital reality for users worldwide [165].

7. Future work

The earlier sections of this study presented the concept of the metaverse, manufacturing, trends in manufacturing, the application of metaverse in manufacturing as well as the current issues associated with the metaverse. In this section, based on the current issues addressed above, we shall attempt to set directions for all possible future solutions aimed at addressing said issues.

Blockchain Integration: Explore the application of blockchain technology to enhance data acquisition and storage security in the metaverse. Investigate how blockchain can provide decentralized and tamper-resistant data storage, authentication, and verification mechanisms to ensure data integrity and protect sensitive information.

Privacy and Security Frameworks: Develop robust privacy and security frameworks specifically tailored for the metaverse in manufacturing [166]. Identify potential vulnerabilities and threats associated with data sharing, access control, and user identification. Design encryption protocols, access management systems, and authentication mechanisms to safeguard against unauthorized access and data breaches.

Efficient Data Sharing: Explore how blockchain can facilitate efficient and secure data sharing between various manufacturing processes in the metaverse. Investigate the implementation of smart contracts and decentralized data marketplaces to enable controlled data exchange, ensuring transparency, trust, and fair compensation for data contributors.

Connectivity and 6th-Generation Networks: Investigate the role of 6G networks in improving connectivity within the metaverse for manufacturing. Analyze the potential benefits of ultra-low latency, high bandwidth, and reliable communication networks in enabling real-time collaboration, remote operations, and seamless integration of manufacturing processes.

User Experience and Human–Machine Interaction: Study and develop user-centered design principles for the metaverse in manufacturing. Explore intuitive interfaces, gesture recognition, voice commands, and immersive interactions to enhance user experience and efficiency in performing manufacturing tasks within the metaverse.

Standardization and Interoperability: Address the challenges of standardization and interoperability in the metaverse for manufacturing. Collaborate with industry organizations, research institutions, and regulatory bodies to establish common protocols, data formats, and interoperable systems that enable seamless integration of diverse manufacturing technologies and platforms.

Ethical and Legal Considerations: Investigate the ethical and legal implications of metaverse application in manufacturing. Examine issues related to data ownership, intellectual property rights, privacy regulations, and liability frameworks. Develop guidelines and policies to ensure responsible and ethical use of the metaverse technology in the manufacturing domain.

By focusing on these directions, future research can contribute to the advancement of the metaverse in manufacturing, addressing current limitations and paving the way for a secure, efficient, and transformative virtual manufacturing environment.

8. Conclusion

Metaverse is an immersive 3D representation of a virtual world. In this study, the concept, meaning, and characteristics of the metaverse were presented. Immersive technologies including VR, AR, XR, and MR were also discussed. Then we looked at three technologies currently making huge impacts in manufacturing, which included AI, AM, and Blockchain. Five possible applications of a metaverse in manufacturing were also addressed. This study also included two sample cases of the metaverse in manufacturing. First is the BMW factory of the future that uses Nvidia Omniverse to create a virtual factory where planning and simulation of their production lines are carried out. In the second sample case, the KAIST metaverse factory experience center was presented. The center allows users to have first-hand experience in the aggregation, analysis, and usage of manufacturing data. The Metaverse can revolutionize the manufacturing industry, bringing us factories of the future. However, as pointed out in this study, there are still issues that need to be addressed if the metaverse is to be used safely and securely. Some of these perceived challenges include software and hardware limitations, users' privacy in the metaverse, and security issues such as DDoS attacks, device vulnerabilities, and data management. To fully exploit to a great extent the benefits of a metaverse in manufacturing, experimentation is the key. Furthermore, further advancements in wearable devices will enable fast adoption. We hope this study can be a template to guide the research community going forward on the applications of a metaverse in the manufacturing industry.

Declaration of competing interest

The authors declare that there is no conflict of interest in this paper.

Acknowledgments

This research was supported by Kumoh National Institute of Technology (2021).

References

[1] S.-M. Park, Y.-G. Kim, A metaverse: Taxonomy, components, applications, and open challenges, IEEE Access 10 (2022) 4209–4251, http://dx.doi.org/10.1109/ACCESS.2021.3140175.

[2] J. Joshua, Information bodies: Computational anxiety in Neal Stephenson's snow crash, Interdiscipl. Lit. Stud. 19 (1) (2017) 17–47.

[3] J.N. Njoku, C.I. Nwakanma, G.C. Amaizu, D.-S. Kim, Prospects and challenges of Metaverse application in data-driven intelligent transportation systems, IET Intell. Transp. Syst. 17 (1) (2023) 1–21, http://dx.doi.org/10.1049/itr2.12252, https://ietresearch.onlinelibrary.wiley.com/doi/abs/10.1049/itr2.12252.

[4] O. Okorie, R. Subramoniam, F. Charnley, J. Patsavellas, D. Widdifield, K. Salonitis, Manufacturing in the time of COVID-19: An assessment of barriers and enablers, IEEE Eng. Manag. Rev. 48 (3) (2020) 167–175, http://dx.doi.org/10.1109/EMR.2020.3012112.

[5] Y.-C. Lin, M.-H. Hung, H.-C. Huang, C.-C. Chen, H.-C. Yang, Y.-S. Hsieh, F.-T. Cheng, Development of advanced manufacturing cloud of things (AMCoT)—A smart manufacturing platform, IEEE Robot. Autom. Lett. 2 (3) (2017) 1809–1816, http://dx.doi.org/10.1109/LRA.2017.2706859.

[6] F.-T. Cheng, H. Tieng, H.-C. Yang, M.-H. Hung, Y.-C. Lin, C.-F. Wei, Z.-Y. Shieh, Industry 4.1 for wheel machining automation, IEEE Robot. Autom. Lett. 1 (1) (2016) 332–339, http://dx.doi.org/10.1109/LRA.2016.2517208.

[7] T.D. Hoa, N. Krommenacker, P. Charpentier, D.S. Kim, The internet of things for logistics: Perspectives, application review, and challenges, IETE Tech. Rev. (2020) 1–29, http://dx.doi.org/10.1080/02564602.2020.1827308.

[8] H. Tran-Dang, N. Krommenacker, P. Charpentier, D. Kim, Toward the internet of things for physical internet: Perspectives and challenges, IEEE Internet Things J. 7 (6) (2020) 4711–4736, http://dx.doi.org/10.1109/JIOT.2020.2971736.

[9] Second life, 2023, URL https://en.wikipedia.org/wiki/Second_Life. (Accessed 01 February 2023).

[10] Bitcoin white paper, 2023, URL https://bitcoin.org/bitcoin.pdf. (Accessed 01 February 2023).

[11] Q. Wang, R. Li, Q. Wang, S. Chen, Non-fungible token (NFT): Overview, evaluation, opportunities and challenges, 2021, arXiv preprint arXiv:2105.07447.

[12] Ethereum white paper, 2023, URL https://ethereum.org/en/whitepaper/. (Accessed 01 February 2023).

[13] L. Wang, A.J. Shih, Challenges in smart manufacturing, J. Manuf. Syst. 40 (2016) 1, http://dx.doi.org/10.1016/j.jmsy.2016.05.005, URL https://www.sciencedirect.com/science/article/pii/S0278612516300188. SI:Challenges in Smart Manufacturing.

[14] A. Petrakou, Interacting through avatars: Virtual worlds as a context for online education, Comput. Educ. 54 (4) (2010) 1020–1027.

[15] C. Anthes, R.J. García-Hernández, M. Wiedemann, D. Kranzlmüller, State of the art of virtual reality technology, in: 2016 IEEE Aerospace Conference, 2016, pp. 1–19, http://dx.doi.org/10.1109/AERO.2016.7500674.

[16] N. Pellas, S. Mystakidis, I. Kazanidis, Immersive virtual reality in K-12 and higher education: A systematic review of the last decade scientific literature, Virtual Real. 25 (3) (2021) 835–861.

[17] R. Tesic, P. Banerjee, Exact collision detection using virtual objects in virtual reality modeling of a manufacturing process, J. Manuf. Syst. 18 (5) (1999) 367–376.

[18] W.B. Lee, C.F. Cheung, J. Li, Applications of virtual manufacturing in materials processing, J. Mater. Process. Technol. 113 (1–3) (2001) 416–423.

[19] S. Robinson, Simulation model verification and validation: Increasing the users' confidence, in: Proceedings of the 29th Conference on Winter Simulation, 1997, pp. 53–59.

[20] M.W. Rohrer, Seeing is believing: The importance of visualization in manufacturing simulation, in: 2000 Winter Simulation Conference Proceedings (Cat. No. 00CH37165), vol. 2, IEEE, 2000, pp. 1211–1216.

[21] J. Carmigniani, B. Furht, Augmented reality: An overview, in: Handbook of augmented reality, Springer, 2011, pp. 3–46.

[22] P.T. Ho, J.A. Albajez, J. Santolaria, J.A. Yagüe-Fabra, Study of augmented reality based manufacturing for further integration of quality control 4.0: A systematic literature review, Appl. Sci. 12 (4) (2022) 1961.

[23] G. Plakas, S. Ponis, K. Agalianos, E. Aretoulaki, S. Gayialis, Augmented reality in manufacturing and logistics: Lessons learnt from a real-life industrial application, Procedia Manuf. 51 (2020) 1629–1635, http://dx.doi.org/10.1016/j.promfg.2020.10.227, URL https://www.sciencedirect.com/science/article/pii/S2351978920320989. 30th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2021).

[24] M.-H. Stoltz, V. Giannikas, D. McFarlane, J. Strachan, J. Um, R. Srinivasan, Augmented reality in warehouse operations: Opportunities and barriers, IFAC-PapersOnLine 50 (1) (2017) 12979–12984, http://dx.doi.org/10.1016/j.ifacol.2017.08.1807, URL https://www.sciencedirect.com/science/article/pii/S2405896317324291. 20th IFAC World Congress.

[25] P.T. Ho, J.A. Albajez, J. Santolaria, J.A. Yagüe-Fabra, Study of augmented reality based manufacturing for further integration of quality control 4.0: A systematic literature review, Appl. Sci. 12 (4) (2022) 1961.

[26] S.K. Ong, M.L. Yuan, A.Y.C. Nee, Augmented reality applications in manufacturing: A survey, Int. J. Prod. Res. 46 (10) (2008) 2707–2742, http://dx.doi.org/10.1080/00207540601064773.

[27] M. Lee, N. Norouzi, G. Bruder, P.J. Wisniewski, G.F. Welch, Mixed reality tabletop gameplay: Social interaction with a virtual human capable of physical influence, IEEE Trans. Vis. Comput. Graph. 27 (8) (2019) 3534–3545.

[28] M. Juraschek, L. Büth, G. Posselt, C. Herrmann, Mixed reality in learning factories, Procedia Manuf. 23 (2018) 153–158.

[29] L. Rodriguez, F. Quint, D. Gorecky, D. Romero, H.R. Siller, Developing a mixed reality assistance system based on projection mapping technology for manual operations at assembly workstations, Procedia Comput. Sci. 75 (2015) 327–333.

[30] J. Lee, S. Han, J. Yang, Construction of a computer-simulated mixed reality environment for virtual factory layout planning, Comput. Ind. 62 (1) (2011) 86–98.

[31] E. Bottani, F. Longo, L. Nicoletti, A. Padovano, G.P.C. Tancredi, L. Tebaldi, M. Vetrano, G. Vignali, Wearable and interactive mixed reality solutions for fault diagnosis and assistance in manufacturing systems: Implementation and testing in an aseptic bottling line, Comput. Ind. 128 (2021) 103429.

[32] D. Mourtzis, J. Angelopoulos, N. Panopoulos, Integration of mixed reality to CFD in industry 4.0: A manufacturing design paradigm, Procedia CIRP 107 (2022) 1144–1149.

[33] L.-H. Lee, T. Braud, P. Zhou, L. Wang, D. Xu, Z. Lin, A. Kumar, C. Bermejo, P. Hui, All one needs to know about metaverse: A complete survey on technological singularity, virtual ecosystem, and research agenda, 2021, arXiv preprint arXiv:2110.05352.

[34] M. Batty, Digital twins, Environ. Plan. B: Urban Anal. City Sci. 45 (5) (2018) 817–820.

[35] J.D. Bolter, M. Engberg, B. MacIntyre, 8 the myth of total VR: The metaverse, 2021.

[36] A. Angrish, B. Starly, Y.-S. Lee, P.H. Cohen, A flexible data schema and system architecture for the virtualization of manufacturing machines (VMM), J. Manuf. Syst. 45 (2017) 236–247, http://dx.doi.org/10.1016/j.jmsy.2017.10.003, URL https://www.sciencedirect.com/science/article/pii/S0278612517301371.

[37] J. Liu, H. Zhou, G. Tian, X. Liu, X. Jing, Digital twin-based process reuse and evaluation approach for smart process planning, Int. J. Adv. Manuf. Technol. 100 (5) (2019) 1619–1634, http://dx.doi.org/10.1007/s00170-018-2748-5.

[38] D. Botkina, M. Hedlind, B. Olsson, J. Henser, T. Lundholm, Digital twin of a cutting tool, Procedia CIRP 72 (2018) 215–218, http://dx.doi.org/10.1016/j.procir.2018.03.178, URL https://www.sciencedirect.com/science/article/pii/S2212827118303378. 51st CIRP Conference on Manufacturing Systems.

[39] F. Longo, L. Nicoletti, A. Padovano, Ubiquitous knowledge empowers the smart factory: The impacts of a service-oriented digital twin on enterprises' performance, Annu. Rev. Control 47 (2019) 221–236, http://dx.doi.org/10.1016/j.arcontrol.2019.01.001, URL https://www.sciencedirect.com/science/article/pii/S1367578818301299.

[40] K.T. Park, Y.W. Nam, H.S. Lee, S.J. Im, S.D. Noh, J.Y. Son, H. Kim, Design and implementation of a digital twin application for a connected micro smart factory, Int. J. Comput. Integr. Manuf. 32 (6) (2019) 596–614, http://dx.doi.org/10.1080/0951192X.2019.1599439.

[41] S. Konstantinov, M. Ahmad, K. Ananthanarayan, R. Harrison, The cyber-physical E-machine manufacturing system: Virtual engineering for complete lifecycle support, Procedia CIRP 63 (2017) 119–124, http://dx.doi.org/10.1016/j.procir.2017.02.035, URL https://www.sciencedirect.com/science/article/pii/S2212827117301324. Manufacturing Systems 4.0 – Proceedings of the 50th CIRP Conference on Manufacturing Systems.

[42] X.V. Wang, L. Wang, Digital twin-based WEEE recycling, recovery and remanufacturing in the background of industry 4.0, Int. J. Prod. Res. 57 (12) (2019) 3892–3902, http://dx.doi.org/10.1080/00207543.2018.1497819.

[43] W. Kritzinger, M. Karner, G. Traar, J. Henjes, W. Sihn, Digital twin in manufacturing: A categorical literature review and classification, Ifac-PapersOnline 51 (11) (2018) 1016–1022.

[44] C. Cimino, E. Negri, L. Fumagalli, Review of digital twin applications in manufacturing, Comput. Ind. 113 (2019) 103130.

[45] J.A. Fairfield, Tokenized: The law of non-fungible tokens and unique digital property, Ind. LJ 97 (2022) 1261.

[46] Q. Wang, R. Li, Q. Wang, S. Chen, Non-fungible token (NFT): Overview, evaluation, opportunities and challenges, 2021, arXiv preprint arXiv:2105.07447.

[47] VMR nft market report, 2023, URL https://www.verifiedmarketresearch.com/product/non-fungible-tokens-market/. (Accessed 01 February 2023).

[48] A. Jaribion, A. Knapen, A. Xamin, J. Holmström, S.H. Khajavi, Non-fungible tokens (NFTs) in additive manufacturing: A digital tool for enhancing IPR protection, in: International Conference on Design Science Research in Information Systems and Technology, 2022.

[49] D. Mouris, N.G. Tsoutsos, NFTs for 3D models: Sustaining ownership in industry 4.0, IEEE Consum. Electron. Mag. (2022) 1, http://dx.doi.org/10.1109/MCE.2022.3164221.

[50] A. Godfrey, V. Hetherington, H. Shum, P. Bonato, N. Lovell, S. Stuart, From a to z: Wearable technology explained, Maturitas 113 (2018) 40–47, http://dx.doi.org/10.1016/j.maturitas.2018.04.012, URL https://www.sciencedirect.com/science/article/pii/S0378512218302330.

[51] M.H. Iqbal, A. Aydin, O. Brunckhorst, P. Dasgupta, K. Ahmed, A review of wearable technology in medicine, J. R. Soc. Med. 109 (10) (2016) 372–380.

[52] M. Çiçek, Wearable technologies and its future applications, Int. J. Electr., Electron. Data Commun. 3 (4) (2015) 45–50.

[53] Harvard business review, 2023, URL https://hbr.org/2023/04/building-a-great-customer-experience-in-the-metaverse. (Accessed 05 July 2023).

[54] Y. Wang, Z. Su, N. Zhang, R. Xing, D. Liu, T.H. Luan, X. Shen, A survey on metaverse: Fundamentals, security, and privacy, IEEE Commun. Surv. Tutor. (2022) 1, http://dx.doi.org/10.1109/COMST.2022.3202047.

[55] X. Yao, J. Zhou, J. Zhang, C.R. Boër, From intelligent manufacturing to smart manufacturing for industry 4.0 driven by next generation artificial intelligence and further on, in: 2017 5th International Conference on Enterprise Systems, ES, IEEE, 2017, pp. 311–318.

[56] A. Ambrosi, M. Pumera, 3D-printing technologies for electrochemical applications, Chem. Soc. Rev. 45 (2016) 2740–2755, http://dx.doi.org/10.1039/C5CS00714C.

[57] K.V. Wong, A. Hernandez, A review of additive manufacturing, ISRN Mech. Eng. 2012 (2012) 208760, http://dx.doi.org/10.5402/2012/208760.

[58] C.W.J. Lim, K.Q. Le, Q. Lu, C.H. Wong, An overview of 3-D printing in manufacturing, aerospace, and automotive industries, IEEE Potentials 35 (4) (2016) 18–22, http://dx.doi.org/10.1109/MPOT.2016.2540098.

[59] Deloitte, 2022, URL shorturl.at/hizC8. (Accessed 21 February 2022).

[60] D. Chaidas, K. Kitsakis, J. Kechagias, S. Maropoulos, The impact of temperature changing on surface roughness of FFF process, IOP Conf. Ser.: Mater. Sci. Eng. 161 (2016) 012033, http://dx.doi.org/10.1088/1757-899x/161/1/012033.

[61] H. Ding, R.X. Gao, A.J. Isaksson, R.G. Landers, T. Parisini, Y. Yuan, State of AI-based monitoring in smart manufacturing and introduction to focused section, IEEE/ASME Trans. Mechatronics 25 (5) (2020) 2143–2154.

[62] K.P. Tran, Artificial intelligence for smart manufacturing: Methods and applications, Sensors 21 (16) (2021) http://dx.doi.org/10.3390/s21165584, URL https://www.mdpi.com/1424-8220/21/16/5584.

[63] D.B. Malkoff, A framework for real-time fault detection and diagnosis using temporal data, Artif. Intell. Eng. 2 (2) (1987) 97–111, http://dx.doi.org/10.1016/0954-1810(87)90144-0, URL https://www.sciencedirect.com/science/article/pii/0954181087901440.

[64] Y. Zhang, Z. Wang, F.E. Alsaadi, Detection of intermittent faults for nonuniformly sampled multi-rate systems with dynamic quantisation and missing measurements, Internat. J. Control 93 (4) (2020) 898–909, http://dx.doi.org/10.1080/00207179.2018.1487083.

[65] Y. Wan, T. Keviczky, M. Verhaegen, Fault estimation filter design with guaranteed stability using Markov parameters, IEEE Trans. Automat. Control 63 (4) (2018) 1132–1139, http://dx.doi.org/10.1109/TAC.2017.2742402.

[66] G. Niu, J.-D. Son, A. Widodo, B.-S. Yang, D.-H. Hwang, D.-S. Kang, A comparison of classifier performance for fault diagnosis of induction motor using multi-type signals, Struct. Health Monit. 6 (3) (2007) 215–229, http://dx.doi.org/10.1177/1475921707081110.

[67] J. Zhang, P. Wang, R.X. Gao, R. Yan, An image processing approach to machine fault diagnosis based on visual words representation, Procedia Manuf. 19 (2018) 42–49, http://dx.doi.org/10.1016/j.promfg.2018.01.007, Proceedings of the 6th International Conference in Through-life Engineering Services, University of Bremen, 7th and 8th November 2017.

[68] X. Ding, Q. He, Energy-fluctuated multiscale feature learning with deep ConvNet for intelligent spindle bearing fault diagnosis, IEEE Trans. Instrum. Meas. 66 (8) (2017) 1926–1935, http://dx.doi.org/10.1109/TIM.2017.2674738.

[69] L. Eren, T. Ince, S. Kiranyaz, A generic intelligent bearing fault diagnosis system using compact adaptive 1D CNN classifier, J. Signal Process. Syst. 91 (2) (2019) 179–189, http://dx.doi.org/10.1007/s11265-018-1378-3.

[70] Remaining useful life, 2023, URL https://www.qult.ai/an-ml-solution-for-predicting-the-remaining-useful-life-of-a-ball-bearing-based-using-vibration-sensors-data-2/. (Accessed 10 January 2023).

[71] W.M. Tan, T.H. Teo, Remaining useful life prediction using temporal convolution with attention, AI 2 (1) (2021) 48–70, http://dx.doi.org/10.3390/ai2010005, URL https://www.mdpi.com/2673-2688/2/1/5.

[72] J. Ma, H. Su, W.-l. Zhao, B. Liu, Predicting the remaining useful life of an aircraft engine using a stacked sparse autoencoder with multilayer self-learning, Complexity 2018 (2018) 3813029, http://dx.doi.org/10.1155/2018/3813029.

[73] L. Liao, W. Jin, R. Pavel, Enhanced restricted Boltzmann machine with prognosability regularization for prognostics and health assessment, IEEE Trans. Ind. Electron. 63 (11) (2016) 7076–7083, http://dx.doi.org/10.1109/TIE.2016.2586442.

[74] T. Wuest, C. Irgens, K.-D. Thoben, An approach to monitoring quality in manufacturing using supervised machine learning on product state data, J. Intell. Manuf. 25 (5) (2014) 1167–1180, http://dx.doi.org/10.1007/s10845-013-0761-y.

[75] R.S. Peres, J. Barata, P. Leitao, G. Garcia, Multistage quality control using machine learning in the automotive industry, IEEE Access 7 (2019) 79908–79916, http://dx.doi.org/10.1109/ACCESS.2019.2923405.

[76] D. Lieber, M. Stolpe, B. Konrad, J. Deuse, K. Morik, Quality prediction in interlinked manufacturing processes based on supervised & unsupervised machine learning, Procedia CIRP 7 (2013) 193–198, http://dx.doi.org/10.1016/j.procir.2013.05.033, Forty Sixth CIRP Conference on Manufacturing Systems 2013.

[77] J.F. Arinez, Q. Chang, R.X. Gao, C. Xu, J. Zhang, Artificial intelligence in advanced manufacturing: Current status and future outlook, J. Manuf. Sci. Eng. 142 (11) (2020) http://dx.doi.org/10.1115/1.4047855, 110804.

[78] P. Leitão, Agent-based distributed manufacturing control: A state-of-the-art survey, Eng. Appl. Artif. Intell. 22 (7) (2009) 979–991, http://dx.doi.org/10.1016/j.engappai.2008.09.005, URL https://www.sciencedirect.com/science/article/pii/S0952197608001437. Distributed Control of Production Systems.

[79] J. Zhang, A. Simeone, Q. Peng, P. Gu, Dependency and correlation analysis of specifications and parameters of products for supporting design decisions, CIRP Ann. 69 (1) (2020) 133–136, http://dx.doi.org/10.1016/j.cirp.2020.03.005.

[80] OpenSource, 2023, URL https://www.opensourceforu.com/2019/08/the-best-open-source-blockchain-platforms/. (Accessed 10 June 2023).

[81] E.W.T. Ngai, A. Gunasekaran, S.F. Wamba, S. Akter, R. Dubey, Big data analytics in electronic markets, Electron. Mark. 27 (3) (2017) 243–245, http://dx.doi.org/10.1007/s12525-017-0261-6.

[82] X. Jin, B.W. Wah, X. Cheng, Y. Wang, Significance and challenges of big data research, Big Data Res. 2 (2) (2015) 59–64, http://dx.doi.org/10.1016/j.bdr.2015.01.006, Visions on Big Data.

[83] Y.-H. Kuo, A. Kusiak, From data to big data in production research: The past and future trends, Int. J. Prod. Res. 57 (15–16) (2019) 4828–4853, http://dx.doi.org/10.1080/00207543.2018.1443230.

[84] J. Lee, E. Lapira, B. Bagheri, H. an Kao, Recent advances and trends in predictive manufacturing systems in big data environment, Manuf. Lett. 1 (1) (2013) 38–41, http://dx.doi.org/10.1016/j.mfglet.2013.09.005.

[85] P. O'Donovan, K. Leahy, K. Bruton, D.T.J. O'Sullivan, Big data in manufacturing: A systematic mapping study, J. Big Data 2 (1) (2015) 20, http://dx.doi.org/10.1186/s40537-015-0028-x.

[86] N. Ivezic, B. Kulvatunyou, V. Srinivasan, On architecting and composing through-life engineering information services to enable smart manufacturing, Procedia CIRP 22 (2014) 45–52, http://dx.doi.org/10.1016/j.procir.2014.07.004, URL https://www.sciencedirect.com/science/article/pii/S2212827114008178. Proceedings of the 3rd International Conference in Through-life Engineering Services.

[87] L.D. Sturm, C.B. Williams, J.A. Camelio, J. White, R. Parker, Cyber-physical vulnerabilities in additive manufacturing systems: A case study attack on the .STL file with human subjects, J. Manuf. Syst. 44 (2017) 154–164, http://dx.doi.org/10.1016/j.jmsy.2017.05.007, URL https://www.sciencedirect.com/science/article/pii/S0278612517300961.

[88] Y. Lu, The blockchain: State-of-the-art and research challenges, J. Ind. Inf. Integr. 15 (2019) 80–90, http://dx.doi.org/10.1016/j.jii.2019.04.002.

[89] S. Krima, T.H. Jr., A.B. Feeney, Securing the digital threat for smart manufacturing: A reference model for blockchain-based product data traceability, 2019, http://dx.doi.org/10.6028/NIST.AMS.300-6.

[90] F. Dabbene, P. Gay, C. Tortia, Traceability issues in food supply chain management: A review, Biosyst. Eng. 120 (2014) 65–80, http://dx.doi.org/10.1016/j.biosystemseng.2013.09.006, Operations Management in Bio-production Systems.

[91] H.M. Kim, M. Laskowski, Toward an ontology-driven blockchain design for supply-chain provenance, Intell. Syst. Account., Finance Manag. 25 (1) (2018) 18–27, http://dx.doi.org/10.1002/isaf.1424.

[92] F. Tian, An agri-food supply chain traceability system for China based on RFID amp; blockchain technology, in: 2016 13th International Conference on Service Systems and Service Management, ICSSSM, 2016, pp. 1–6, http://dx.doi.org/10.1109/ICSSSM.2016.7538424.

[93] F. Tao, Y. Zhang, Y. Cheng, J. Ren, D. Wang, Q. Qi, P. Li, Digital twin and blockchain enhanced smart manufacturing service collaboration and management, J. Manuf. Syst. (2020) http://dx.doi.org/10.1016/j.jmsy.2020.11.008.

[94] N. Rožman, J. Diaci, M. Corn, Scalable framework for blockchain-based shared manufacturing, Robot. Comput.-Integr. Manuf. 71 (2021) 102139, http://dx.doi.org/10.1016/j.rcim.2021.102139.

[95] I. Rio-Torto, A.T. Campaniço, A. Pereira, L.F. Teixeira, V. Filipe, Automatic quality inspection in the automotive industry: A hierarchical approach using simulated data, in: 2021 IEEE 8th International Conference on Industrial Engineering and Applications, ICIEA, 2021, pp. 342–347, http://dx.doi.org/10.1109/ICIEA52957.2021.9436742.

[96] F. Arena, M. Collotta, L. Luca, M. Ruggieri, F.G. Termine, Predictive maintenance in the automotive sector: A literature review, Math. Comput. Appl. 27 (1) (2022) http://dx.doi.org/10.3390/mca27010002, URL https://www.mdpi.com/2297-8747/27/1/2.

[97] N.S. Ab Razak, H. Mansor, S. Sharmin, A secure framework for vehicle maintenance service using blockchain, in: Proceedings of the 2023 12th International Conference on Software and Computer Applications, ICSCA '23, Association for Computing Machinery, New York, NY, USA, 2023, pp. 267–272, http://dx.doi.org/10.1145/3587828.3587868.

[98] X. Xu, F. Rahman, B. Shakya, A. Vassilev, D. Forte, M. Tehranipoor, Electronics supply chain integrity enabled by blockchain, ACM Trans. Des. Automat. Electron. Syst. (TODAES) 24 (3) (2019) http://dx.doi.org/10.1145/3315571.

[99] J. Li, S. King, I. Jennions, Intelligent fault diagnosis of an aircraft fuel system using machine learning&mdash. A literature review, Machines 11 (4) (2023) http://dx.doi.org/10.3390/machines11040481, URL https://www.mdpi.com/2075-1702/11/4/481.

[100] R. Wasim Ahmad, H. Hasan, I. Yaqoob, K. Salah, R. Jayaraman, M. Omar, Blockchain for aerospace and defense: Opportunities and open research challenges, Comput. Ind. Eng. 151 (2021) 106982, http://dx.doi.org/10.1016/j.cie.2020.106982.

[101] H.K. Sharma, A. Kumar, S. Pant, M. Ram, 4 application of artificial intelligence in smart healthcare, in: Artificial Intelligence, Blockchain and IoT for Smart Healthcare, 2022, pp. 37–46.

[102] A. Haleem, M. Javaid, R.P. Singh, R. Suman, S. Rab, Blockchain technology applications in healthcare: An overview, Int. J. Intell. Netw. 2 (2021) 130–139, http://dx.doi.org/10.1016/j.ijin.2021.09.005, URL https://www.sciencedirect.com/science/article/pii/S266660302100021X.

[103] S. Sundaram, A. Zeid, Artificial intelligence-based smart quality inspection for manufacturing, Micromachines 14 (3) (2023) http://dx.doi.org/10.3390/mi14030570, URL https://www.mdpi.com/2072-666X/14/3/570.

[104] M.A. Khan, S. Saqib, T. Alyas, A. Ur Rehman, Y. Saeed, A. Zeb, M. Zareei, E.M. Mohamed, Effective demand forecasting model using business intelligence empowered with machine learning, IEEE Access 8 (2020) 116013–116023, http://dx.doi.org/10.1109/ACCESS.2020.3003790.

[105] Blockchain in consumer goods, 2023, URL https://www2.deloitte.com/nl/nl/pages/consumer-industrial-products/articles/blockchain-in-the-consumer-products-industry.html. (Accessed 05 June 2023).

[106] S. Zhao, F. Blaabjerg, H. Wang, An overview of artificial intelligence applications for power electronics, IEEE Trans. Power Electron. 36 (4) (2021) 4633–4658, http://dx.doi.org/10.1109/TPEL.2020.3024914.

[107] J. Bao, D. He, M. Luo, K.-K.R. Choo, A survey of blockchain applications in the energy sector, IEEE Syst. J. 15 (3) (2021) 3370–3381, http://dx.doi.org/10.1109/JSYST.2020.2998791.

[108] R. Khan, I. Kumar, J. Rawat, N. Mohd, S. Husain, Opportunities of artificial intelligence and machine learning in the food industry, J. Food Qual. 2021 (2021) 4535567, http://dx.doi.org/10.1155/2021/4535567.

[109] S. Tanwar, A. Parmar, A. Kumari, N.K. Jadav, W.-C. Hong, R. Sharma, Blockchain adoption to secure the food industry: Opportunities and challenges, Sustainability 14 (12) (2022) http://dx.doi.org/10.3390/su14127036.

[110] O. Rodríguez-Espíndola, S. Chowdhury, A. Beltagui, P. Albores, The potential of emergent disruptive technologies for humanitarian supply chains: The integration of blockchain, artificial intelligence and 3D printing, Int. J. Prod. Res. 58 (15) (2020) 4610–4630, http://dx.doi.org/10.1080/00207543.2020.1761565.

[111] D. Guo, S. Ling, H. Li, D. Ao, T. Zhang, Y. Rong, G.Q. Huang, A framework for personalized production based on digital twin, blockchain and additive manufacturing in the context of industry 4.0, in: 2020 IEEE 16th International Conference on Automation Science and Engineering, CASE, 2020, pp. 1181–1186, http://dx.doi.org/10.1109/CASE48305.2020.9216732.

[112] A. Ekramifard, H. Amintoosi, A.H. Seno, A. Dehghantanha, R.M. Parizi, A systematic literature review of integration of blockchain and artificial intelligence, in: Blockchain Cybersecurity, Trust and Privacy, Springer International Publishing, 2020, pp. 147–160, http://dx.doi.org/10.1007/978-3-030-38181-3_8.

[113] K. Okulicz, Virtual reality-based approach to manufacturing process planning, Int. J. Prod. Res. 42 (17) (2004) 3493–3504, http://dx.doi.org/10.1080/00207540410001699426.

[114] G. Reinhart, C. Patron, Integrating augmented reality in the assembly domain - Fundamentals, benefits and applications, CIRP Ann. 52 (1) (2003) 5–8, http://dx.doi.org/10.1016/S0007-8506(07)60517-4, URL https://www.sciencedirect.com/science/article/pii/S0007850607605174.

[115] C. Calderon, M. Cavazza, D. Diaz, A new approach to virtual design for spatial configuration problems, in: Proceedings on Seventh International Conference on Information Visualization, 2003. IV 2003, 2003, pp. 518–523, http://dx.doi.org/10.1109/IV.2003.1218034.

[116] M. Iqbal, M. Hashmi, Design and analysis of a virtual factory layout, J. Mater Process. Technol. 118 (1) (2001) 403–410, http://dx.doi.org/10.1016/S0924-0136(01)00908-6, PART 1: CONTAINING PAPERS PRESENTED AT INTERNATIONAL CONFERENCE ON ADVANCES IN MATERIALS PROCESSING TECHNOLOGY.

[117] D. ZETU, P. BANERJEE, P. SCHNEIDER, Data input model for virtual reality-aided facility layout, IIE Trans. 30 (7) (1998) 597–620, http://dx.doi.org/10.1080/07408179808966505.

[118] J. Gausemeier, J. Fründ, C. Matysczok, AR-planning tool: designing flexible manufacturing systems with augmented reality, in: ACM International Conference Proceeding Series, 23, 2002, pp. 19–25.

[119] F. Doil, W. Schreiber, T. Alt, C. Patron, Augmented reality for manufacturing planning, in: Proceedings of the Workshop on Virtual Environments 2003, 2003, pp. 71–76.

[120] A. Nee, S. Ong, G. Chryssolouris, D. Mourtzis, Augmented reality applications in design and manufacturing, CIRP Annals 61 (2) (2012) 657–679, http://dx.doi.org/10.1016/j.cirp.2012.05.010.

[121] Siemens VR plant simulator, 2023, URL https://blogs.sw.siemens.com/tecnomatix/video-virtual-reality-for-plant-simulation/. (Accessed 10 January 2023).

[122] P. Li, A.A. Azadi, A. Gaurav, A. García-Holgado, Y.-C. Fung, Z. Bai, Metaverse: A new tool for real-time monitoring of dynamic circumstances in the physical production system, in: N. Nedjah, G. Martínez Pérez, B.B. Gupta (Eds.), International Conference on Cyber Security, Privacy and Networking (ICSPN 2022), Springer International Publishing, Cham, 2023, pp. 397–405.

[123] G.A.R. Sampedro, D.J.S. Agron, G.C. Amaizu, D.-S. Kim, J.-M. Lee, Design of an in-process quality monitoring strategy for FDM-type 3D printer using deep learning, Appl. Sci. 12 (17) (2022) http://dx.doi.org/10.3390/app12178753, URL https://www.mdpi.com/2076-3417/12/17/8753.

[124] S.M. Rachmawati, M.A.P. Putra, J.M. Lee, D.S. Kim, Digital twin-enabled 3D printer fault detection for smart additive manufacturing, Eng. Appl. Artif. Intell. 124 (2023) 106430, http://dx.doi.org/10.1016/j.engappai.2023.106430, URL https://www.sciencedirect.com/science/article/pii/S0952197623006140.

[125] D. Mourtzis, T. Togias, J. Angelopoulos, P. Stavropoulos, A digital twin architecture for monitoring and optimization of fused deposition modeling processes, Procedia CIRP 103 (2021) 97–102.

[126] Thyssenkrupp hololens usage video, 2023, URL https://www.youtube.com/watch?v=gNWmU-9DJ4E. (Accessed 10 January 2023).

[127] Thyssenkrupp hololens usage, 2023, URL https://blogs.windows.com/devices/2016/09/15/microsoft-hololens-enables-thyssenkrupp-to-transform-the-global-elevator-industry/. (Accessed 10 January 2023).

[128] T. Wang, Y. Liu, Y. Wang, Infrared marker based augmented reality system for equipment maintenance, in: 2008 International Conference on Computer Science and Software Engineering, vol. 5, 2008, pp. 816–819, http://dx.doi.org/10.1109/CSSE.2008.8.

[129] J. Zhu, A.-C. Nee, S.-K. Ong, Online authoring for augmented reality remote maintenance, 2011.

[130] S.J. Henderson, S. Feiner, Evaluating the benefits of augmented reality for task localization in maintenance of an armored personnel carrier turret, in: 2009 8th IEEE International Symposium on Mixed and Augmented Reality, 2009, pp. 135–144, http://dx.doi.org/10.1109/ISMAR.2009.5336486.

[131] S. Henderson, S. Feiner, Opportunistic tangible user interfaces for augmented reality, IEEE Trans. Vis. Comput. Graphics 16 (1) (2010) 4–16, http://dx.doi.org/10.1109/TVCG.2009.91.

[132] J. Lee, P. Kundu, Integrated cyber-physical systems and industrial metaverse for remote manufacturing, Manuf. Lett. 34 (2022) 12–15, http://dx.doi.org/10.1016/j.mfglet.2022.08.012, URL https://www.sciencedirect.com/science/article/pii/S2213846322001833.

[133] H. da Rocha, J. Pereira, R. Abrishambaf, A. Espirito Santo, An interoperable digital twin with the IEEE 1451 standards, Sensors 22 (19) (2022) http://dx.doi.org/10.3390/s22197590, URL https://www.mdpi.com/1424-8220/22/19/7590.

[134] A.B. Mahmoud, The metaverse and web 3.0: Revolutionising consumption and communication for the future, in: P. Keikhosrokiani (Ed.), Handbook of Research on Consumer Behavioral Analytics in Metaverse and the Adoption of a Virtual World, IGI Global, 2023, pp. 322–345, http://dx.doi.org/10.4018/978-1-6684-7029-9.ch015.

[135] Z. Allam, A. Sharifi, S.E. Bibri, D.S. Jones, J. Krogstie, The metaverse as a virtual form of smart cities: Opportunities and challenges for environmental, economic, and social sustainability in urban futures, Smart Cities 5 (3) (2022) 771–801, http://dx.doi.org/10.3390/smartcities5030040, URL https://www.mdpi.com/2624-6511/5/3/40.

[136] Z. Guo, Z. Wang, X. Jin, "Avatar to person"(ATP) virtual human social ability enhanced system for disabled people, Wirel. Commun. Mob. Comput. 2021 (2021) 1–10.

[137] J.E. Naranjo, D.G. Sanchez, A. Robalino-Lopez, P. Robalino-Lopez, A. Alarcon-Ortiz, M.V. Garcia, A scoping review on virtual reality-based industrial training, Appl. Sci. 10 (22) (2020) http://dx.doi.org/10.3390/app10228224, URL https://www.mdpi.com/2076-3417/10/22/8224.

[138] S. Werrlich, A. Daniel, A. Ginger, P.-A. Nguyen, G. Notni, Comparing HMD-based and paper-based training, in: 2018 IEEE International Symposium on Mixed and Augmented Reality, ISMAR, 2018, pp. 134–142, http://dx.doi.org/10.1109/ISMAR.2018.00046.

[139] M. Javaid, A. Haleem, R.P. Singh, R. Suman, Enabling flexible manufacturing system (FMS) through the applications of industry 4.0 technologies, Internet Things Cyber-Phys. Syst. 2 (2022) 49–62, http://dx.doi.org/10.1016/j.iotcps.2022.05.005, URL https://www.sciencedirect.com/science/article/pii/S2667345222000153.

[140] A.C. Bavelos, N. Kousi, C. Gkournelos, K. Lotsaris, S. Aivaliotis, G. Michalos, S. Makris, Enabling flexibility in manufacturing by integrating shopfloor and process perception for mobile robot workers, Appl. Sci. 11 (9) (2021) 3985.

[141] Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy, Int. J. Inf. Manage. 66 (2022) 102542, http://dx.doi.org/10.1016/j.ijinfomgt.2022.102542.

[142] S. Azarby, A. Rice, Understanding the effects of virtual reality system usage on spatial perception: The potential impacts of immersive virtual reality on spatial design decisions, Sustainability 14 (16) (2022) http://dx.doi.org/10.3390/su141610326, URL https://www.mdpi.com/2071-1050/14/16/10326.

[143] Nvidia omniverse BMW factory, 2023, URL https://www.youtube.com/watch?v=6-DaWgg4zF8. (Accessed 10 January 2023).

[144] Omniverse, 2022, URL https://developer.nvidia.com/nvidia-omniverse-platform. (Accessed 3 March 2022).

[145] KAIST metaverse factory, 2022, URL https://www.kaist.ac.kr/newsen/html/news/?mode=V&mng_no=17010. (Accessed 3 March 2022).

[146] H. Nguyen Ngoc, G. Lasa, I. Iriarte, Human-centred design in industry 4.0: Case study review and opportunities for future research, J. Intell. Manuf. 33 (1) (2022) 35–76, http://dx.doi.org/10.1007/s10845-021-01796-x.

[147] A. Páez-Montoro, M. García-Valderas, E. Olías-Ruíz, C. López-Ongil, Solar energy harvesting to improve capabilities of wearable devices, Sensors (Basel) 22 (10) (2022) 3950, http://dx.doi.org/10.3390/s22103950.

[148] X. Zhu, Q. Li, G. Chen, APT: Accurate outdoor pedestrian tracking with smartphones, in: 2013 Proceedings IEEE INFOCOM, 2013, pp. 2508–2516, http://dx.doi.org/10.1109/INFCOM.2013.6567057.

[149] Y.-W. Chong, W. Ismail, K. Ko, C.-Y. Lee, Energy harvesting for wearable devices: A review, IEEE Sens. J. 19 (20) (2019) 9047–9062, http://dx.doi.org/10.1109/JSEN.2019.2925638.

[150] S. Seneviratne, Y. Hu, T. Nguyen, G. Lan, S. Khalifa, K. Thilakarathna, M. Hassan, A. Seneviratne, A survey of wearable devices and challenges, IEEE Commun. Surv. Tutor. 19 (4) (2017) 2573–2620.

[151] F. O'Brolcháin, T. Jacquemard, D. Monaghan, N. O'Connor, P. Novitzky, B. Gordijn, The convergence of virtual reality and social networks: Threats to privacy and autonomy, Sci. Eng. Ethics 22 (1) (2016) 1–29, http://dx.doi.org/10.1007/s11948-014-9621-1.

[152] Y. Huang, Y.J. Li, Z. Cai, Security and privacy in metaverse: A comprehensive survey, Big Data Min. Anal. 6 (2) (2023) 234–247, http://dx.doi.org/10.26599/BDMA.2022.9020047.

[153] M. Conti, N. Dragoni, V. Lesyk, A survey of man in the middle attacks, IEEE Commun. Surv. Tutor. 18 (3) (2016) 2027–2051, http://dx.doi.org/10.1109/COMST.2016.2548426.

[154] G. Amaizu, C. Nwakanma, S. Bhardwaj, J. Lee, D. Kim, Composite and efficient DDoS attack detection framework for B5G networks, Comput. Netw. 188 (2021) 107871, http://dx.doi.org/10.1016/j.comnet.2021.107871, URL https://www.sciencedirect.com/science/article/pii/S1389128621000438.

[155] S. Cresci, A decade of social bot detection, Commun. ACM 63 (10) (2020) 72–83, http://dx.doi.org/10.1145/3409116.

[156] D. Boneh, A.J. Grotto, P. McDaniel, N. Papernot, How relevant is the turing test in the age of sophisbots?, 2019, arXiv:1909.00056.

[157] S. Hussain, P. Neekhara, B. Dolhansky, J. Bitton, C.C. Ferrer, J. Mcauley, F. Koushanfar, Exposing vulnerabilities of deepfake detection systems with robust attacks, Digit. Threat: Res. Pract. 3 (3) (2022) 30, http://dx.doi.org/10.1145/3464307, 23 pages.

[158] OpenSea, 2023, URL https://markets.businessinsider.com/news/currencies/nft-opensea-hack-phishing-stolen-millions-smart-contract-crypto-attack-2022-2. (Accessed 07 June 2023).

[159] NFT attacks, 2023, URL https://www.linkedin.com/pulse/largest-nftmetaverse-hacks-20212022-entersoft-security/. (Accessed 07 June 2023).

[160] B. Falchuk, S. Loeb, R. Neff, The social metaverse: Battle for privacy, IEEE Technol. Soc. Mag. 37 (2) (2018) 52–61, http://dx.doi.org/10.1109/MTS.2018.2826060.

[161] A.S. Rajawat, S. Goyal, R. Solanki, M.S. Raboaca, T.C. Mihaltan, Z. Illés, C. Verma, Blockchain-based security framework for metaverse: A decentralized approach, in: 2023 15th International Conference on Electronics, Computers and Artificial Intelligence, ECAI, 2023, pp. 01–06, http://dx.doi.org/10.1109/ECAI58194.2023.10193962.

[162] B.B. Gupta, A. Gaurav, K.T. Chui, L. Wang, V. Arya, A. Shukla, D. Peraković, Ddos attack detection through digital twin technique in metaverse, in: 2023 IEEE International Conference on Consumer Electronics, ICCE, 2023, pp. 1–5, http://dx.doi.org/10.1109/ICCE56470.2023.10043433.

[163] H. Liu, D. Xu, Y. Tian, C. Peng, Z. Wu, Z. Wang, Wasserstein generative adversarial networks based differential privacy metaverse data sharing, IEEE J. Biomed. Health Inf. (2023) 1–12, http://dx.doi.org/10.1109/JBHI.2023.3287092.

[164] G. Li, T.H. Luan, Z. Li, C. Lai, N. Cheng, L. Zhu, A lightweight and secure three-factor access authentication scheme in metaverse, in: 2023 IEEE International Conference on Metaverse Computing, Networking and Applications, MetaCom, 2023, pp. 488–495, http://dx.doi.org/10.1109/MetaCom57706.2023.00090.

[165] L. Chang, Z. Zhang, P. Li, S. Xi, W. Guo, Y. Shen, Z. Xiong, J. Kang, D. Niyato, X. Qiao, Y. Wu, 6G-enabled edge AI for metaverse: Challenges, methods, and future research directions, J. Commun. Inf. Netw. 7 (2) (2022) 107–121, http://dx.doi.org/10.23919/JCIN.2022.9815195.

[166] G. Amaizu, J. Njoku, J. Lee, D. Kim, Security in metaverse: A closer look, in: Proceedings of the KICS 2022 Winter Conference, Pyeongchang, South Korea, 2022, pp. 199–200, https://www.dbpia.co.kr/journal/articleDetail?nodeId=NODE11047406.