JOURNAL OF METAVERSE

E-ISSN: 2792-0232

INTERNATIONAL, OPEN ACCESS, PEER-REVIEWED JOURNAL

https://dergipark.org.tr/jmv

İZMİR AKADEMİ
DERNEĞİ

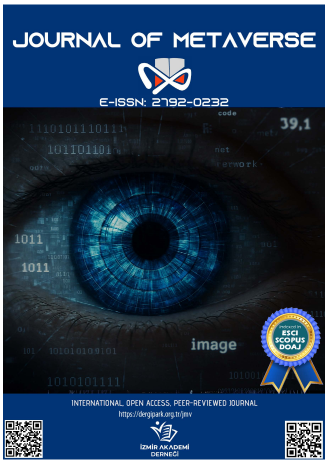
JOURNAL OF METAVERSE

(JMV)

E-ISSN: 2792-0232

Volume :5 | Number:1 | Year:2025

Indexing and Abstracting



Journal of Metaverse is indexed in WoS ESCI, SCOPUS and DOAJ

INDEXED IN EMERGING SOURCES CITATION (Web of Science) CLARIVATE ANALYTICS

Clarivate Analytics

ELSEVIER Scopus

DOAJ

Citation Indexes

Scopus

Emerging Sources Citation Index (ESCI)

Other Indexes

- SCOPUS
- WoS ESCI
- ScimagoJR
- DOAJ
- CABELLS
- ERIH PLUS
- OpenAIRE
- Google Scholar
- Harvard Hollis
- ResearchGate
- ROAD
- Scilit
- ASOS Index
- IAD

JOURNAL OF METAVERSE

Volume: 5 **No:** 1 **Year:** 2025 **Period:** January-June

Head Office : İzmir
Type of Publication : It is published electronically twice a year.
Publisher : İzmir Akademi Derneği (www.izmirakademi.org)

JOURNAL OF METAVERSE

Volume: 5 **No:** 1 **Year:** 2025 **Period:** January-June

JOURNAL OF METAVERSE

Address : Büyükkale Mh. Kerimoğlu Sok. No:40/2 Tire, İzmir Türkiye
Web : https://dergipark.org.tr/en/pub/jmv
Emails : journalmetaverse@gmail.com
: izmirakademidernegi@gmail.com

Journal of Metaverse publishes scientific/original research and review articles. It is published electronically twice a year. It is an **international scientific refereed journal** that publishes articles written in **English**, and includes acedemicians from different countries in its boards. Uses "*Double-Blind Peer Review*" in reviewing processes. It has adopted the open access principle. No fee is requested from the authors for open access, processing, publication fee or otherwise. It is totally **FREE.**

The responsibility of the articles published in this journal in terms of science and language belongs to the authors. The articles published in the journal cannot be used without reference.

CONTENT

Journal of Metaverse
Research Article
Received: 2024-11-20 | **Reviewing:** 2024-11-21 & 2025-01-12 | **Accepted:** 2025-01-13 | **Online:** 2025-01-19 | **Issue Date:** 2025-06-30
Year:2025, **Volume:**5, **Issue:**1, **Pages:**1-24, **Doi:** 10.57019/jmv.1588762

Valuation and Volatility of Virtual Properties in Metaverse: Exploring New Market Opportunities and Speculative Dynamics Based on Decentraland

Dawid Narowski
Department of Integrated Geodesy and Cartography
AGH University of Krakow
Krakow, Poland
dawski18@gmail.com
0009-0005-5056-1441

Celso A. G. Santos
Department of Civil and Environmental Engineering
Federal University of Paraíba
João Pessoa, Brazil
celso@ct.ufpb.br
0000-0001-7927-9718

Łukasz Borowski
Faculty of Social Sciences
University of the National Education Commission, Krakow
Krakow, Poland
lukasz.borowski@uken.krakow.pl
0000-0001-7356-5377

Michal Apollo
Institute of Earth Sciences
University of Silesia
Katowice, Poland
michal.apollo@us.edu.pl
0000-0002-7777-5176

Kamil Maciuk
Department of Integrated Geodesy and Cartography
AGH University of Krakow
Krakow, Poland
maciuk@agh.edu.pl
0000-0001-5514-8510
(Corresponding Author)

***Abstract*— Existing reality has been repeatedly subjected to multifaceted and multidimensional analyses. However, alongside it, a virtual reality exists, populated with virtual art, objects in games, cyber-pets, and virtual properties, collectively worth billions of real dollars. This virtual reality is associated with the concept of the 'metaverse' (a term derived from 'meta' and 'universe'), signifying a space that facilitates life in a virtual world. This space has a quantifiable value and is traded on specially designed platforms. The study focuses on the largest of these platforms, Decentraland, where users can purchase virtual properties using a cryptocurrency called MANA. Based on an analysis of 207 property transactions, the study examines whether these properties can be appraised using typical approaches applicable to "real" properties. It explores the relationship between spatial attributes, property price, and price volatility over time, calculating correlation coefficients for this purpose. Additionally, the study investigates the number of property sales, including multiple sales, and the proportion of properties with ITEMs on them, determining the correlation coefficients between price and parcel attributes. This study is the first to accomplish what researchers in the real estate market have long been doing. The results distinctly show that the virtual real estate market is governed by different factors compared to the traditional market, with property price and location remaining as two crucial aspects in the decision-making process for purchasing a property.**

Keywords*— *Metaverse, virtual real estate, Decentraland, parcel, real estate, real estate valuation, virtual reality, blockchain, NFT

I. INTRODUCTION

The development of civilization, along with the technological advances that accompany it, despite their drawbacks, brings many opportunities. These include easier access to information, improved communication and transportation, increased productivity, and the advancement of information technology [8]. It is the latter that has enable the creation of what is known as virtual reality [34]. The relationship between virtuality and reality has been a subject of consideration since ancient times, notably in the ideas of the Greek philosopher Plato and his concept of good and bad illusions. The motif of transitioning to another, parallel space-time is also frequently explored in film and literature, often using a mirror, window, or door as a portal [50]. However, what was once associated with science fiction has now become a reality. Today, 'the door' to the virtual world is the computer [67]. It is a sign of our times that we live our lives equally in the real and virtual worlds, where processes and events in the virtual dimension increasingly replace or supplement the real ones [30]. Examples include meeting other others (other virtual world users), purchasing digital goods and products, and even real estate [17]. It is predicted that by 2026, a quarter of the population will spend at least one hour a day in the metaverse, engaging mainly in education, health care, marketing, and other services [21]. Virtual reality (VR) is a computer-generated three-dimensional environment that allows users to move and interact within it. An alternate term for VR, derived from English, is 'metaverse,' a combination of 'meta' (beyond) and 'verse' (from 'universe' - space) [26]. The Metaverse can thus be defined as an environment where users worldwide can connect, establish relationships, and exchange goods; in other words, it is an alternative, computer-generated world where people can share and interact globally. With reference to the above definitions, the metaverse's characteristics include sustainability, synchronicity, openness to all with no user limit, a fully functioning economy with property rights, a link between the virtual and real worlds, interoperability, and content created collaboratively [9].

This paper analyses the real estate market of the Decentraland platform. This focus is due to the platform's high popularity and the easy accessibility of data, such as transaction histories. Furthermore, Decentraland's design ensures its status as a truly decentralized platform, independent

Cite (APA): Narowski, D., Santos, C. A. G., Borowski, L., Apollo, M., Maciuk, K. (2025). Valuation and volatility of virtual properties in Metaverse: Exploring new market opportunities and speculative dynamics based on Decentraland. *Journal of Metaverse*. *5*(1), 1-24. **Doi:** 10.57019/jmv.1588762

of the influence of large-scale investors [12][36]. Decentraland operates on the Ethereum blockchain, using MANA as its native currency, which serves as both a transactional utility within the marketplace and a stable currency that aligns with real-world exchange rates. This dual functionality distinguishes MANA from tokens on other platforms, which may lack such versatility, thus providing Decentraland with a stable economic framework for virtual real estate valuation and transactions. However, the rapid expansion of virtual real estate platforms like Decentraland and others presents certain risks, such as market saturation due to the potential oversupply of virtual properties. This oversupply, combined with the speculative appeal of virtual assets, may lead to increased volatility and impact long-term valuations. Recognizing these dynamics, this study analyses the Decentraland platform's real estate market to understand the valuation mechanisms and volatility trends that differentiate virtual from traditional property markets.

Metaverse platforms are primarily built on blockchain technology, which has seen significant development in recent years [48]. Blockchain is a method of data storage that forms a one-way (chronological) chain of records, known as blocks. The technology has emerged in response to the anticipated increase in user-generated data within the metaverse space [55]. It facilitates transactions directly between users — peer-to-peer — without the need for intermediaries [18]. Notable features characterizing blockchain technology include [43]:

- Immutability: Data entered cannot be modified;
- Decentralization: Every user has access to the data;
- Consensus-based: A mechanism that is resistant to fraud attempts, increasing user confidence;
- Transparency: The entire chain is publicly available, providing an opportunity for verification;
- Internationality: The system is open to everyone;
- Anonymity: User data is not disclosed.

II. METAVERSE

The metaverse is defined as "*a virtual reality setting where users may engage in sustained and immersive interactions with other users and digital information*" [6]. It is a loosely defined term referring to three-dimensional virtual worlds where users, represented by avatars, interact [15][44]. The term 'Metaverse' originated in the 1992 science fiction novel 'Snow Crash', as a portmanteau of 'meta' and 'universe' [10][66]. As a relatively new phenomenon, it has not been extensively studied by researchers. Existing studies include applications of accounting and auditing in virtual worlds [5]. They necessitate the creation of new digital tools and call for legal regulation, especially in international trade. Further mover, the Metaverse, offering an interactive environment with vast potential, can be utilised in education and training for students and employees. Businesses have been quick, willing, and effective in adopting and implementing new technologies such as virtual reality, blockchain, artificial intelligence, and augmented reality. These technologies are seen as the future of business, offering number opportunities, including increased data interoperability, development of new strategies and business models, and enhanced precision in point cloud data for as-built models of existing facilities [53]. The COVID-19 pandemic has led to an increased interest in virtual life across almost all aspects of human life. Unprecedented before, virtual medical consultations have become a standard, and most corporations, for cost reasons, prefer a hybrid mode of work (both stationary and virtual). This trend extends to property viewing through virtual tours using VR or 360-degree virtual videos and applications in higher education [14][49][51].

In the Metaverse, the graphical elements essentially comprise three components: scenes, which are sets of shapes resembling real-world elements like buildings and monuments; and two types of users: so-called independent (non-player characters) and real users (represented as avatars) [31]. The former are entities that cannot be controlled, as they operate under artificial intelligence, while the later are digital representations of real-life users. The greatest scope for customisation lies with the avatar, allowing users to determine aspects such as facial expressions, outfit, and more [4]. Various platforms facilitate exploration of the virtual world, with the largest being Decentraland ($1.31 billion)[1], Sandbox ($1.31 billion), Theta Network ($1.1 billion), Axie Infinity ($1.01 billion), and Enjin Coin ($474.53 million) [16].

Built upon blockchain architecture, a digital unit of data known as the NFT (non-fungible token) has been developed. Each NFT possesses a unique identification code and distinct metadata, acting as a means of facilitating transactions [20]. However, the primary function of NFTs is to establish ownership of digital assets. These tokens can be purchased on specially designed virtual 'marketplaces' or 'bazaars', such as OpenSea, Axie Marketplace, and Rarible. On these platforms, investors not only engage in buying and selling transactions but can also exchange rights to individual tokens [42]. There are generally six main categories of non-fungible tokens, based on their use: art, collectibles, games, metaverse, other, and utility. The most significant features of NFTs are their uniqueness, traceability, authenticity, and adaptability [11]. The popularity of the NFT market saw a substantial increase in 2020/2021; the daily value of concluded transactions was 183,121 US dollars in 2020, which surged to 38 million dollars in 2021 [42].

Another crucial aspect in the realm of virtual reality trading is cryptocurrency, a type of digital currency specific to each metaverse platform. Unlike NFTs, each cryptocurrency operates on its own individual blockchain. Both cryptocurrencies and the metaverse space are underpinned by the same technological foundation, which significantly contributes to their popularity. This is attributed to their being the simplest, most convenient, and cost-effective means of payment in virtual spaces. Many transactions related to virtual real estate are conducted using cryptocurrencies. When the value of a particular cryptocurrency increases, the worth of virtual properties denominated in that currency may also rise

[1] The values in brackets represent the exchange value of the respective platform in US dollars as of 18 September 2022.

[25]. For instance, an appreciation in the price of Bitcoin could lead to a corresponding increase in the value of virtual properties priced in Bitcoins. Some investors utilise cryptocurrencies both as a means of payment and as an investment in virtual real estate [35]. The rising popularity and value of a specific cryptocurrency can lead to an increase in the value of the virtual properties that can be acquired with it. However, the cryptocurrency market is characterised by high volatility and speculation. Wide fluctuations in cryptocurrency prices can significantly impact the value of virtual properties. Conversely, a decline in a cryptocurrency's value may result in a decrease in the value of virtual properties, expressed in that currency [57]. Nevertheless, it is important to note that virtual properties possess intrinsic value independent of cryptocurrencies. Factors such as the popularity of the virtual world, the uniqueness and appeal of the property, user experience quality, and market supply and demand all influence the value of virtual real estate [52]. While the price of cryptocurrency may be a significant factor, it is not the sole determinant of virtual property values [56]. Examples of cryptocurrencies include MANA (Decentraland), SAND (Sandbox), and AXS/SLP (Axie Infinity) [4]. In the metaverse, intermedia art can be represented through a combination of various NFTs, encompassing elements related to human aesthetic, such as avatars, domains, utilities, or even land [26]. The acquisition of virtual property typically occurs on a 'marketplace', where ownership is secured in the form of an NFT stored on the blockchain, with the transaction conducted in a specific cryptocurrency.

III. DECENTRALAND

The virtual real estate market pertains to the trading, sale, and rental of virtual properties within the digital realm [38]. Virtual properties are digital spaces utilised for various activities, including video games, entertainment, virtual meetings, e-commerce, among others [3]. This market is dynamic, evolving alongside technological advancements and represents an emerging areas of interest for users, developers, investors, and businesses seeking to explore the opportunities provided by the digital virtual space [7][62][64].

Decentralized Finance (DeFi) refers to financial services that operate on blockchain technology, removing intermediaries by enabling peer-to-peer transactions through smart contracts. DeFi enables various applications, including lending, borrowing, and trading without traditional banks or financial institutions. Within the metaverse, Decentralized Finance extends these capabilities to virtual worlds, allowing for secure property transactions, lending, and even leveraging assets for additional investments. Decentraland employs DeFi through its use of MANA, facilitating property transactions directly between users. Another example of DeFi in the metaverse is seen in the platform Sandbox, which uses its native token SAND to enable similar decentralized, peer-to-peer interactions for trading virtual assets, further illustrating the diverse implementations of DeFi in virtual spaces.

The virtual real estate market includes several unique aspects:

- Virtual Worlds: Pertains to three-dimensional, interactive digital environments that users and virtual characters can explore and inhabit. Notable examples are Second Life, Decentraland, VRChat, and Sansar.
- Virtual Property: Users have the opportunity to purchase and own virtual assets, such as houses, apartments, plots of land, or offices within these worlds, gaining control over these spaces.
- Trade and Economy: Governed by the principles of supply and demand, owners may sell, rent, or trade their virtual properties for virtual currency or other digital assets. Platforms exist specifically for the buying and selling of virtual properties.
- Investments and Speculation: Mirroring the physical real estate market, the virtual domain offers investment and speculation opportunities. Certain virtual properties may appreciate in value, attracting investors predicting future value increases.
- Creating Virtual Experiences: Virtual spaces are often used to host experiences like concerts, art exhibitions, conferences, or social events. Businesses and organisations may rent virtual spaces for events or promotional activities, a practice increasingly observed in reality.
- Use of Technology: The interaction with and personalisation of virtual properties are enhanced by technologies such as Virtual Reality (VR), Augmented Reality (AR), blockchain, and cryptocurrencies. These technologies facilitate transaction tracking and ensure the security and authenticity of virtual properties.

Decentraland is the largest and possibly the most popular virtual blockchain world which in existence today [13]. It was the first large-scale blockchain-based virtual world [41]. According to Goldberg et al. (2024), Decentraland has a multi-layered architecture that creates a truly decentralised virtual world, where the supply cannot be increased by anyone, and investors do not face any risks [22]. Decentraland was founded in 2017 by Ariel Meilich and Esteban Ordano. The original design and layout of the sites are shown in ATTACHMENT I. Decentraland consists of four colours that represent roads, with different characteristics (ATTACHMENT II). The lines in light grey represent roads, which are not for sale. The green areas represent plazas, which are places where users are directed upon logging into Decentraland; hence, these areas have a high concentration of users. There are nine such places on the map, each with its own name. When the user logs in for the first time, they are directed to Genesis Plaza, located at the heart of the map, at coordinates 0,0. The dark blue areas are 'districts', which are meeting places for users who share common interests. The dark grey areas represent parcels of land ('parcels') and estates, consisting of two or more parcels, which are the primary focus of transactions.

However, after some time, it became apparent that some districts did not meet the criteria set by Decentraland. As a result, 17 of the existing 56 districts were dissolved in January 2019 (ATTACHMENT II). The status of the parcels forming them was changed to 'land', and they became subject to market transactions. The largest district is currently Aetheria, with 8,008 parcels, and the smallest is DPR Yetepey, with 28 parcels.

Each user of the platform can acquire ownership of a plot of land or, in the case of several plots of land combined, a property with fixed coordinates on the map. All plots are square-shaped with dimensions of 16m × 16m. Each one has its own coordinates, facilitating navigation for users and enabling investors to purchase the desired plot easily. Decentraland comprises 90,601 individual plots, of which 43,689 are for private use, 33,886 plots are included in 'districts', 9,438 plots are designated as roads and 3,588 plots are included in 'plazas' [23]. FIGURE I shows a sample parcel measuring 16 m × 16 m with a couple of ITEMs on it.

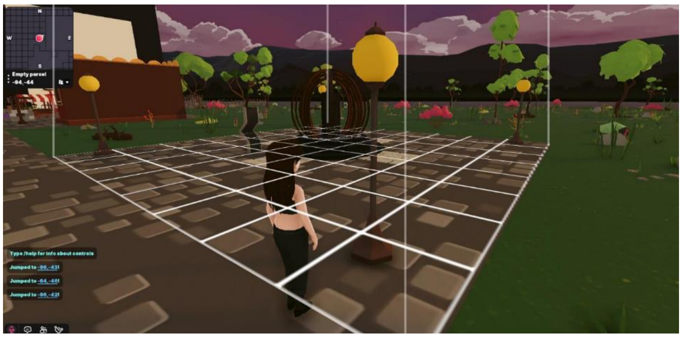


FIGURE I. THE SMALLEST PARCEL SIZES [23].

A plot of land represents the smallest unit available for purchase. An up-to-date map of Decentraland, showing visible development elements, is included in ATTACHMENT III. Eight plazas are observed forming the characteristic shape of an octagon, with the ninth located at its centre. The most intensively developed area is found in the central and south-central parts of Decentraland, which also boast the highest density of roads. In contrast, the least urbanised area is the south-western part, predominantly characterised by undeveloped properties, i.e., those without an ITEM on their site.

The name and price of the property are visible on the home page of the Marketplace. It is possible to sort the properties, with one option being to sort them from the cheapest to the most expensive. It appears that the cheapest property costs 3,390 MANA, while the most expensive property costs 1,000,000,000 MANA (as of 09 Sep 2022; with an exchange rate of 1 MANA = USD 0.80, meaning that the price of the cheapest property is USD 2,712, and the most expensive property is USD 800,000,000). When you click on a property of your choice, details such as the current owner of the property, the distance to amenities like the plaza, district, and road, as well as the transaction history are displayed.

A. *Legal Aspects of Metaverse*

At the moment, for the most part, there are still no regulations dedicated specifically to the Metaverse environment - their drafting is still under consideration [45][46]. Nevertheless, general regulations related to trademarks, bribery, or selling private data are observed [32]. Transactions recorded on blockchains remain a permanent record, providing some form of protection against theft, yet there is still a growing need for regulation in this kind of market [47]. The Metaverse faces challenges as there are currently no laws that can be directly applied, thus making it a risky area for those who advocate the necessity of regulations and laws for the proper functioning of a global industry. The authors suggest some aspects that must be regulated legally in the future:

1. Data security and privacy: regulations concerning the principles of collection, storage, and processing of data, including users' consent to the use of their data.
2. Intellectual property: copyright and patent protection for creators, along with rules on trade and ownership of virtual objects.
3. Contract and obligation law: enabling users to engage in transactions, enter into contracts, and undertake obligations, with regulations covering the binding force of virtual contracts, dispute resolution, and consumer protection.
4. Security: regulations should include preventative measures against fraud, cyberbullying, etc., and penalties for perpetrators of such activities.
5. Taxation: regulations covering the taxation of virtual transactions, income generated in the Metaverse, and other tax aspects.

In conclusion, it is worth noting that due to the dynamic development of Metaverse technology, regulation will continue to evolve alongside the technology. It is important to monitor this area and introduce new legislation to adapt to the changing realities of the Metaverse and protect social, economic, and legal interests.

B. *Metaverse vs NFT*

Virtual real estate, akin to NFTs, represents assets within virtual spaces but differs from consumer goods and services in that they are not direct substitutes [59]. This distinction primarily arises because virtual properties exist in virtual worlds and metaviews, signifying that they are digital representations of real estate without physical counterparts in reality, unlike tangible consumer goods and services or those offered as part of a real-world experience [33]. Moreover, virtual real estate is predominantly created and utilised today for entertainment, community-building, or investment purposes [58], serving as spaces where users can meet or interact with others. Conversely, consumer goods and services typically cater to everyday necessities such as food, clothing, health services, and transport [65]. Another notable distinction lies in their investment value; virtual properties, especially in the form of NFTs, often possess investment potential, subject to market speculation and trading [60]. People can buy, sell, and collect NFTs associated with virtual real estate as an investment form. In contrast, consumer goods and services are generally consumed to satisfy immediate needs and are not regarded as investment objects in the same manner [54]. When evaluating the value of NFTs and virtual real estate, it is crucial to recognise that the value of virtual real estate largely hinges on the subjective preferences and expectations of users. For consumer goods and services, value is often determined by their specific function, utility, and availability [27].

Therefore, although virtual properties may share certain similarities with consumer goods and services, they are not complete substitutes. They represent a distinct domain of digital interaction and experience, unique to virtual worlds and metaviews.

C. Virtual real estate market characteristics

The virtual property market encompasses the trading, buying, and selling of digital properties that exist within virtual worlds rather than physical reality. These virtual properties can assume various forms, such as land, buildings, islands, and decorative objects, available in computer games, virtual worlds, and entertainment platforms. The dynamics of the virtual real estate market often hinge on the popularity and demand for specific games or platforms. Should a particular game gain popularity, the demand for virtual properties within that game increases, potentially leading to higher prices. Similarly, the introduction of an attractive new virtual world or the opportunity to purchase unique properties on a specific platform can attract new players and boost demand. There are also platforms dedicated exclusively to the trading of virtual properties, allowing users to buy, sell, and trade virtual properties with others. Prices for virtual properties are determined by the market based on supply and demand and the value and popularity of the virtual world in question. In some instances, virtual properties may possess external value outside the game, with some players willing to pay significant amounts for rare or unique virtual properties that become collectors' items or hold prestige value within the gaming community. However, it is crucial to recognise that the virtual property market is a unique market often influenced by the decisions and policies of game and platform developers, who can impact the availability, resources, and prices of virtual properties, thereby affecting their market value.

An important factor in the development of virtual properties is the potential for collaboration between leading brands to offer unique experiences. Leading fashion brands including Nike, Adidas, and Reebok have announced partnerships with metaverse start-ups such as RTFKT to offer virtual product listings in the Metaverse [19]. Similar initiatives have been explored by investors through virtual museums and offerings. This collaborative development enables brand enthusiasts to experience new iterations of their favourite concepts and discover innovative entertainment methods. Beyond the real estate landscape, art collections such as Beeple's “Everyday's - The First 5000 Days” have managed to raise over $69 million in partnership with Christie's [39].

While virtual and traditional real estate markets share certain similarities, such as being governed by supply and demand principles, there are notable distinctions. In traditional real estate, property values are influenced by physical location, infrastructure, legal frameworks, and broader economic factors, which often result in gradual and relatively stable appreciation. By contrast, the value of virtual real estate is largely speculative and influenced by platform popularity, user engagement, and cryptocurrency market trends. For example, in Decentraland, the value of properties is closely tied to the value of MANA, a cryptocurrency subject to high volatility. Additionally, while real properties have intrinsic value derived from their physical attributes and utility, virtual properties derive value from digital attributes like proximity to popular virtual locations and the potential for creative digital customization, thus appealing to a different set of investor motivations.

IV. Methods

The research component of this paper focused on exploring the market for one of the metaverse platforms, Decentraland. This platform, among the most well-known and based on blockchain technology, grants open access to any user, thereby preserving the principles of a free market during transactions. The study focused on Decentraland due to its decentralized structure and the unique role of MANA within its economic framework. Unlike some other platforms where currencies primarily serve speculative purposes, MANA functions both as a transactional utility token and as a measure closely tied to real-world values, providing a stable foundation for evaluating virtual real estate. The data comprised transactions in the virtual properties market and the MANA cryptocurrency exchange rate to the US dollar.

The first task involved selecting sample data (sub-markets), termed fields, evenly distributed across the map. The selection considered the proximity to roads, districts, and plazas, ensuring an even distribution of fields across Decentraland to secure a representative sample of the property market. In total, 12 test fields were chosen, each consisting of 16 individual properties (so-called 'parcels') (Attachment IV). All test fields are square-shaped, measuring 4×4 parcels, except for field 6, which has a unique shape due to its neighbouring parcels. Consequently, land area was not considered a price factor. Attributes for each parcel were defined, with integer values from 0 to 10, based on their distance from roads, districts, and plazas. The appraisal standards adhered to the International Valuation Standards (IVS) [28] regarding the approach used, the definition of attributes, and their impact on value [24][61]. As a part of the market approach, the statistical analysis method was used, based on Pearson correlation coefficient as a base, and Kendall rank correlation as an auxiliary (checking) coefficient [2][29]. Parcel prices (and their dates) were obtained from the Decentraland marketplace on 15 September 2022.

The second task focuses on the performance of the MANA cryptocurrency against the US dollar. MANA, based on the Ethereum blockchain and linked to Decentraland as a currency, was analysed from its inception (09 November 2017, 1 MANA = 0.015 USD) to the end of the period on 16 September 2022 (MANA/USD 0.726), covering over 4.5 years. The daily exchange MANA/USD rate was illustrated in Figure II, with a logarithmic scale on the Y-axis for better interpretation. During the studied period, key moments included: (a) the lowest MANA/USD ratio (21 November 2017), (b) the dissolution of 17 districts (20 January 2019), (c) the official platform launch (20 February 2020), (d) the first MANA peak, and (e) the highest ratio (second peak, 25 November 2021). The official platform launch marked a significant event, with every dollar invested in Decentraland from that day yielding $12.4 by the end of the analysis period (2.57 years).

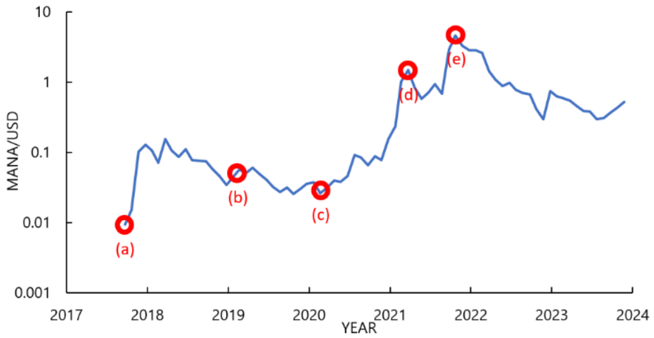


FIGURE II. HISTORICAL MANA/USD EXCHANGE RATE (Yahoo, 2024).

This paper explores the relationship between spatial attributes, property price, and price volatility over time, calculating correlation coefficients. Similar to real estate, a meta-estate is defined by specific attributes such as its location within the platform, its dimensions, ownership rights, and its market value. However, to be more precise, investors may focus on many more attributes. Thus, this analysis takes into account 10 attributes: Field No., Coordinates, ITEM, Road, District, Plaza, Transaction Date, Price [MANA], MANA/USD ratio, Price [USD], and one comment (Current offer price [MANA/USD]).

Overall, in total, the developed dataset comprises 207 records for 103 land parcels (some parcels were sold multiple times) and was organised into 10 – mentioned above – attributes (ATTACHMENT VII). The first property was sold on 14 October 2018, and the last transaction in the analysis period occurred on 18 June 2022.

V. RESULTS

The analysis of Decentraland's property market was based on 12 test fields, evenly distributed across the map, each consisting of 16 (4 × 4) parcels, with their distribution shown in ATTACHMENT IV. All property information and transactional data underpinning the analysis are compiled in ATTACHMENT VII. The results of the property transaction history analysis were visualised in the form of 12 (4 × 4) parcel tables, one for each test field. The table's layout mirrors the field's shape, and each cell represents a single virtual property. For each parcel of land, a cell was assigned the highest transaction price in its (ATTACHMENT V). Additionally, prices are colour-coded for easy differentiation - dark green represents the highest price for a given test plot, while white indicates the lowest price. Highlighting denotes the presence of ITEMs within the respective plot.

The largest number of parcels sold was recorded in test field 7 (located in the central part of Decentraland), with 15 transactions, while the smallest number, 3, was noted for test field 15 (located in the western part). The highest transaction price was achieved by undeveloped properties with coordinates (144, −29) and (144, −30) in test field 3, reaching 34,197 USD. In contrast, the lowest price, 380 USD, was observed for the property with coordinates (55, −121).

To analyse price changes over time, graphs were produced for "triples" of test fields, i.e., graph 1 for test fields 1–3, graph 2 for fields 4–6, graph 3 for fields 7–9, and graph 4 for fields 10–12 (ATTACHMENT IV). These graphs display parcels that were sold at least twice to illustrate how prices have evolved, e.g., parcel (−69, −18) from test field 1 was sold twice - in February 2022 and March 2022 (as per TABLE I). Colours represent the fields in each graph, transactions within a field are distinguished by line types, and markers denote transactions for each parcel.

In the very centre of Decentraland lie fields 6 and 7. Due to their location, the properties in these fields have similar attributes. However, only seven parcels were sold in field 6, compared to as many as 15 in field 7. This discrepancy is also reflected in the average price: for field 6, it was 8,303 USD, while for field 7, it was 12,165 USD. Therefore, the correlation between attributes and price is low. Both fields 2 and 3 are situated in the eastern part of Decentraland and are equidistant from the road. Despite field 2 being located closer to the plaza and district, suggesting greater attractiveness, it recorded fewer transactions (6) than field 3 (12). Moreover, the highest price for field 2 reached 17,157 USD, whereas field 3's highest price was twice as much, at 34,197 USD. Fields 1, 4, and 2 are almost identically positioned relative to the centre of the map, situated between plazas. The largest number of plots was sold in field 1 (9), while the smallest number was sold in field 2 - 6 plots. The average maximum price of the properties was 9,778 USD for field 1 and 8,004 USD for field 2, and 11,484 USD for field 4. Fields 9 and 10, located in the southern part of Decentraland, also share similar attributes. For both fields, 11 parcels were sold. Yet, there is a difference in the average price - 5,371 USD for field 9 and 3,839 USD for field 10. Although this difference is smaller than that between fields 6 and 7, it is still significant.

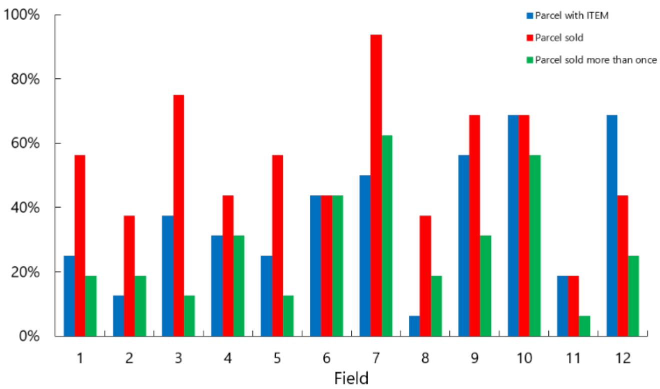


FIGURE III. GRAPH SHOWING THE PERCENTAGE OF PARCELS SOLD, PARCELS SOLD SEVERAL TIMES, AND PARCELS CONTAINING ITEM IN THE ANALYSED FIELDS.

In addition, the impact of attaching ITEMs to properties on their sales was analysed. Furthermore, for each of the test fields, the number of properties sold multiple times was examined (ATTACHMENT VI). The results of these analyses have been compiled in Table I and are also presented in the chart (FIGURE III). The largest number of parcels sold was recorded in test field No. 7, with as many as 15, representing approximately 94% of all properties in that field. This field also had the highest number of properties that were sold at least twice, with 10 such properties (63%). The high number of transactions in this field can be attributed to its central location on the map. The highest number of properties where ITEM exists was observed in field 12, with 11 (69%). Field 11 was the least successful, with only 3 properties sold, one of which was sold multiple times. In contrast, the smallest number of properties with ITEM was in field 8, with just one such property. The average number of plots sold across all fields is 8.6, the average number of plots with ITEM is 5.9, and the average number of parcels sold multiple times is 4.5.

To examine the impact of each attribute on the property price (in US dollars), a correlation coefficient value was calculated for each attribute (TABLE I), divided into three-time spans: before the platform launch (February 2020), after the launch, and in total. Before the official platform launch, the correlation coefficients indicate that the property price was significantly influenced by the amount of MANA (Price – MANA). The MANA/USD exchange rate was below 10 cents (0.02–0.09), and property costs were relatively low. While the MANA-USD correlation is noteworthy, the market activity may suggest that the primary factor was the belief in the project's success among virtual world enthusiasts rather than market speculation. After the release date, the property market underwent significant changes. The average transaction value increased more than 13-fold (from \$659.76 to \$9074.04). Tests of the mean (Welsh's T-test) and variance (Levene's test) indicate that these represent two distinct property markets, despite the high standard deviation of the means (0.5 and 0.79 respectively). The tests for significant differences (α=0.05) for correlations (transformed by Fisher z-transformation) for Price-Time, Price-MANA, and Price – MANA/USD reject the null hypothesis of equality. In the post-launch market, the Price – MANA and MANA-USD factors indicate that investors are influenced by the value in real currency (US dollar), not the virtual one (Price – MANA factor should be omitted). Thus, the significant factors are time and MANA-US dollar rate. This situation suggests that the real estate market is strongly influenced by speculation on the entire platform (i.e., dependent on external factors) and only slightly by its internal features (e.g., selected property features). It should be noted that the selected attributes were limited, primarily spatially defined, and do not include social factors (e.g., genius loci, etc.).

TABLE I. CORRELATION COEFFICIENTS FOR PRICE AND OTHER ATTRIBUTES BEFORE AND AFTER THE OFFICIAL PLATFORM RELEASE.

Correlation values	**The Decentraland periods**		
	Before launch (<Feb. 2020)	After launch (>Feb. 2020)	Total (Oct. 2018–June 2022)
Price - Time	−0.22	0.59	0.72
Price - ITEM	−0.08	−0.22	−0.14
Price - Road	0.00	0.18	0.20
Price - District	−0.14	0.01	0.02
Price - Plaza	−0.03	−0.03	−0.07
Price - MANA	0.73	−0.45	−0.53
Price - MANA/USD	0.63	0.88	0.93

Other aspects that might affect a parcel's price are not measurable and cannot be accurately estimated. The value of real estate in Decentraland stems from a combination of traditional market mechanisms and the unique characteristics of the virtual world. Factors such as location, infrastructure development, income generation potential, cryptocurrency fluctuations, and community engagement are key determinants. In the long term, the value of LAND will depend on the success of Decentraland as a platform and the growing interest in the Metaverse and blockchain, which may lead to increased demand for virtual real estate. Plots of land can be rented out or used for activities such as virtual shops, events, or brand promotions. The more traffic an area receives, the greater its potential for revenue generation. Additionally, community involvement and visits to the Decentraland world enhance the attractiveness of properties. Another contributing factor can be the plot's history—if it has previously been used by well-known brands, its value can increase. Furthermore, announcements of new features, partnerships, or developments on Decentraland can also raise the value of properties.

VI. DISCUSSION

Metaverse platforms offer users the opportunity to meet others online. Additionally, owning property can yield profits. Decentraland, in particular, due to its decentralised structure, grants complete freedom to acquire and then dispose of property. Property owners have access to a wide range of solutions, including the placement of digital skyscrapers, palaces, and art galleries, among others. However, it is important to note that this market is relatively new and carries considerable risk.

The analysis covered 207 sales across 103 land parcels: 82 before (2017–2020) and 125 after the platform's launch (2020–2022). The virtual currency (MANA) to US dollar exchange rate served as a reference.

The virtual property market is highly volatile, marked by its dependence on the virtual currency (MANA) to the US dollar rate. From the released day (02.2020) to the end of the analysed period (09.2002), the currency increased from 0.05 to 0.73 MANA per US dollar. This indicates that every dollar invested from the launch day yielded \$12.4 in 2.57 years. Consequently, the values of analysed virtual properties increased more than 13-fold on average. Before the official release, property values were relatively low, correlating only with Price-to-MANA and Price-to-MANA/US dollar rate. This situation might suggest that the market was primarily driven by metaverse enthusiasts, inclined to invest in the "game" rather than in property market. After the launch day, statistically significant changes in correlation were observed: the price to time factor became significant (from −0.22 to 0.59), the price to MANA/US correlation rose to a high level (from 0.63 to 0.88), and the price to MANA shifted from strong correlated (0.73) to an average level of negative correlation (−0.45).

Other property attributes were selected by following the International Valuation Standards in terms of the approach used, the definition of attributes, and their impact on value [24][61]. The considered factors were mostly limited to spatial ones, based on the distance from roads, districts, and plazas. The analysis did not include social factors (e.g., genius loci, etc.). The chosen method (Pearson correlation) yielded negative results: no correlation was found between these factors and the price of the property. This outcome is quite unusual, as investors would typically prefer plots closer to the aforementioned locations due to the greater likelihood of visitation, which aligns with the primary purpose of investing in Decentraland - to attract other users. The location's proximity to the city centre also seems to have a slight impact on the price. This can be justified by the fact that within the platform, any user can move their avatar to any location using the teleportation tool, which requires only a few clicks. The presence of ITEMs on a property, described as 0 (ITEMs free) and 1 (existing ITEMs), has a very slight negative correlation (−0.22) with the price.

In general, the proposed attributes that could potentially generate price had little impact on property prices. This indicates that valuation using the comparative approach is not viable. Similarly, valuation through the income approach is unfeasible, as the virtual property itself is not profitable; it can merely serve as a venue for product advertisement. The cost approach is inherently not applicable as virtual objects do not deteriorate. Therefore, following the International Valuation Standards, it may be concluded that virtual properties on the Decentraland platform cannot be evaluated as real estate. Moreover, the impact of MANA/US dollar rate on properties suggests that they should not be valuated separately (as real estate), but rather in conjunction with the MANA currency. This means that evaluations should employ methods from the financial markets.

Given the high volatility of the Decentraland environment, it is crucial to consider that factors which currently have no impact on a property's value may become significant in the near future, both positively and negatively. The study focused primarily on real estate trading. However, virtual reality may offer numerous opportunities, such as advertising products or organising cultural events, which could influence the property market and its valuation. The advantages of investing in Decentraland real estate include the relatively easy acquisition of property, the possibility of making a quick profit with minimal effort, and accessibility to users worldwide. On the downside, the high volatility of cryptocurrencies and the need for creativity and technical skills to develop the property, despite the simplicity of the purchase process, are notable disadvantages.

To contextualise these findings, a comparison between virtual and physical real estate markets highlights the unique investment risks and valuation challenges faced in the metaverse. In addition to the specific valuation factors analysed, it is critical to consider the broader speculative dynamics, and oversupply risks inherent to virtual real estate markets. The rapid development and expansion of platforms like Decentraland, Sandbox, and other metaverse spaces expand the supply of virtual properties, potentially leading to market saturation. Such oversupply could dilute the value of individual assets and intensify speculative trading, as users and investors may perceive limited long-term value in a market with minimal physical constraints. The speculative nature of these assets, largely tied to fluctuating cryptocurrency values, may exacerbate volatility, complicating valuation stability in the metaverse. These dynamics underscore the need for continuous monitoring of supply-demand equilibrium in virtual markets, which may help mitigate the risk of bubbles and abrupt valuation declines. This comparison not only underscores the divergent dynamics of virtual and physical markets but also emphasises the importance of developing tailored investment strategies for the metaverse.

The comparison of virtual and physical real estate markets highlights significant differences in investment risks and valuation perspectives. In traditional real estate markets, investment risks are generally tied to physical factors such as property location, infrastructure, market conditions, and legal frameworks, which provide a degree of stability and predictability. Investors can rely on established valuation methods, including comparative market analysis, income-based approaches, and cost analysis, all of which are grounded in tangible, regulated assets. In contrast, virtual real estate markets, like Decentraland, present unique investment risks. These include extreme market volatility driven by cryptocurrency fluctuations, platform-specific factors, and speculative trading behaviours. The value of virtual properties is often linked to non-tangible attributes, such as proximity to popular virtual locations, community engagement, and the presence of notable digital assets or events. For example, properties in high-traffic virtual districts or those used for brand collaborations may command premium prices, despite lacking physical constraints. From a valuation perspective, traditional real estate benefits from well-defined methodologies and regulatory oversight. However, virtual real estate relies heavily on speculative and subjective factors. Decentraland's virtual properties, for instance, cannot be evaluated using conventional real estate valuation methods such as the cost approach, as virtual assets do not deteriorate over time. Instead, valuation in the metaverse requires integrating financial market methodologies, accounting for cryptocurrency exchange rates, platform growth, and user demand. Furthermore, investment risks in virtual markets are amplified by the lack of established regulations and the potential for market saturation. The speculative nature of virtual assets, coupled with the rapid expansion of metaverse platforms, creates uncertainty for long-term value stability.

Conversely, physical real estate investments are supported by enduring demand and intrinsic utility, offering a more predictable return on investment. These differences underscore the need for prospective virtual property investors to adopt a cautious approach, considering both the opportunities and the inherent risks. While the virtual market offers the potential for significant short-term gains, particularly in high-demand platforms like Decentraland, it also requires a higher tolerance for risk and a deep understanding of digital market dynamics. Future research could further explore strategies to mitigate these risks and enhance valuation methods, bridging the gap between traditional and virtual real estate markets.

ACKNOWLEDGEMENT

We thank AGH University of Krakow for their support.

FUNDING

This research was funded by the AGH University of Krakow grant no. 16.16.150.545.

AUTHORS` CONTRIBUTIONS

All authors have participated in drafting the manuscript. All authors read and approved the final version of the manuscript. Author contribution percentages are as follows: DN 35%, CAGS 10%, LB 10%, MA 10%, KM 35%.

CONFLICT OF INTEREST

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

DATA AVAILABILITY

The data supporting the findings of this study are available upon request from the authors.

ETHICAL STATEMENT

In this article, the principles of scientific research and publication ethics were followed. This study did not involve human or animal subjects and did not require additional ethics committee approval.

DECLARATION OF AI USAGE

No AI tools were used in the creation of this manuscript.

REFERENCES

[1] @carrotcake. (2018). Decentraland: An Epic Virtual World Powered by Cryptocurrency.

[2] Abdi, H. (2007). The Kendall Rank Correlation. In Encyclopedia of Measurement and Statistics. Thousand Oaks (CA): Sage. https://personal.utdallas.edu/~herve/Abdi-KendallCorrelation2007-pretty.pdf

[3] Adegoke, A. S., Oladokun, T. T., Ayodele, T. O., Agbato, S. E. & Jinadu, A. A. (2022). DEMATEL method of analysing the factors influencing the decision to adopt virtual reality technology by real estate firms in Lagos property market. Smart and Sustainable Built Environment, 11(4), 891–917. https://doi.org/10.1108/SASBE-09-2020-0135

[4] Akkus, H. T., Gursoy, S., Dogan, M. & Demir, A. B. (2022). Metaverse and metaverse cryptocurrencies (meta coins): bubbles or future. Pressacademia, 9, 22–29. https://doi.org/10.17261/pressacademia.2022.1542

[5] Al-Gnbri, M. K. A. (2022). Accounting and Auditing in the Metaverse World from a Virtual Reality Perspective: A Future Research. Journal of Metaverse, 2(1), 29–41.

[6] Allouzi, A. S. & Alomari, K. M. (2023). Adequate legal rules in settling metaverse disputes: Hybrid legal framework for metaverse dispute resolution (HLFMDR). International Journal of Data and Network Science, 7(4), 1627–1642. https://doi.org/10.5267/j.ijdns.2023.8.001

[7] Anderson, K. C., Freybote, J. & Manis, K. T. (2022). The Impact of Virtual Marketing Strategies on the Price-TOM Relation. Journal of Real Estate Finance and Economics. https://doi.org/10.1007/S11146-022-09908-X

[8] Ante, L., Wazinski, F. P. & Saggu, A. (2023). Digital real estate in the metaverse: An empirical analysis of retail investor motivations. Finance Research Letters, 58(31), 1–14. https://doi.org/10.1016/j.frl.2023.104299

[9] Ball, M. (2020). The metaverse: What It Is, Where to Find it, and Who Will Build It.

[10] Ball, M. (2022). The Metaverse and how it will revolutionize everything. Liveright.

[11] Bao, H. & Roubaud, D. (2022). Non-Fungible Token: A Systematic Review and Research Agenda. Journal of Risk and Financial Management, 15(5). https://doi.org/10.3390/jrfm15050215

[12] Bartels, N. & Hahne, K. (2023). Teaching Building Information Modeling in the Metaverse—An Approach Based on Quantitative and Qualitative Evaluation of the Students Perspective. Buildings, 13(9). https://doi.org/10.3390/buildings13092198

[13] blockee.co. (2024). What Are The Most Popular Virtual Worlds?

[14] Chen, C. & Yao, M. Z. (2022). Strategic use of immersive media and narrative message in virtual marketing: Understanding the roles of telepresence and transportation. Psychology and Marketing, 39(3), 524–542. https://doi.org/10.1002/mar.21630

[15] Clark, P. A. (2021). What is the Metaverse? Here's Why It Matters. Time.

[16] Coinmarketcap. (2022). Top Metaverse Tokens by Market Capitalization.

[17] Jach, W., Hubar, Y., Trojański, P., Maciuk, K. (2023) Trends in primary apartments market during COVID-19 pandemic. Budownictwo i Architektura. 22(4), 27–37. https://doi.org/10.35784/bud-arch.3728

[18] Duan, H., Li, J., Fan, S., Lin, Z., Wu, X. & Cai, W. (2021). Metaverse for Social Good: A University Campus Prototype. MM 2021 - Proceedings of the 29th ACM International Conference on Multimedia, 153–161. https://doi.org/10.1145/3474085.3479238

[19] Egede, I. (2022). Reebok joins the Metaverse bandwagon after Nike and Adidas. Crypto.News.

[20] Febriandika, N. R., Fadli, F. & Mi'raj, D. A. (2022). How are NFT (Non-Fungible Token) transactions reviewed according to Islamic law? Borobudur Law Review, 3(1), 1–12.

[21] Gartner. (2022). Predicts 2022: 4 technology bets for building the digital future. Gartner Report.

[22] Goldberg, M., Kugler, P. & Schär, F. (2024). Land valuation in the metaverse: location matters. In Journal of Economic Geography (Vol. 24, Issue August). https://doi.org/10.1093/jeg/lbae027

[23] Güven, İ. & Ercan, T. (2022). Determining Factors of Virtual Land Value: The Case of Decentraland. ITESDES: International Technology Sciences and Design Symposium, July, 518–537.

[24] Hasan, G. M. J., Jabir, A. Al & Anam, M. M. (2022). Monitoring bank-line movements of the rivers flowing across the Sundarbans

using remote sensing and GIS techniques. Regional Studies in Marine Science, 56. https://doi.org/10.1016/j.rsma.2022.102679

[25] Hirsch, P. B. (2022). Adventures in the metaverse. Journal of Business Strategy, 43(5), 332–336. https://doi.org/10.1108/JBS-06-2022-0101

[26] Hong, R. & He, H. (2021). Interference and Consultation in Virtual Public Space: The Practice of Intermedia Art in Metaverse. Proceedings - 2021 17th International Conference on Mobility, Sensing and Networking, MSN 2021, 792–797. https://doi.org/10.1109/MSN53354.2021.00124

[27] Hwang, Y. (2023). When makers meet the metaverse: Effects of creating NFT metaverse exhibition in maker education. Computers and Education, 194. https://doi.org/10.1016/J.COMPEDU.2022.104693

[28] IVSC. (2021). International Valuation Standards. https://viewpoint.pwc.com/dt/gx/en/ivsc/international_valuat/assets/IVS-effective-31-Jan-2022.pdf

[29] Kendall, M. G. . & Gibbons, J. D. (1990). Rank correlation methods. E. Arnold ; Oxford University Press. https://search.worldcat.org/title/21195423

[30] Kęsy, M. (2014). Rzeczywistość wirtualna w procesie kształcenia technicznego. Edukacja-Technika-Informatyka, 42–47.

[31] Kosciesza, A. J. (2022). The Moral Service of Trans NPCs: Examining the Roles of Transgender Non-Player Characters in Role-Playing Video Games. Games and Culture, 155541202210881. https://doi.org/10.1177/15554120221088118

[32] Kostenko, O., Furashev, V., Zhuravlov, D. & Dniprov, O. (2022). Genesis of Legal Regulation Web and the Model of the Electronic Jurisdiction of the Metaverse. Bratislava Law Review, 6(2), 21–36. https://doi.org/10.46282/blr.2022.6.2.316

[33] Lee, J. & Kwon, K. H. (2022). Novel pathway regarding good cosmetics brands by NFT in the metaverse world. Journal of Cosmetic Dermatology, 21(12), 6584–6593. https://doi.org/10.1111/JOCD.15277

[34] Lee, U. K. & Kim, H. (2022). UTAUT in Metaverse: An “Ifland” Case. Journal of Theoretical and Applied Electronic Commerce Research, 17(2), 613–635. https://doi.org/10.3390/jtaer17020032

[35] Mackenzie, S. (2022). Criminology Towards the Metaverse: Cryptocurrency Scams, Grey Economy and the Technosocial. The British Journal of Criminology, 62(6), 1537–1552. https://doi.org/10.1093/bjc/azab118

[36] Marin, O., Cioara, T., Toderean, L., Mitrea, D. & Anghel, I. (2023). Review of Blockchain Tokens Creation and Valuation. Future Internet, 15(12), 382. https://doi.org/10.3390/fi15120382

[37] Marketplace. (2022). Marketplace (Land).

[38] Miljkovic, I., Shlyakhetko, O. & Fedushko, S. (2023). Real Estate App Development Based on AI/VR Technologies. Electronics (Switzerland), 12(3). https://doi.org/10.3390/ELECTRONICS12030707

[39] Mittal, A. (2021). Metaverse riding on NFT boom, says owner of $69 million digital artwork. The Economic Times.

[40] NFZ Plazas. (2022). Decentraland Map.

[41] Ordano, E., Meilich, A., Jardi, Y. & Araoz, M. (2017). Decentraland: A Blockchain-based Virtual World.

[42] Pinto-Gutiérrez, C., Gaitán, S., Jaramillo, D. & Velasquez, S. (2022). The NFT Hype: What Draws Attention to Non-Fungible Tokens? Mathematics, 10(3). https://doi.org/10.3390/math10030335

[43] Poux, P. (2022). A Unified Framework for the Governance of the Commons with Blockchain-Based Tools: An Application to Customary Land Commons in Ghana. SSRN Electronic Journal, 1–40. https://doi.org/10.2139/ssrn.4077127

[44] Ritterbusch, G. D. & Teichmann, M. R. (2023). Defining the Metaverse: A Systematic Literature Review. IEEE Access, 11, 12368–12377. https://doi.org/10.1109/ACCESS.2023.3241809

[45] Rosenberg, L. (2022). Regulation of the Metaverse: A Roadmap The risks and regulatory solutions for largescale consumer platforms. ACM International Conference Proceeding Series, July, 21–26. https://doi.org/10.1145/3546607.3546611

[46] Rosenberg, L. B. (2022). Regulating the Metaverse, a Blueprint for the Future. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), 13445 LNCS, 263–272. https://doi.org/10.1007/978-3-031-15546-8_23

[47] Rosenberg, L. B. (2023). The Growing Need for Metaverse Regulation. Lecture Notes in Networks and Systems, 544 LNNS(September), 540–547. https://doi.org/10.1007/978-3-031-16075-2_39

[48] Sarmah, G. (2020). The Emergence of Block chain Technology and its Economic Significance. Journal of Critical Reviews, 07(13), 4485–4491.

[49] Shwedeh, F. (2024). Harnessing digital issue in adopting metaverse technology in higher education institutions: Evidence from the United Arab Emirates. International Journal of Data and Network Science, 8(1), 489–504. https://doi.org/10.5267/j.ijdns.2023.9.007

[50] Siwak, W. (2016). Matrix i pół-Matrix czyli rzeczywistość wirtualna i rzeczywistość rozszerzona jako wyzwania dla tożsamości, kultury, sztuki i edukacji. Rocznik Naukowy Kujawsko-Pomorskiej Szkoły Wyższej w Bydgoszczy, 11, 355–388.

[51] Solaiman, B. (2023). Telehealth in the Metaverse: Legal & Ethical Challenges for Cross-Border Care in Virtual Worlds. Journal of Law, Medicine and Ethics, 51(2), 287–300. https://doi.org/10.1017/jme.2023.64

[52] Syuhada, K., Tjahjono, V. & Hakim, A. (2023). Dependent Metaverse Risk Forecasts with Heteroskedastic Models and Ensemble Learning. Risks, 11(2), 32. https://doi.org/10.3390/risks11020032

[53] Tesmer, V., Steigenberger, P., van Dam, T. & Mayer-Gürr, T. (2011). Vertical deformations from homogeneously processed GRACE and global GPS long-term series. Journal of Geodesy, 85(5), 291–310. https://doi.org/10.1007/s00190-010-0437-8

[54] Thenjono, K., Ratana, F. & Hendratno, S. P. (2022). The Business Prospect in Metaverse and NFT Era (User, Accountant, and Gaming Community Perspectives). 2022 4th International Conference on Cybernetics and Intelligent System, ICORIS 2022. https://doi.org/10.1109/ICORIS56080.2022.10031392

[55] van der Merwe, D. F. (2022). The metaverse as virtual heterotopia. 3rd World Conference on Research in Social Sciences. https://doi.org/10.33422/3rd.socialsciencesconf.2021.10.61

[56] Vidal-Tomás, D. (2022). The new crypto niche: NFTs, play-to-earn, and metaverse tokens. Finance Research Letters, 47, 102742. https://doi.org/10.1016/j.frl.2022.102742

[57] Vidal-Tomás, D. (2023). The illusion of the metaverse and meta-economy. International Review of Financial Analysis, 86, 102560. https://doi.org/10.1016/j.irfa.2023.102560

[58] Wang, C., Yu, C. & Li, Y. (2022). Toward Understanding Attention Economy in Metaverse: A Case Study of NFT Value. IEEE Transactions on Computational Social Systems. https://doi.org/10.1109/TCSS.2022.3221669

[59] Wang, C., Yu, C. & Zhang, Y. (2022). Attention Economy in Metaverse: An NFT Value Perspective. 2022 IEEE 24th International Workshop on Multimedia Signal Processing, MMSP 2022. https://doi.org/10.1109/MMSP55362.2022.9949153

[60] Wang, M. & Lau, N. (2023). NFT Digital Twins: A Digitalization Strategy to Preserve and Sustain Miao Silver Craftsmanship in the Metaverse Era. Heritage, 6(2), 1921–1941. https://doi.org/10.3390/HERITAGE6020103

[61] Wang, Y., Tang, P., Liu, K., Cai, J., Ren, R., Lin, J. J., Cai, H., Zhang, J., El-Gohary, N., Berges, M. & Golparvar Fard, M. (2023). Characterizing Data Sharing in Civil Infrastructure Engineering: Current Practice, Future Vision, Barriers, and Promotion Strategies. Journal of Computing in Civil Engineering, 37(2). https://doi.org/10.1061/jccee5.cpeng-5077

[62] Xiong, C., Cheung, K. S., Levy, D. S. & Allen, M. (2022). The effect of virtual reality on the marketing of residential property. Housing Studies. https://doi.org/10.1080/02673037.2022.2074971

[63] Yahoo. (2024). Decentraland USD (MANA-USD).

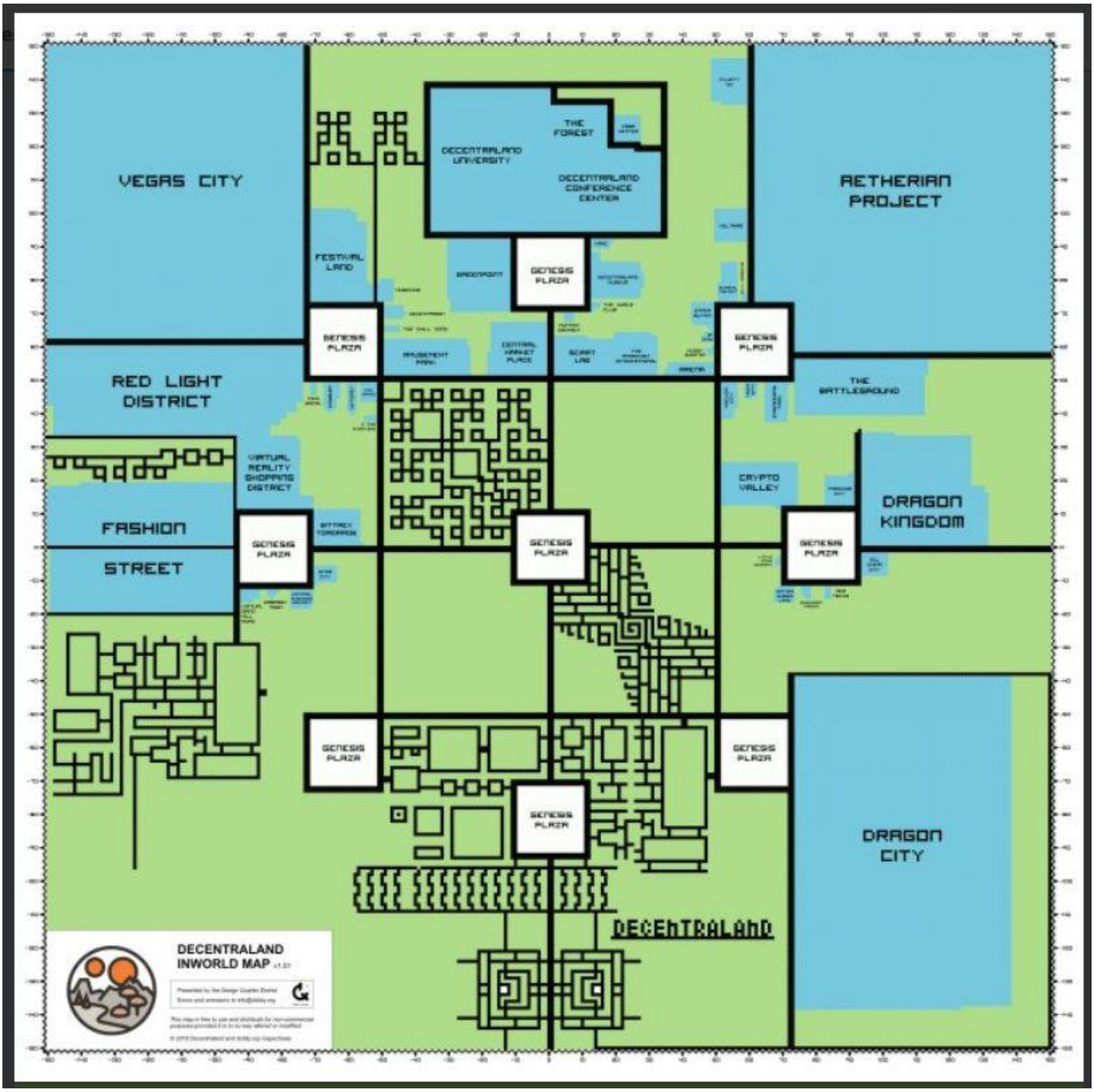
[64] Yasnitsky, L. N., Yasnitsky, V. L. & Alekseev, A. (2022). Simulation of Residential Real Estate Markets in the Largest Russian Cities. Economy of Regions, 18(2), 609–622. https://doi.org/10.17059/EKON.REG.2022-2-22

[65] Zelenyanszki, D., Hóu, Z., Biswas, K. & Muthukkumarasamy, V. (2023). A privacy awareness framework for NFT avatars in the metaverse. 2023 International Conference on Computing, Networking and Communications, ICNC 2023, 431–435. https://doi.org/10.1109/ICNC57223.2023.10074107

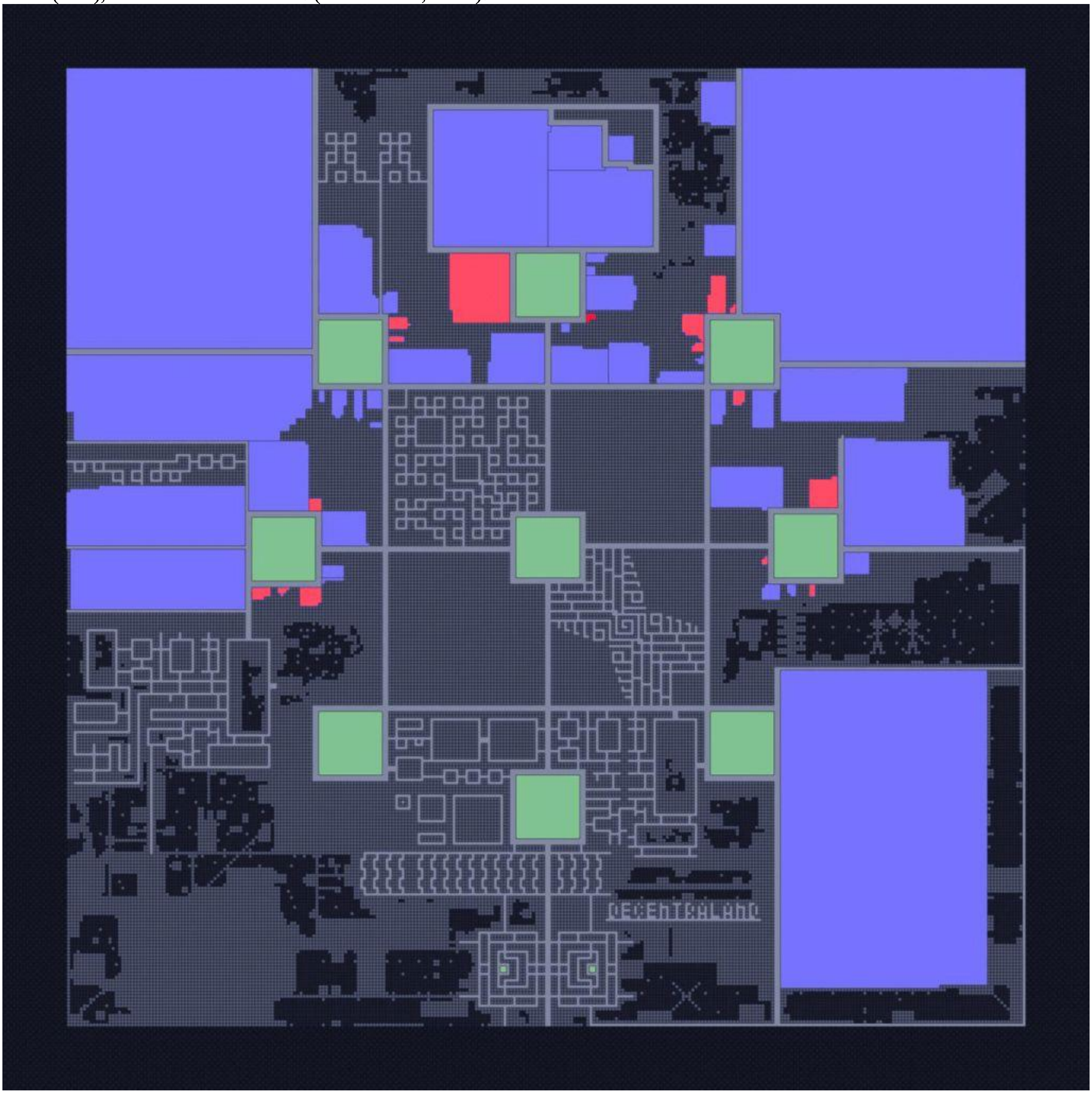
[66] Zenou, T. (2022). A novel predicted the metaverse (and hyperinflation) 30 years ago. The Washington Post.

[67] Zhao, Y., Jiang, J., Chen, Y., Liu, R., Yang, Y., Xue, X. & Chen, S. (2022). Metaverse: Perspectives from graphics, interactions and visualization. Visual Informatics, 6(1), 56–67. https://doi.org/10.1016/j.visinf.2022.03.002

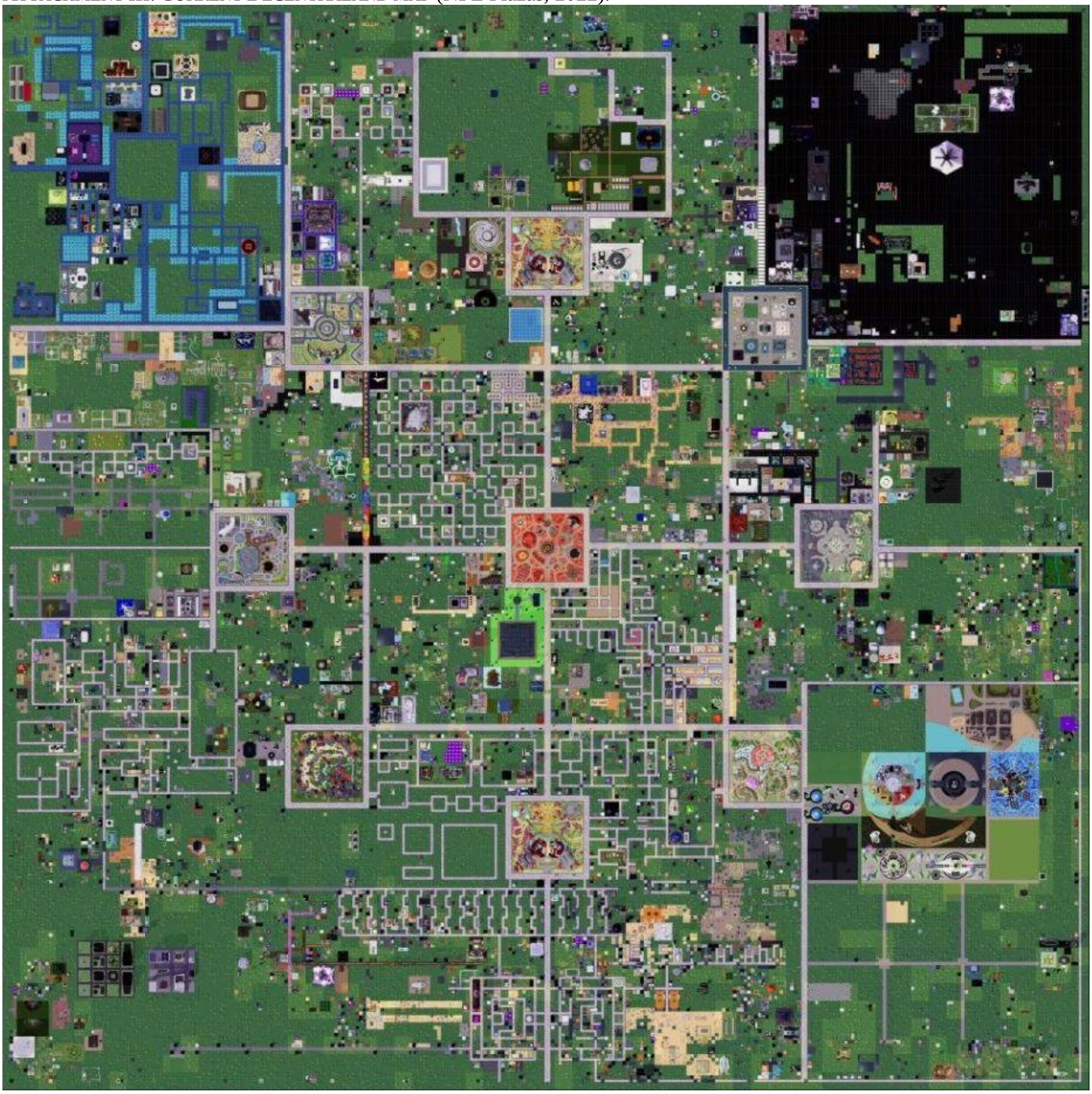
ATTACHMENT I. VERY FIRST MAP - DISTRICT VIEW OF DECENTRALAND MAP BY DESIGN QUARTER (@carrotcake, 2018).



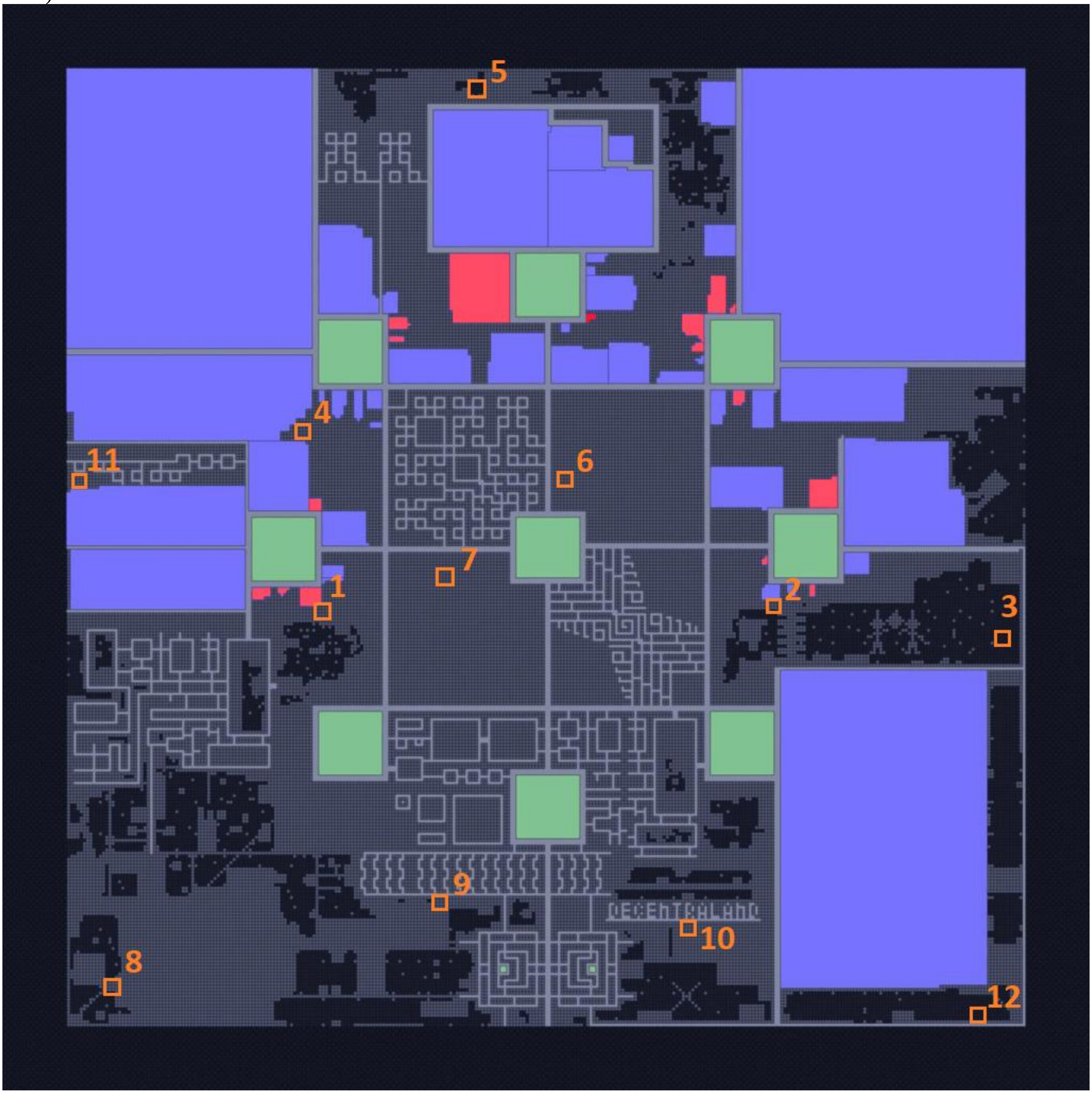
ATTACHMENT II. JANUARY 2019: DECENTRALAND MAP HIGHLIGHTING: CURRENT DISTRICTS (DARK BLUE) AND DISSOLVED ONES (RED), OWN STUDY BASED ON: (NFZ Plazas, 2022).



ATTACHMENT III. CURRENT DECENTRALAND MAP (NFZ Plazas, 2022).



ATTACHMENT IV. LOCATION OF 12 TEST FIELDS (ORANGE) ANALYSED IN THE STUDY, OWN STUDY BASED ON: (NFZ Plazas, 2022).



ATTACHMENT V. PRICES IN AN ANALYSED FIELD

Field 1

	4867		15196
15263			14317
		11490	11088
5325	779	9680	

Field 2

17157	800	11113	
		1050	
		17105	
800			

Field 3

	4539	14606	14606
	15496	14490	18200
	15603	13398	34197
	15603	16591	34197

Field 4

		1920	
6120		18500	
		14552	17576
	16675		5047

Field 5

10725	9781		10163
			10163
460	12998	1100	
	12845	599	

Field 6

10299	1063		1245
		22519	
	8519		1500
		12978	

Field 7

4 897	4 859	14 395	3 100
4 253	17 312	24 325	5 398
15 433	26 004	13 074	5 392
23 181	15 886	4 968	

Field 8

743			
		625	
	475	524	
499	15675		

Field 9

1056	1000	13836	1320
3416	16682	17133	2842
719	540		540

Field 10

2480		1160	15776
543	570	7187	595
380	600		
500	12436		

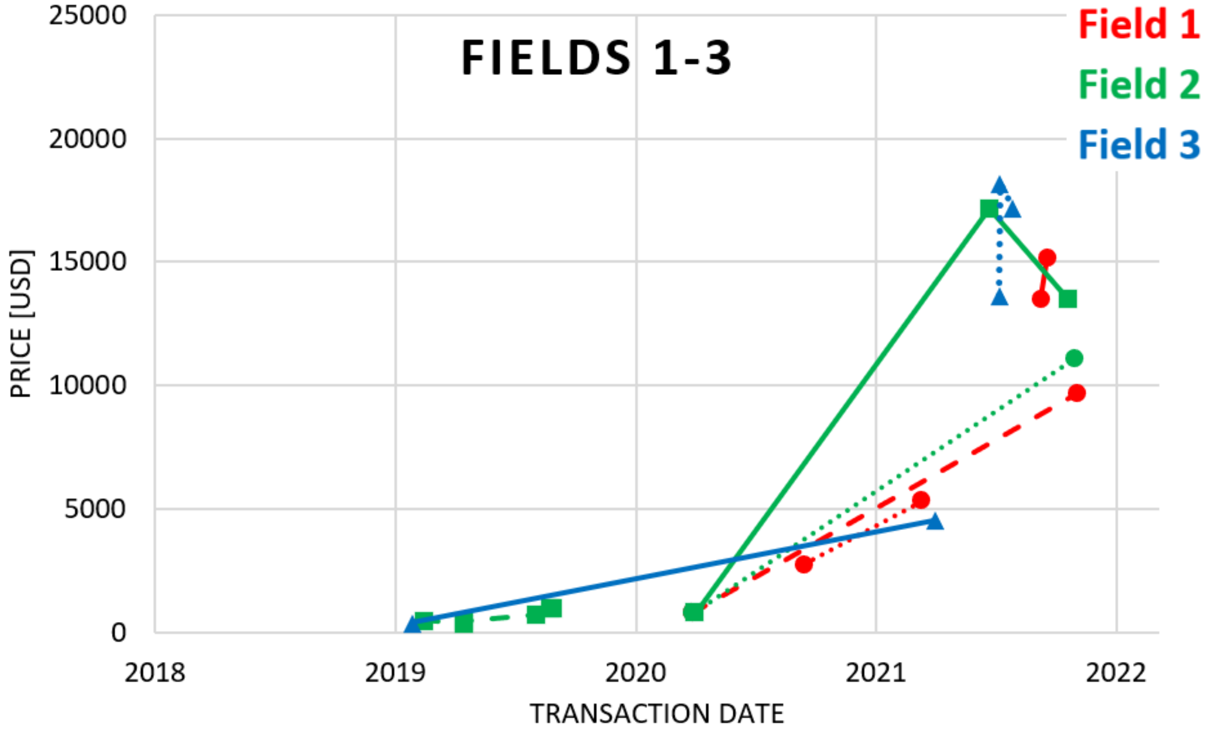
Field 11

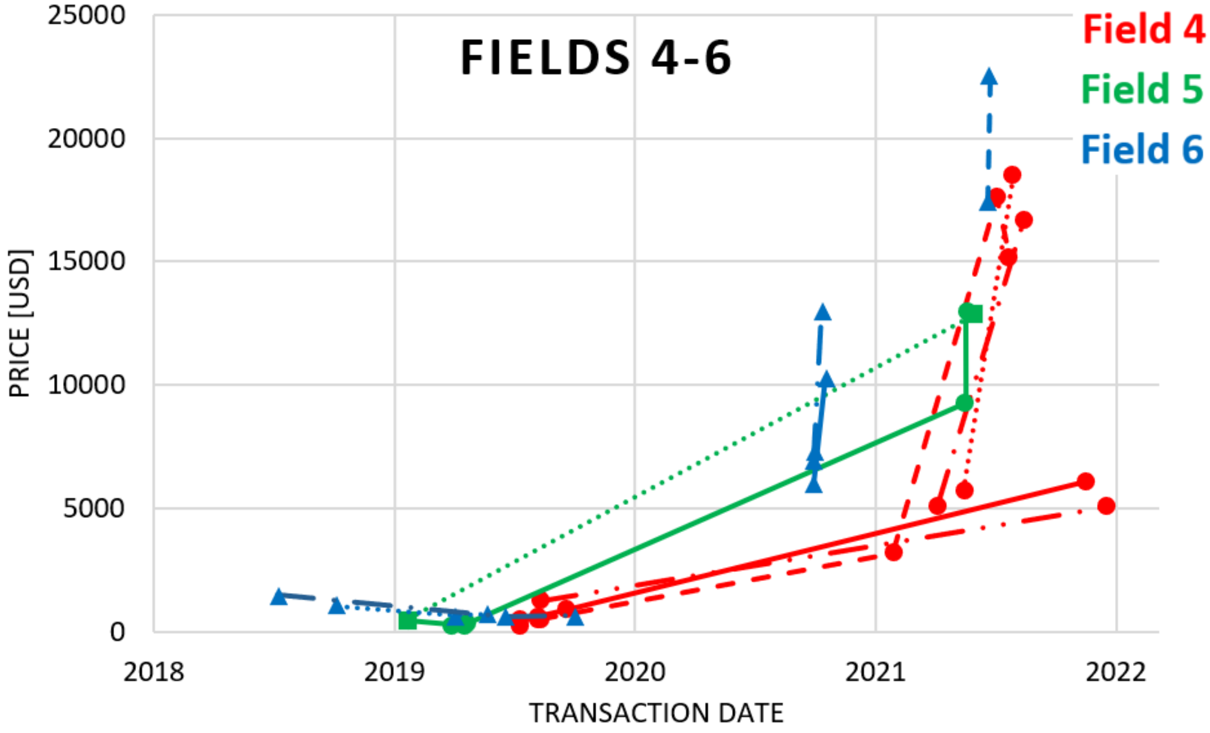
			7014
			14214
			4228

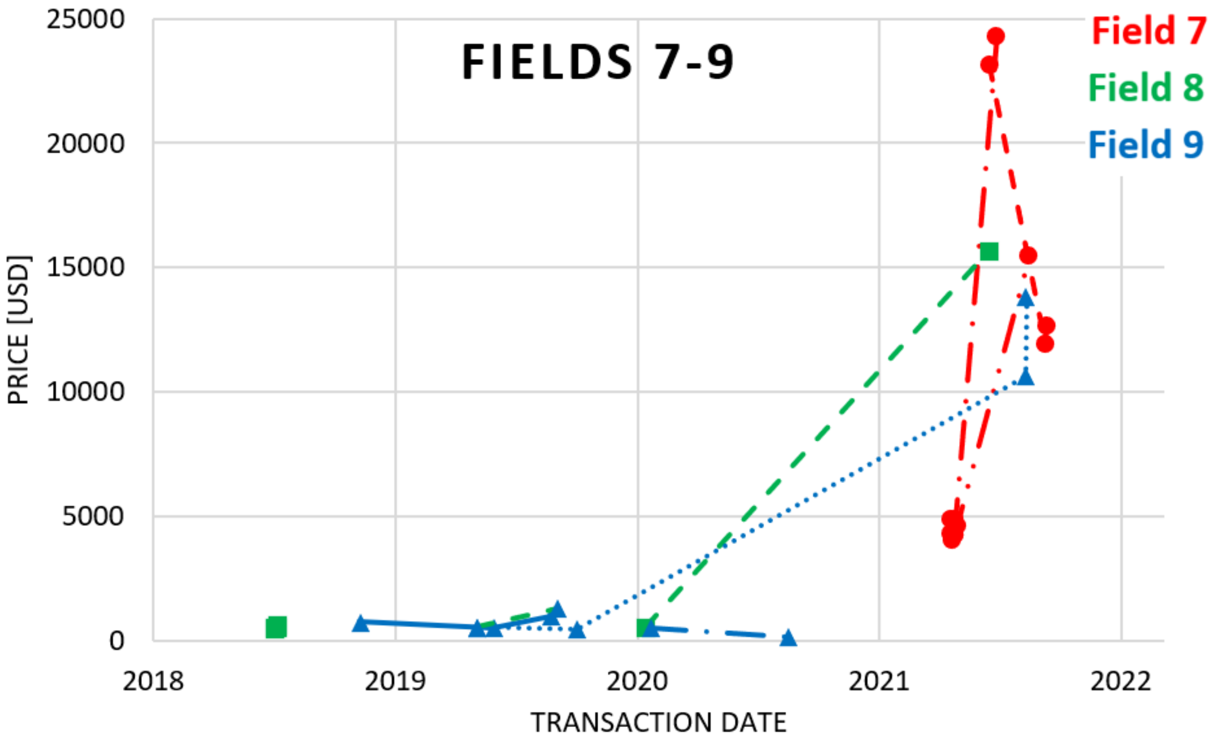
Field 12

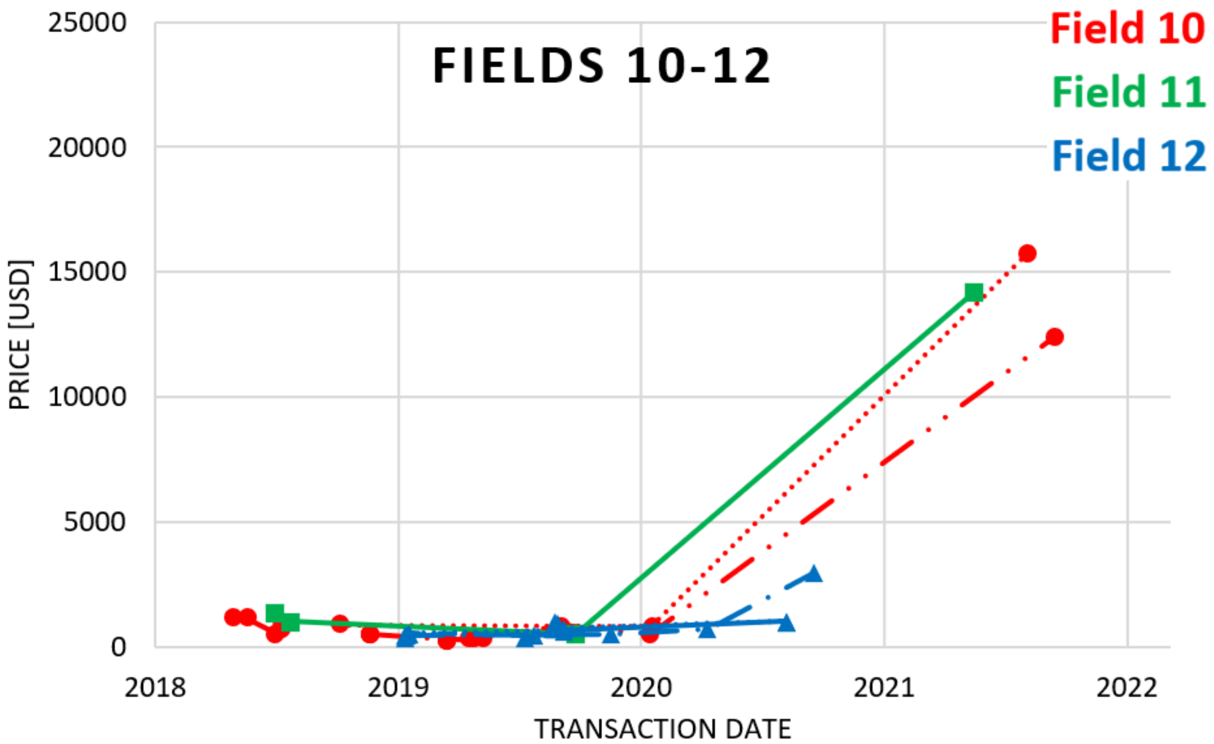
569		1014	1014
11422			12190
12190			2970

Attachment VI. Transactions price changes of the same parcels since Decentraland establishment, graphs below shows parcels sold more than once and its prices changes in time






FIELDS 7-9
Field 7
Field 8
Field 9
PRICE [USD]
25000
20000
15000
10000
5000
0
2018
2019
2020
2021
2022
TRANSACTION DATE


FIELDS 10-12
Field 10
Field 11
Field 12
PRICE [USD]
25000
20000
15000
10000
5000
0
2018
2019
2020
2021
2022
TRANSACTION DATE

ATTACHMENT VII. TRANSACTIONS IN ANALYSED FIELDS (MARKETPLACE, 2022) (ACCESS DATE: 15 SEP 2022)

Field no	Coordinates	Item	Road	District	Plaza	Transaction date	Price [MANA]	MANA/ USD	Price [USD]	Current offer price[2] [MANA/USD]
1	(-72, -18)		5	6	7					
	(-71, -18)		5	6	7	21.11.2021	5,233	0.93	4,867	
	(-70, -18)		5	6	7					
	(-69, -18)	+	5	6	7	22.02.2022	5,250	2.58	13,545	
						4.03.2022	5,800	2.62	15,196	
	(-72, -19)		6	7	8	12.02.2022	5,245	2.91	15,263	
	(-71, -19)		6	7	8					
	(-70, -19)		6	7	8					
	(-69, -19)		6	7	8	23.02.2022	5,150	2.78	14,317	
	(-72, -20)		7	8	9					
	(-71, -20)		7	8	9					
	(-70, -20)	+	7	8	9	23.01.2022	5,420	2.12	11,490	
	(-69, -20)	+	7	8	9	27.03.2022	4,200	2.64	11,088	8,000 MANA/5,840 USD
	(-72, -21)	+	8	9	10+	1.03.2021	11,000	0.25	2,750	
						26.08.2021	5,788	0.92	5,325	
	(-71, -21)		8	9	10+	10.09.2020	9,735	0.08	779	
	(-70, -21)		8	9	10+	10.09.2020	10,000	0.08	800	9,999 MANA/7,299 USD
						20.04.2022	4,420	2.19	9,680	
	(-69, -21)		8	9	10+					
2	(70, -17)	+	5	0	7	16.09.2020	10,000	0.08	800	
						6.12.2021	5,199	3.30	17,157	
						5.04.2022	5,100	2.65	13,515	
	(71, -17)	+	5	0	7	20.09.2020	10,000	0.08	800	
	(72, -17)		5	0	7	12.09.2020	10,000	0.08	800	13,950 MANA/10,184 USD
						16.04.2022	5,169	2.15	11,113	
	(73, -17)		5	0	7					
	(70, -18)		6	1	8					
	(71, -18)		6	1	8					
	(72, -18)		6	1	8	31.07.2019	12,300	0.04	492	
						1.10.2019	12,500	0.03	375	
						1.10.2019	16,000	0.03	480	
						18.01.2020	18,000	0.04	720	
						9.02.2020	15,000	0.07	1,050	
						11.02.2020	17,400	0.06	1,044	
	(73, -18)		6	1	8					
	(70, -19)		7	2	9					
	(71, -19)		7	2	9					
	(72, -19)		7	2	9	6.02.2022	5,500	3.11	17,105	
	(73, -19)		7	2	9					
	(70, -20)		8	3	10+	19.06.2020	19,999	0.04	800	
	(71, -20)		8	3	10+					
	(72, -20)		8	3	10+					
	(73, -20)		8	3	10+					
3	(141, -27)	+	8	10+	10+					
	(142, -27)	+	7	10+	10+	15.07.2019	9,725	0.04	389	
						14.09.2021	5,469	0.83	4,539	
	(143, -27)		6	10+	10+	28.11.2021	3,088	4.73	14,606	
	(144, -27)		5	10+	10+	28.11.2021	3,088	4.73	14,606	
	(141, -28)	+	8	10+	10+					
	(142, -28)		7	10+	10+	3.12.2021	3,587	4.32	15,496	
	(143, -28)		6	10+	10+	18.12.2021	4,200	3.45	14,490	20,000 MANA/14,600 USD
	(144, -28)		5	10+	10+	21.12.2021	4,200	3.25	13,650	

[2] Exchange rate 1 MANA = 0.73 USD at 15 Sep 2022

						23.12.2021	5,600	3.25	18,200	
						11.01.2022	6,200	2.77	17,174	
	(141, -29)	+	8	9	10+					
	(142, -29)	+	7	9	10+	2.12.2021	3,587	4.35	15,603	
	(143, -29)		6	9	10+	14.12.2021	4,200	3.19	13,398	
	(144, -29)		5	9	10+	10.02.2021	9,999	3.42	34,197	
	(141, -30)	+	7	8	10+					
	(142, -30)		7	8	10+	2.12.2021	3,587	4.35	15,603	
	(143, -30)		6	8	10+	9.12.2021	4,366	3.8	16,591	
	(144, -30)		5	8	10+	10.02.2021	9,999	3.42	34,197	
4	(-78, 38)	+	10+	0	10+					
	(-77, 38)		10+	1	10+					
	(-76, 38)		10+	2	10+	3.11.2018	23,999	0.08	1,920	
	(-75, 38)	+	10+	2	10+					
	(-78, 37)		10+	1	10+	25.12.2019	9,000	0.03	270	
						27.12.2019	13,440	0.04	538	
						21.01.2020	14,500	0.04	580	
						21.01.2020	16,000	0.04	640	
						4.03.2020	22,000	0.04	880	
						4.05.2022	4,000	1.53	6,120	
	(-77, 37)		10+	1	10+					
	(-76, 37)		10+	2	10+	29.10.2021	5,000	1.14	5,700	
						12.01.2022	6,250	2.96	18,500	
	(-75, 37)		10+	3	10+					
	(-78, 36)		10+	2	10+					
	(-77, 36)		10+	2	10+					
	(-76, 36)	+	10+	2	10+	2.11.2021	4,450	3.27	14,552	20,000 MANA/14,600 USD
	(-75, 36)		10+	2	10+	27.01.2020	18,000	0.03	540	
						14.07.2021	5,225	0.61	3,187	
						19.12.2021	5,200	3.38	17,576	
						6.01.2022	5,287	2.87	15,174	
	(-78, 35)		10+	1	10+					
	(-77, 35)		10+	1	10+	19.09.2021	6,249	0.82	5,124	
						28.01.2022	7,444	2.24	16,675	
	(-76, 35)	+	10+	1	10+					
	(-75, 35)	+	10+	1	10+	27.01.2020	21,000	0.06	1,260	
						4.06.2022	5,150	0.98	5,047	
5	(-24, 146)	+	6	8	10+	3.11.2021	3,750	2.86	10,725	
	(-23, 146)	+	6	8	10+	3.11.2021	3,420	2.86	9,781	
	(-22, 146)		6	8	10+					
	(-21, 146)		6	8	10+	8.11.2021	3,750	2.71	10,163	
	(-24, 145)		5	7	10+					
	(-23, 145)		5	7	10+					
	(-22, 145)		5	7	10+					
	(-21, 145)		5	7	10+	8.11.2021	3,750	2.71	10,163	
	(-24, 144)	+	4	6	10+	1.07.2019	9,195	0.05	460	
	(-23, 144)		4	6	10+	8.07.2019	9,490	0.05	475	
						13.09.2019	9,900	0.03	297	
						3.10.2019	8,000	0.03	240	
						8.10.2019	12,700	0.03	381	
						1.11.2021	3,000	3.09	9,270	
						2.11.2021	3,975	3.27	12,998	
	(-22, 144)		4	6	10+	18.01.2021	9,999	0.11	1,100	
	(-21, 144)		4	6	10+					
	(-24, 143)		3	5	10+					
	(-23, 143)	+	3	5	10+	9.07.2019	9,850	0.05	493	
						13.11.2021	3,500	3.67	12,845	

	(-22, 143)		3	5	10+	24.12.2018	9,985	0.06	599	
	(-21, 143)		3	5	10+					
6	(4, 23)	+	2	10+	10+	15.03.2021	6,000	1.00	6,000	Closed area; 15,000 MANA/10,950 USD
						3.04.2021	9,999	1.03	10,299	
	(5, 23)	+	3	10+	10+	23.03.2019	21,250	0.05	1,063	
						19.09.2019	22,500	0.03	675	
						7.11.2019	24,001	0.03	720	
	(6, 23)		4	10+	10+					
	(7, 23)	+	5	10+	10+	3.02.2020	24,900	0.04	996	100,000 MANA/73,000 USD
						24.02.2020	24,900	0.05	1,245	
	(8, 23)		6	10+	10+					
	(4, 22)		2	10+	10+					
	(5, 22)	+	3	10+	10+					
	(6, 22)		4	10+	10+	4.12.2021	5,250	3.31	17,378	
						9.12.2021	5,926	3.80	22,519	
	(7, 22)		5	10+	10+					
	(4, 21)	+	2	10+	10+					
	(5, 21)	+	3	10+	10+	22.03.2021	8,000	0.97	7,760	
						12.05.2021	5,999	1.42	8,519	
	(6, 21)		4	10+	10+					
	(7, 21)		5	10+	10+	24.12.2018	25,000	0.06	1,500	
						4.12.2019	30,000	0.02	600	
						19.03.2020	34,000	0.02	680	
	(4, 20)		2	10+	10+					
	(5, 20)		3	10+	10+					
	(6, 20)	+	4	10+	10+	14.03.2021	6,688	1.04	6,956	
						17.03.2021	8,900	0.82	7,298	
						27.03.2021	14,420	0.90	12,978	
7	(-34, -7)		5	10+	10+	4.10.2021	5,450	0.79	4,306	
						4.10.2021	6,199	0.79	4,897	
	(-33, -7)		5	10+	10+	9.10.2021	5,200	0.81	4,212	
						9.10.2021	5,999	0.81	4,859	
	(-32, -7)	+	5	10+	10+	9.10.2021	5,200	0.81	4,212	
						26.04.2022	7,420	1.94	14,395	
	(-31, -7)	+	5	10+	10+	21.02.2021	9,999	0.31	3,100	
	(-34, -8)		6	10+	10+	9.10.2021	5,250	0.81	4,253	
	(-33, -8)		6	10+	10+	9.10.2021	5,200	0.81	4,212	
						5.11.2021	6,789	2.55	17,312	
	(-32, -8)		6	10+	10+	9.10.2021	5,200	0.81	4,212	
						12.12.2021	6,891	3.53	24,325	
	(-31, -8)	+	6	10+	10+	4.09.2021	5,190	1.04	5,398	
						16.05.2022	4,299	1.18	5,073	
	(-34, -9)		7	10+	10+	6.10.2021	5,450	0.74	4,033	
						13.10.2021	6,199	0.74	4,587	
						30.01.2022	6,100	2.53	15,433	
	(-33, -9)	+	7	10+	10+	25.11.2021	4,888	5.32	26,004	
	(-32, -9)		7	10+	10+	9.03.2022	3,678	2.52	9,269	
						9.03.2022	5,188	2.52	13,074	
	(-31, -9)	+	7	10+	10+	20.11.2018	26,000	0.06	1,560	
						4.09.2021	5,185	1.04	5,392	
	(-34, -10)	+	8	10+	10+	1.12.2021	5,140	4.51	23,181	
						23.02.2022	4,300	2.78	11,954	
						25.02.2022	4,899	2.59	12,688	
	(-33, -10)	+	8	10+	10+	17.11.2021	4,888	3.25	15,886	
	(-32, -10)	+	8	10+	10+	24.10.2021	6,288	0.79	4,968	
	(-31, -10)		8	10+	10+		,			
8	(-138, -136)		10+	10+	10+	11.03.2019	14,850	0.05	743	
	(-137, -136)	+	10+	10+	10+					

	(-136, -136)		10+	10+	10+					
	(-135, -136)		10+	10+	10+					
	(-138, -137)		10+	10+	10+					
	(-137, -137)		10+	10+	10+					7,800 MANA/5,694 USD
	(-136, -137)		10+	10+	10+	21.12.2018	10,800	0.05	540	
						21.12.2018	12,490	0.05	625	
	(-135, -137)		10+	10+	10+					
	(-138, -138)		10+	10+	10+					
	(-137, -138)		10+	10+	10+	20.12.2018	9,500	0.05	475	
	(-136, -138)		10+	10+	10+	20.12.2018	9,500	0.05	475	
						20.12.2018	10,489	0.05	524	
	(-135, -138)		10+	10+	10+					
	(-138, -139)		10+	10+	10+	16.12.2018	9,988	0.05	499	
	(-137, -139)		10+	10+	10+	1.07.2020	14,567	0.04	583	
						30.11.2021	3,335	4.70	15,675	
	(-136, -139)		10+	10+	10+					
	(-135, -139)		10+	10+	10+					
9	(-36. -110)	+	0	10+	10+	10.03.2019	21,111	0.05	1,056	
	(-35, -110)	+	0	10+	10+	26.04.2019	15,339	0.05	767	
						13.11.2019	17,200	0.03	516	
						8.02.2020	20,000	0.05	1,000	
	(-34, -110)	+	0	10+	10+	20.10.2019	18,900	0.03	567	
						19.03.2020	22,000	0.02	440	
						24.01.2022	5,750	1.85	10,638	
						26.01.2022	6,095	2.27	13,836	
	(-33, -110)		0	10+	10+	20.10.2019	18,900	0.03	567	
						18.02.2020	22,000	0.06	1,320	
	(-36, -111)		1	10+	10+	7.03.2021	8,990	0.38	3,416	
	(-35, -111)		1	10+	10+	1.12.2021	3,699	4.51	16,682	
	(-34, -111)	+	1	10+	10+	01,12.2021	3,799	4.51	17,133	
	(-33, -111)	+	1	10+	10+	4.07.2021	4,900	0.58	2,842	
	(-36, -112)	+	2	10+	10+	10.11.2018	7,990	0.09	719	
	(-35, -112)	+	2	10+	10+	18.03.2020	13,499	0.02	270	
						4.07.2020	13,500	0.04	540	
	(-34, -112)	+	2	10+	10+					
	(-33, -112)	+	2	10+	10+	6.07.2020	13,500	0.04	540	
						2.02.2021	8,500	0.02	170	
	(-36, -113)		3	10+	10+					
	(-35, -113)		3	10+	10+					
	(-34, -113)		3	10+	10+					
	(-33, -113)		3	10+	10+					
10	(55, -119)	+	1	10+	10+	9.07.2021	4,000	0.62	2,480	
	(56, -119)		1	10+	10+					
	(57, -119)		1	10+	10+	14.10.2018	16,485	0.07	1,154	
						3.11.2018	14,500	0.08	1,160	
						16.12.2018	10,985	0.05	549	
						24.12.2018	12,000	0.06	720	
						24.12.2018	12,900	0.06	774	
	(58, -119)	+	1	10+	10+	21.03.2019	17,500	0.05	875	
						3.07.2020	21,000	0.04	840	
						18.01.2022	5,555	2.84	15,776	
	(55, -120)	+	2	10+	10+	6.05.2019	10,000	0.05	500	
						8.05.2019	10,850	0.05	543	
	(56, -120)	+	2	10+	10+	15.05.2019	8,250	0.05	413	30,000 MANA/21,900 USD
						16.05.2019	9,500	0.06	570	
	(57, -120)		2	10+	10+	18.03.2021	5,200	1.07	5,564	
						1.04.2021	6,911	1.04	7,187	
	(58, -120)	+	2	10+	10+	22.08.2019	10,000	0.03	300	

						29.08.2019	9,100	0.03	273	
						6.10.2020	8,500	0.07	595	
	(55, -121)	+	3	10+	10+	13.08.2019	9,500	0.04	380	
						5.09.2019	9,890	0.03	297	
	(56, -121)	+	3	10+	10+	21.06.2019	9,999	0.06	600	15,000 MANA/10,950 USD
	(57, -121)	+	3	10+	10+					
	(58, -121)		3	10+	10+					
	(55, -122)	+	4	10+	10+	8.05.2019	9,999	0.05	500	
						29.08.2019	9,699	0.03	291	
						8.10.2019	10,900	0.03	327	
						24.10.2019	11,000	0.03	330	
	(56, -122)	+	4	10+	10+	29.08.2019	9,699	0.03	291	
						4.10.2019	10,900	0.03	327	
						12.10.2019	12,950	0.03	389	
						16.02.2020	13,900	0.06	834	
						21.02.2020	14,250	0.06	855	
						30.06.2020	12,480	0.04	499	
						28.02.2022	4,820	2.58	12,436	
	(57, -122)		4	10+	10+					
	(58, -122)	+	4	10+	10+					
11	(-148, 22)		1	3	10+					
	(-147, 22)	+	1	3	10+					
	(-146, 22)		1	3	10+					
	(-145, 22)	+	1	3	10+	16.03.2021	6,945	1.01	7,014	
	(-148, 21)		2	2	10+					
	(-147, 21)		2	2	10+					
	(-146, 21)		2	2	10+					
	(-145, 21)		2	2	10+					
	(-148, 20)		3	1	10+					
	(-147, 20)		3	1	10+					
	(-146, 20)		3	1	10+					
	(-145, 20)	+	3	1	10+	14.12.2018	27,500	0.05	1,375	
						8.01.2019	20,999	0.05	1,050	
						12.03.2020	17,990	0.03	540	
						1.11.2021	4,600	3.09	14,214	
	(-148, 19)		4	0	10+					
	(-147, 19)		4	0	10+					
	(-146, 19)		4	0	10+					
	(-145, 19)		4	0	10+	18.06.2022	5,351.89	0.79	4,228	
12	(134, -145)	+	4	7	10+	5.07.2019	9,488	0.06	569	
	(135, -145)	+	4	7	10+					
	(136, -145)	+	4	7	10+	25.12.2019	11,888	0.03	357	
						22.02.2020	13,500	0.05	675	
						20.01.2021	7,800	0.13	1,014	
	(137, -145)	+	4	7	10+	27.06.2019	8,000	0.05	400	
						5.07.2019	8,999	0.06	540	
						7.02.2020	13,777	0.05	689	
						9.02.2020	14,111	0.07	988	
						23.02.2020	15,000	0.05	750	
						20.01.2021	7,800	0.13	1,014	
	(134, -146)	+	3	8	10+	3.04.2022	4,246	2.69	11,422	
	(135, -146)	+	3	8	10+					
	(136, -146)	+	3	8	10+					
	(137, -146)		3	8	10+	27.06.2019	8,300	0.05	415	
						5.07.2019	9,700	0.06	582	
						7.01.2020	11,500	0.04	460	
						10.02.2020	11,500	0.06	690	

						10.02.2020	12,000	0.06	720	
						10.02.2020	12,890	0.06	773	
						11.02.2020	14,999	0.06	900	
	(134, -147)		2	9	10+	9.11.2021	4,600	2.65	12,190	
	(135, -147)		2	9	10+					
	(136, -147)	+	2	9	10+					
	(137, -147)	+	2	9	10+	1.07.2019	8,999	0.05	450	
						3.05.2020	13,333	0.04	533	
						27.09.2020	8,887	0.08	711	
						3.03.2021	9,900	0.30	2,970	
	(134, -148)	+	1	10+	10+					
	(135, -148)		1	10+	10+					
	(136, -148)		1	10+	10+					
	(137, -148)	+	1	10+	10+					

Journal of Metaverse
Research Article
Received: 2024-12-27 | **Reviewing:** 2024-12-29 & 2025-03-02 | **Accepted:** 2025-03-08 | **Online:** 2025-03-09 | **Issue Date:** 2025-06-30
Year:2025, **Volume:**5, **Issue:**1, **Pages:**25-37, **Doi:** 10.57019/jmv.1608255

Economic Transformation from Physical to Digital: A Bibliometric Analysis of the Metaverse Economy

Zihni TUNÇSİPER
Department of Economics
Graduate School of Social Sciences
Dokuz Eylul University
İzmir, Türkiye
zihni.tuncsiper@celsusanalysis.com
0009-0000-9291-3410

Selim ŞANLISOY
Department of Economics
Faculty of Economics and Administrative Sciences
Dokuz Eylul University
İzmir, Türkiye
selim.sanlisoy@deu.edu.tr
0000-0002-0629-0905

Üzeyir AYDIN
Department of Economics
Faculty of Economics and Administrative Sciences
Dokuz Eylul University
İzmir, Türkiye
uzeyir.aydin@deu.edu.tr
0000-0003-2777-6450
(Corresponding Author)

Abstract— **The metaverse is a virtual ecosystem formed by the combination of innovative technologies such as augmented reality (AR), virtual reality (VR) and blockchain, which are reshaping global trade, consumption patterns and cross-sector collaboration. This ecosystem offers a new economic structure that combines the physical and digital worlds with elements such as the appreciation of digital assets, the proliferation of NFTs and the integration of decentralised finance (DeFi) applications. This new economic structure is the subject of interest and research both in the business world and in the academic world. In this study, the data obtained from the Scopus database covering the period between 2018-2024 were analysed by bibliometric analysis method. The institutions, countries, cited studies and keyword links that produced the most works were evaluated in detail. The key findings of this study indicate that research on the metaverse economy has experienced exponential growth, with significant contributions from the United Kingdom, China, and the United States. Additionally, performance analysis reveals that blockchain, metaverse, NFT, and digital transformation are the most frequently explored topics in the academic literature.**

Keywords*— *Metaverse economy, metanomics, digital transformation, blockchain, NFT, virtual reality

I. INTRODUCTION

As one of the last major technological changes of today's world, the metaverse has the potential to create significant changes in many areas of society, especially in the economy. In the historical process, the term "metaverse" was first used to describe the fictional universe in a science fiction novel titled "Snow Crash" by Neil Stephenson in 1992 [1]. The metaverse economy is rapidly developing as a field where physical and digital worlds come together to create a new economic structure and redefine technology and human experience [2, 3]. Technologies such as digital currencies, NFTs, blockchain, augmented reality (AR) and virtual reality (VR) play a critical role in this new economic order and offer innovative opportunities for businesses and consumers [4, 5]. The metaverse transcends the boundaries of the physical world and transforms into a global business, education and socialisation platform. In this context, this ecosystem, which reshapes consumer behaviour and offers businesses opportunities to develop different business models, challenges the traditional economic system [6].

The metaverse economy is not only a product of technological innovation, but also an environment in which economic systems are being restructured. It leads to comprehensive changes at both the microeconomic and macroeconomic levels in sectors such as health, education, retail and international trade [7, 8]. For example, applications such as virtual hospitals or educational platforms offer a wider reach by overcoming geographical barriers, while digital retailing and avatar-based commerce are radically changing the consumer experience [9, 10]. In short, the integration of the digital and physical worlds is about to place the metaverse economy at the centre of the global economic system.

In this study, bibliometric analysis method was used to examine the literature in the field of metaverse and blockchain economics. Despite the increasing number of studies on the metaverse economy, there is a lack of research explicitly addressing how the transition from the physical to the digital economy impacts global economic structures, business models, and value creation processes. This study aims to fill this gap by formulating the following research question: “How does the transformation created by the metaverse economy in the global economic system, business models, value creation processes and scientific collaborations between countries?” This study aims to analyse the historical development of research on the Metaverse Economy and to identify prominent researchers and institutions in this field.

Data were obtained from the Scopus database using key terms such as "metaverse", "metaverse economy", "blockchain economy" and "blockchain economics". Only articles, reviews and conference proceedings published in English were included. The dataset was visualised with VOSviewer v1.6.20 software to analyse important themes of the field, collaboration networks between authors and the most influential studies. Within the scope of the study, the distribution of publications by years, institutions and countries producing the most works, keyword networks, citation analyses and linkage maps between countries were examined to reveal the general trends of academic production in the field of metaverse economy and blockchain.

Cite (APA): Tuncsiper, Z., Sanlisoy, S., Aydin, U. (2025). Economic Transformation from Physical to Digital: A Bibliometric Analysis of the Metaverse Economy. *Journal of Metaverse*. *5*(1), 25-37. **Doi:** 10.57019/jmv.1608255

II. Metaverse Economy

The Metaverse is a next-generation internet universe supported by technologies such as blockchain and artificial intelligence, which enables users to have interactive and immersive experiences in a three-dimensional digital environment by combining physical and virtual realities [11]. This universe creates brand new opportunities in almost every sector with its qualities that make it possible to go beyond the traditional economic patterns in the physical world. Therefore, besides providing economic transformation, the metaverse creates sector-specific opportunities and challenges, and leads to macroeconomic and financial impacts.

JP. Morgan (2022) expressed the economic structure of the Metaverse as metanomics by quoting Bloomfield [12] in his report titled “Opportunities in the Metaverse” in which he revealed the growth opportunities related to the Metaverse for businesses. Metanomics refers to an economic structure in which the virtual needs of people and virtual assets are met in virtual universes, production, distribution and finance processes are designed for this purpose, and which interacts with the real universe [1].

A. Metaverse and Economic Transformation

The metaverse economy refers to a transformation in which economic activities are redefined in a virtual environment created by blending digital and physical realities. This economy is shaped by the use of digital currencies and the integration of innovative technologies such as blockchain technology and augmented reality [2]. The appreciation of digital assets and the transformation of consumption models are among the main characteristics of this new economy [3].

According to Ball [13], the Metaverse consists of 8 components: Hardware, Networking, Computing, Virtual Platforms, Exchange Tools and Standards, Payments, Metaverse Content, Services and Assets, and User Behaviour. However, Tapscott [14], while mentioning the importance of these technologies, states that the basic building block of the Metaverse is blockchain, especially because it brings the phenomenon of decentralisation. Digital currencies and blockchain technology are among the elements that form the basis of the metaverse economy. Blockchain increases security, privacy and transaction speed by enabling a decentralised structure [15]. It also provides a transparent framework for protecting property rights and increasing the security of economic systems. This technology allows the ownership and transfer of digital assets to be tracked transparently, while at the same time reducing the dependence of transactions on intermediary institutions [4]. Decentralised applications and smart contracts contribute to a wider acceptance of these technologies within the metaverse [5]. In particular, luxury brands within the metaverse are integrating elements such as unique ownership and digital scarcity using NFT technology. It can be said that NFTs enable consumers to have new experiences in the digital space by ensuring the uniqueness and rarity of digital luxury, and in this context, they contribute to the virtual transformation of luxury brands [16]. For example, Gucci's offering its digital products for sale through the metaverse is a typical example of the commercial application of such innovations [5].

Technologies such as Extended Reality (XR), Augmented Reality (AR) and Mixed Reality (MR) play a critical role in transforming the consumer experience of the metaverse economy. These technologies enable users to interact more deeply and interactively with the metaverse [17]. At the same time, these platforms offer businesses opportunities to interact directly with their customers and develop innovative business models. For example, virtual business meetings, training platforms and shopping experiences have become more accessible thanks to these technologies [3].

The effects of the metaverse economy on the global economic structure are quite extensive. The integration between digital and physical assets leads to changes at both microeconomic and macroeconomic levels [2]. This change brings new business models and value creation mechanisms to the agenda with the integration of the physical and digital worlds. Mancuso et al. [6] state that the metaverse economy develops innovative "physital" business models by combining physical and virtual elements, and that the transition from the physical world to virtual reality means a radical change in business models and value creation processes. V-commerce stands out as an important element of this transformation. Damaševičius [18] states that virtual reality technologies reshape consumer behaviour and make shopping processes more personalised and interactive. This new trade model allows users to make more informed choices in their shopping decisions, while enabling companies to interact with consumers more effectively.

The metaverse not only reshapes economic structures within national borders but also plays a crucial role in redefining global economic relations. It accelerates digital trade, decentralises financial transactions, and creates new economic actors beyond traditional state and corporate entities [19]. However, this transformation also deepens existing inequalities in technological access and digital financial literacy between developed and developing countries [20]. The digital divide manifests in disparities in blockchain adoption, virtual real estate investments, and accessibility to metaverse-based financial services, potentially exacerbating global economic stratification [21].

The metaverse opens new horizons for economic activities in different sectors. Koohang et al. [7] stated that metaverse technologies enable innovative applications in various fields such as marketing, healthcare and education and provide a level of interaction beyond physical borders. At the same time, Saridakis et al. [8] emphasise that the metaverse facilitates inter-firm interaction by eliminating geographical barriers in the context of international trade and paves the way for the re-evaluation of traditional trade theories.

The possibilities offered by avatar-based commerce in the transformation of value creation processes have attracted attention. For example, theoretical frameworks such as Avatar Business Value Analysis (ABV Analysis) have been developed for the strategic management of economic activities carried out with digital identities through virtual platforms such as Second Life [22]. This analysis allows to empirically assess the business value of virtual commerce initiatives by measuring the interaction rates of virtual stores. Moreover, the interactions of avatars with virtual stores are considered in line with strategies that increase brand awareness and transform the consumer experience [22]. Of course, personalisation and avatar-based interactions can be said to influence consumer behaviour and differentiate shopping experiences [10]. In this context, the dynamic nature of the metaverse platform reveals the necessity to strategically utilise the innovative opportunities of virtual environments by expanding the boundaries of traditionally defined business models in the physical world.

B. Sectoral Impacts, Opportunities, Challenges

Metaverse, as a digital ecosystem shaped by the combination of augmented reality (AR) and virtual reality (VR) technologies, offers vast opportunities for entrepreneurship and investment. This environment provides opportunities for digital entrepreneurs to develop innovative business models and increase user engagement. For example, creating digital twins, gamification elements and collaborative spaces in the metaverse technology makes virtual environments more attractive [23]. It is emphasised that technology, design and immersive experiences are critical for entrepreneurship in the metaverse. In particular, digital twins highlight the potential for companies to improve customer service and provide sectoral diversification by developing technically complex platforms [23]. Innovations that make user experiences in the Metaverse real-time and interactive provide an important foundation for digital entrepreneurship [24].

Applications in different sectors demonstrate the huge potential of the metaverse platform. For example, in the field of education, immersive learning environments are created with the use of VR and AR, and student engagement and learning outcomes are improved through simulations of historical events or biological processes. Adopting an inclusive approach by overcoming geographical barriers, the metaverse provides access to disadvantaged individuals through distance learning platforms and reshapes individual and collective learning by creating global collaborative communities [25].

In healthcare, the metaverse is increasing access to care for individuals in rural and underserved areas by creating virtual hospitals and clinics [9, 26]. It is also revolutionising medical education with realistic simulations of surgical procedures and clinical scenarios. These simulations allow medical professionals to practice and improve their skills in a risk-free environment [27]. Metaverse also provides patient education and psychosocial support by allowing patients to receive peer support and access health information through virtual communities. These virtual environments provide emotional support and empowerment, reducing isolation and stigmatisation, especially for individuals affected by chronic or rare diseases [28]. These innovative digital platforms make healthcare services more accessible and effective for both individuals and communities.

It is observed that brands in retail and marketing use the metaverse platform to create innovative shopping experiences that increase customer interaction [7]. In this context, it is stated that investment in technological infrastructure, especially the development of AR, VR and mixed reality technologies, is critical to improve the quality of metaverse experiences [29]. In addition, developing platforms that increase the motivation of users, taking into account social connections and psychological needs, strengthens the social benefits of the metaverse platform [24].

Cultural and social dynamics have been transformed as metaverse technology blurs the boundaries between the virtual and the real, creating a new cultural landscape. Leshkevich [30] argues that metaverse technology encourages the emergence of multiple identities and enables the preservation of digital cultural heritage. Florido-Benítez [31], with the concept of "MetaTourPolis", revealed that the metaverse platform offers innovative applications focused on sustainability and accessibility in tourism cities, especially improving the quality of life of disabled people.

The metaverse economy also offers significant advantages in terms of environmental sustainability. Studies by Zhao and You [32] have shown that metaverse technology can significantly reduce greenhouse gas emissions by reducing the need for physical travel. For example, it was suggested that it is possible to reduce 10 gigatonnes of CO_2e in the United States by 2050. In addition, Go and Kang [33] stated that metaverse tourism expands tourism resources and supports sustainable development in line with the United Nations Sustainable Development Goals.

There are also various challenges related to the adoption of Metaverse technology. Inadequate technological infrastructure and high investment costs pose a significant barrier for small-scale retailers [7, 29]. At the same time, concerns about data privacy and security are critical to ensuring consumer trust [34, 7]. In addition, the psychological effects of virtual shopping experiences and possible negative consequences for social interactions are also among the factors to be considered [24]. In particular, problems such as the effect of the customisable structure of avatars on body perception and the difficulty of users to establish a balance between the real world and the virtual environment come to the fore [24, 34].

C. Macroeconomic and Financial Impacts

The rise of the metaverse economy represents a transition from the physical economy to a new economic structure that integrates virtual and real world elements. This transformation has led to the obsolescence of traditional economic patterns and has reshaped economic behaviours such as production, consumption and money supply in virtual environments. Castronova et al.'s [35] study on a large-scale virtual world revealed that economic behaviour closely follows physical world patterns.

Metaverse has important effects in the macroeconomic field. First of all, productivity will increase and growth rates will increase [1].

One of the macroeconomic areas that will be affected by the Metaverse is labour and employment. The Metaverse creates new business areas and professions and creates the need for appropriate labour force. The Metaverse also has an impact on the way work is done. It creates opportunities such as working in virtual environments, working, meeting, and breaks the work from being tied to the place [1].

Metaverse technology will also have effects on unemployment. Although every new technological development until today firstly creates technological and structural unemployment problems, after a while, new occupations and employment areas required by new technologies have brought along the solution of unemployment problems. With the metaverse technology, some professions disappear and some employees become unemployed. However, in today's technological environment where artificial intelligence technology and automation are increasingly intensified, artificial intelligence and intelligent robots are gradually replacing humans. As a result, it seems likely that the employment-enhancing effect of metaverse technology will be very limited and an intense unemployment is likely to emerge [1].

As an emerging digital ecosystem, the metaverse economy has the potential to have profound impacts on income distribution and economic inequality. This potential may increase or decrease existing inequalities depending on the structure, accessibility and governance models of metaverse technology. In particular, the distribution of economic power in the metaverse is shaped by the ownership of virtual assets and digital entrepreneurship opportunities. Turner [19] analysed the political-economic aspects of the metaverse platform from four different perspectives and emphasised the importance of understanding the social impacts of this structure. In this framework, the digital divide, wealth inequalities and differences in technological access stand out as key elements that reinforce the potential of the metaverse economy to exacerbate existing inequalities.

In a world where the digital divide exists, the metaverse can create access problems for individuals and communities with limited access to infrastructure. Zhou et al. [20] highlight how digital literacy and infrastructure limitations can affect global inequalities. In particular, these limitations can increase marginalisation in the metaverse economy and reinforce patterns of wealth accumulation that become evident in virtual world economies. Fuchs and Thurner [21] found that in virtual worlds , early adopters and those with strong social networks have higher wealth accumulation, which resembles the dynamics of wealth inequality in the real world. Such a structure may further deepen economic inequalities by limiting access to economic opportunities within the metaverse.

However, the metaverse economy also offers opportunities to reduce economic inequalities. The integration of blockchain technology can increase financial inclusion by enabling the decentralisation of economic control and transparent transactions [36]. Moreover, decentralised finance (DeFi) applications increase access to financial services and provide new opportunities for individuals who do not have access to the banking system. In the study of Weking et al. [37], it is stated that metaverse-based entrepreneurship enables individuals to generate income from digital content and services and provides economic opportunities for individuals who do not have access to traditional labour markets. Such innovative models can reduce barriers to economic participation and contribute to a more equitable distribution of income.

The social and cultural impacts of metaverse technology also play an important role for economic equality. Lim et al.'s [38] research has shown that avatar customisation and self-presentation practices in the virtual workplace can contribute to the empowerment of marginalised groups in virtual spaces. Black individuals and women exhibit higher motivation to customise their avatars in virtual workplaces. This points to the potential for self-expression in virtual worlds to balance social inequalities by increasing diversity. Indeed, the metaverse economy can become an important tool in achieving both economic and social equality through technological and social innovations.

III. METHODOLOGY

A. Research Objectives and Significance

Metaverse economy is a rapidly developing field of digital transformation. This study was carried out to contribute to the accumulation of knowledge in this new field, to contribute to scientific development in the field, and to identify new research trends in the field. The study is aimed to contribute to academics to develop new research questions by having knowledge about the scientific productivity and themes related to the Metaverse economy; sectoral professionals to understand the effects of digital transformation and blockchain technologies on business models; and policy makers to develop regulatory policies by evaluating the macroeconomic effects of the Metaverse economy. In this context, this research seeks an answer to the question "*How does the transformation created by the Metaverse economy in the global economic system exhibit an orientation in the context of business models, value creation processes and scientific collaborations between countries?*".

B. Bibliometric Analysis Approach

Bibliometric analysis is an effective method for studying and analysing large scientific datasets and for understanding the evolution of scientific knowledge production. This method aims to reveal the evolution of a particular research area from past to present and its future trends. In cases where classical methods of analysis are insufficient due to the growing volume of scientific data, bibliometric analysis provides an overview of the field by evaluating objective criteria such as scientific articles, citations, keywords and authors. This method, which consists of two basic components such as performance analysis and scientific mapping, evaluates the contributions of research components on the one hand and analyses the relationship networks between these components on the other. Techniques such as citation analysis, co-citation analysis, bibliographic linking, keyword and co-authorship analysis are among the methods commonly used in the bibliometric analysis process [39].

C. Data Collection and Analysis Process

In this study, a bibliometric analysis of the literature on metaverse and blockchain economics was carried out. The data were downloaded from the Scopus database. The reason for limiting the research to Scopus is that the filtering options are more advanced, the number of indexed journals in which studies in this field are published is relatively high, the number of studies that can be accessed with the same search parameters as Web of Science is both low and common with Scopus.

In the search process, terms such as "metaverse", "metaverse economy", "blockchain economy", "blockchain economics" were used to identify studies between 2018-2024; only articles, reviews and conference proceedings were included by focusing on the field of economics. A total of 523 publications were analysed in this study. The selection criteria excluded books, book chapters, editorials, and non-peer-reviewed documents. Only articles, reviews, and conference proceedings were included in the analysis. Furthermore, only publications written in English were considered to ensure consistency in bibliometric data collection and analysis. The reason for selecting articles, reviews and conference proceedings published between 2018 and 2024 is that metaverse economics and blockchain technologies started to appear rapidly in the academic literature during this period. These document types provide peer-reviewed and scientifically reliable sources on the subject. In the analysis, works published in English were selected and keywords related to (but not limited to) "Blockchain", "Metaverse", "Cryptocurrency", "Virtual Reality", "Artificial Intelligence" and "NFT" were used. The search parameters can be found in Appendix 1. The data set, excluding the references to the authors' own works, was analysed with VOSviewer v1.6.20. The distribution of the literature by years, the most influential countries, institutions and studies were analysed; the network connections between keywords and studies were visualised.

IV. Findings

A. *Annual Publication Trends (2018–2024)*

Figure 1 shows the annual increase in the number of documents from 2018 to 2024. From only 2 documents in 2018, the number of documents reached 271 in 2024. Among the standout years, it is seen that the number of documents reached 154 in 2023, a big leap compared to previous years. In 2024, this growth accelerated further, reaching 271 documents. It can be stated that the awareness created by the pandemic period in digital transformation is reflected in academic publications and new technologies are being researched more. The rate of increase in publications over the years also reveals how high the momentum has developed.

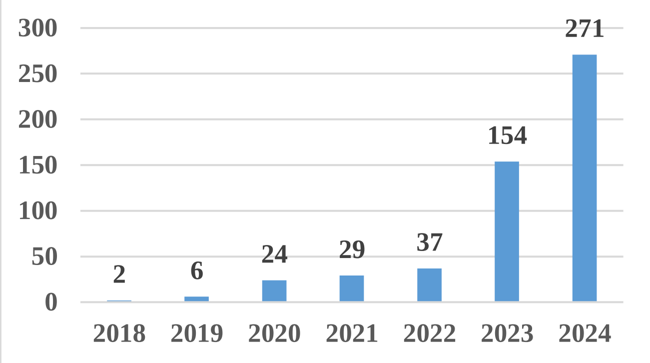


Figure I: Number of Documents by Year

B. *Institutions Producing the Most Works*

Figure 2 shows the institutions that produced the most artefacts. RMIT University ranks first with 11 artefacts, while the University of Oxford ranks second with 9 artefacts. Symbiosis International Deemed University and University College London share third place with 8 artefacts each. The College of Business and Law and Lebanese American University are the other prominent institutions with 7 works each.

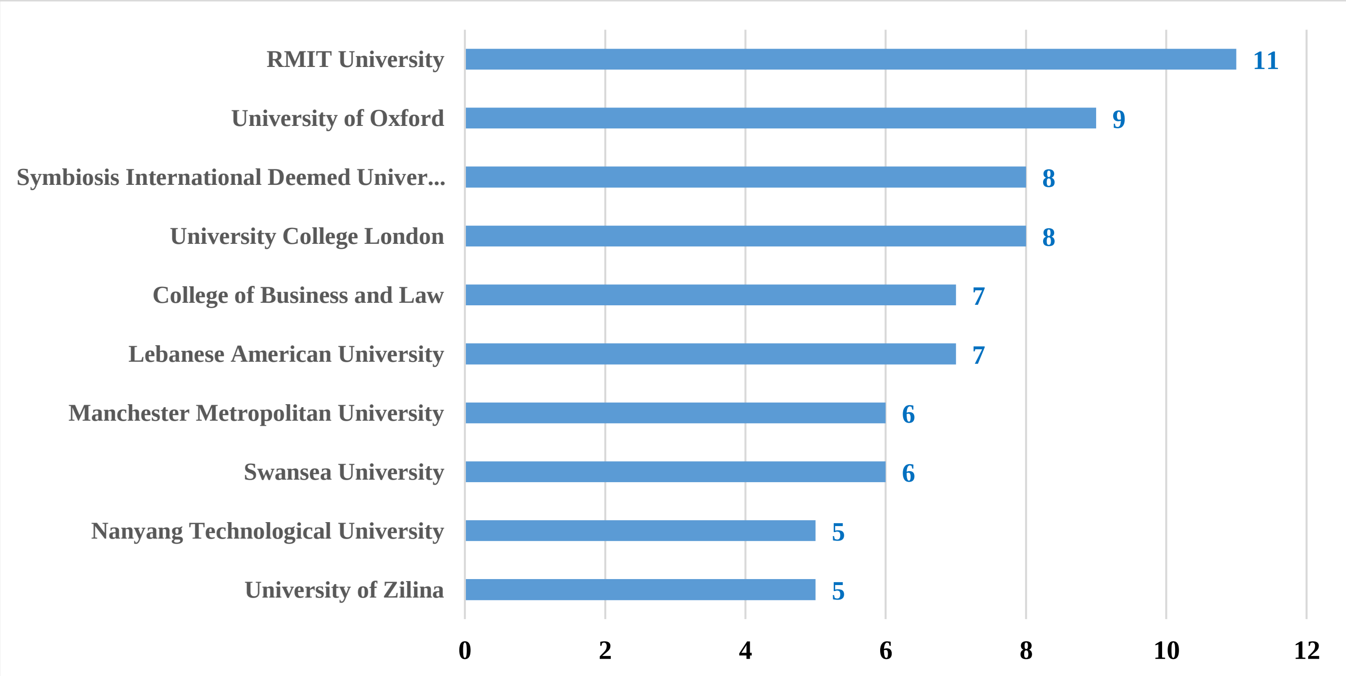


Figure II: Institutions with the Most Studies

TABLE I: COUNTRIES PRODUCING THE MOST ARTEFACTS BY TOTAL CONNECTION POWER*

#	Country	Number of Documents	Citation Count	Total Connection Power
1	United Kingdom	74	1259	114
2	China	80	776	98
3	United States	68	1859	63
4	Australia	41	593	56
5	Malaysia	20	222	40
6	France	23	483	37
7	India	34	344	37
8	Canada	22	300	35
9	Czech Republic	11	181	33
10	Germany	32	584	32

* There are two standard link weight attributes: Links attribute and Total link strength attribute. For a given item, these attributes refer to the number of links the item has with other items and the total strength of those links, respectively. For example, in the case of co-authorship links between researchers, the Links Attribute indicates the number of co-authorships links a researcher has with other researchers. The Total Tie Strength Attribute refers to the total strength of a researcher's co-authorship ties with other researchers [40].

C. *Countries with the Most Studies*

Table 1 shows the countries producing the most artefacts by total link strength. The United Kingdom ranks first with 74 documents, 1259 citations and 114 total linking power. China ranks second with 80 documents and 98 total linking power, while the United States ranks third with 68 documents, 1859 citations and 63 total linking power. Australia (41 documents, 56 linkages) and Malaysia (20 documents, 40 linkages) rank fourth and fifth, respectively. While the table reveals the scientific cooperation and productivity levels of the countries, it shows that the United Kingdom and the United States stand out with their high citation rates.

When Figure 2 and Table 1 are taken into consideration together, it can be said that countries and, of course, economies where the technological environment and human capital are strong in this direction come to the fore. On the other hand, the fact that the UK has three institutions in the top ten in the list of institutions that produce the most artefacts has brought the highest total connection power in Table 1.

Figure 3 shows the linkage map between countries that have contributed to at least 5 studies. The United Kingdom, which leads the studies in the field of metaverse economy, is in the Green Cluster together with European countries such as Spain, Ireland, France, Poland and Ukraine. China, on the other hand, carries out joint studies with countries such as Malaysia, Pakistan, Kuwait, Jordan, United Arab Emirates in the red cluster. The purple cluster includes countries close to each other such as Russia, South Korea, Taiwan and Singapore, while the yellow cluster includes countries in the southern hemisphere such as Australia, South Africa and Thailand. In the blue cluster, there are developed countries such as the USA, Germany and Switzerland.

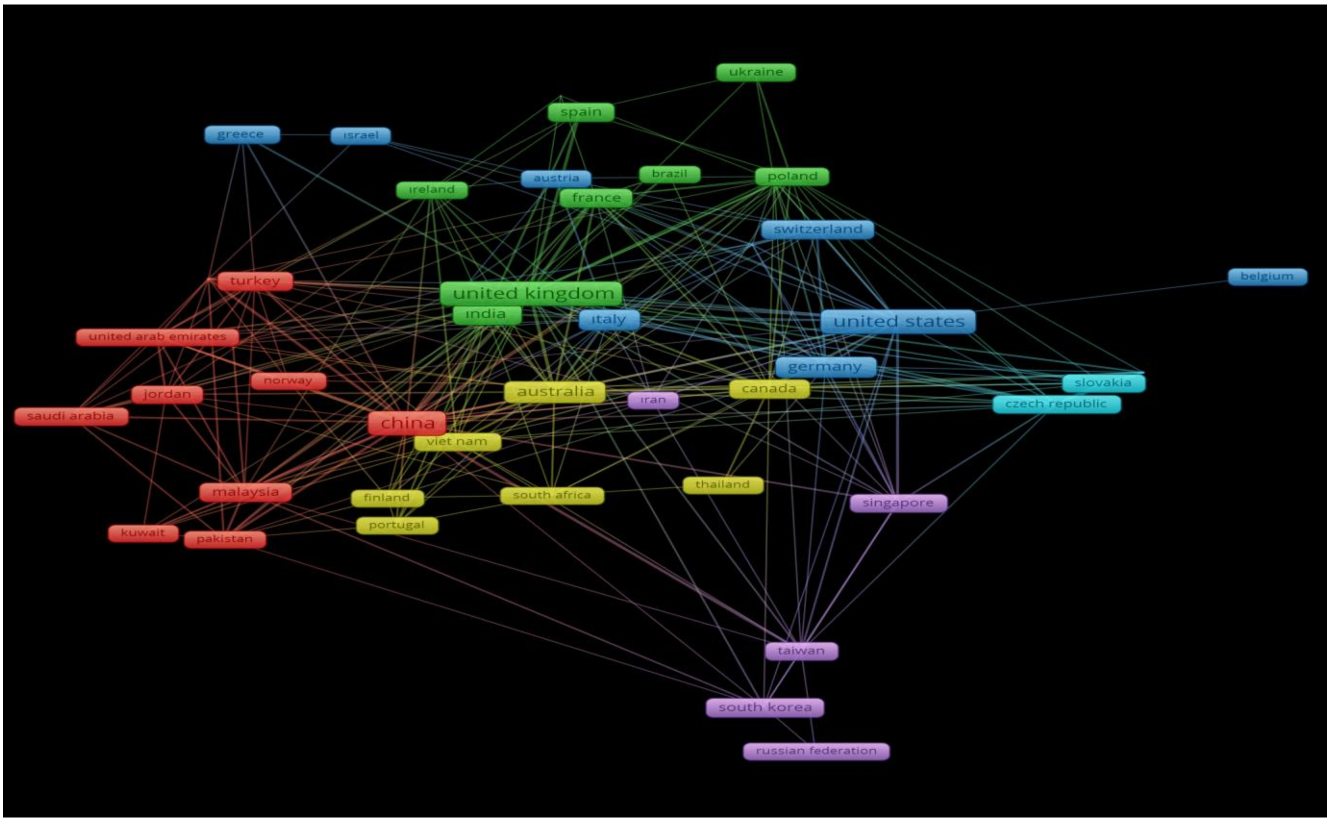


FIGURE III: INTER-COUNTRY CONNECTIVITY MAP*

*: Link map between countries contributing at least 5 articles

Figure 4 shows the linkage map between countries that contributed to at least 5 studies in terms of years. Accordingly, while Australia and Belgium started their studies in this field in 2022, countries such as the UK, Germany and Switzerland started their studies in 2023. The most recent studies were carried out in countries such as Iran, South Korea, France, Spain and Iran, including Türkiye.

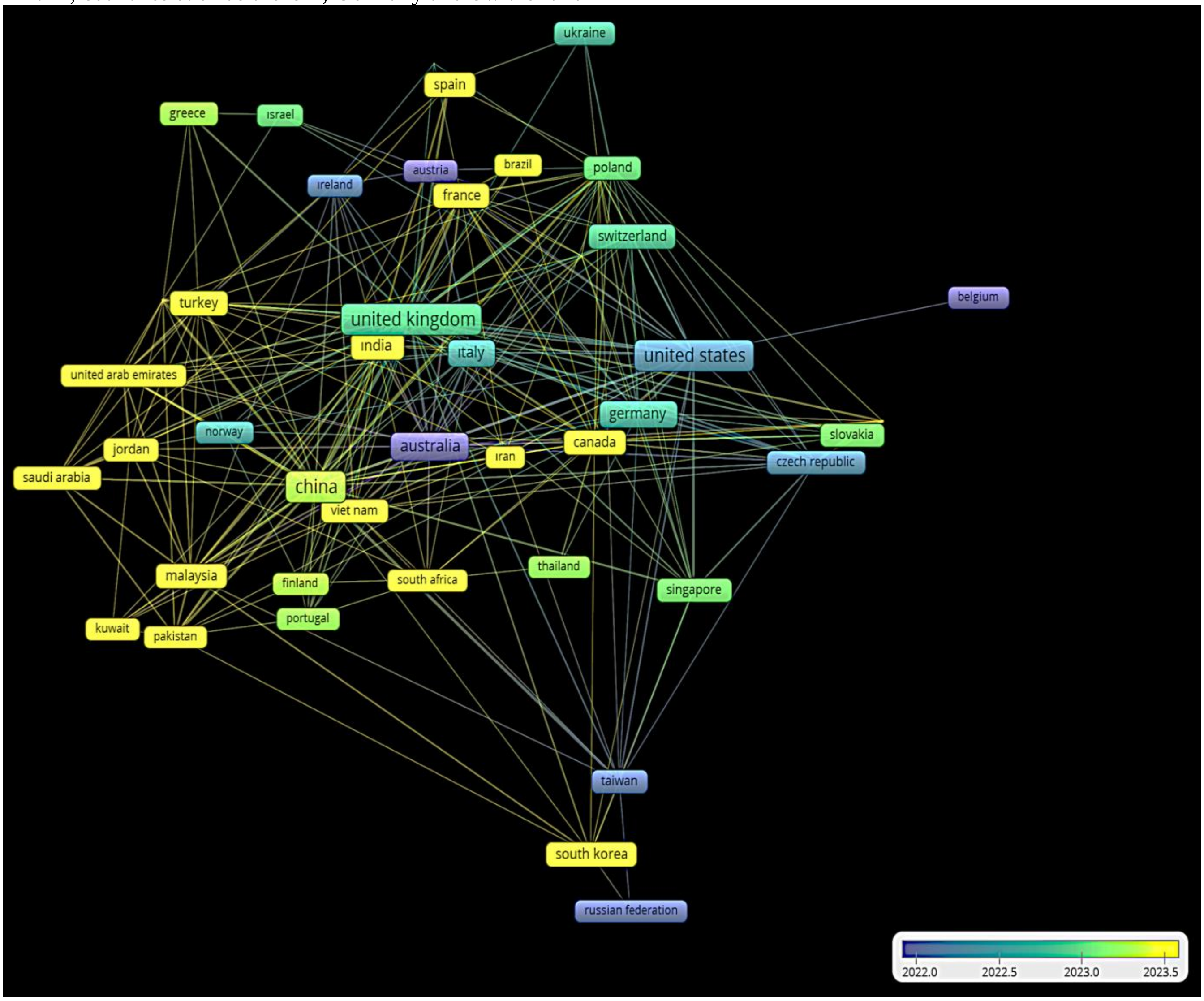


FIGURE IV: CONNECTION MAP BETWEEN COUNTRIES BY YEAR*

*: Link map between countries contributing at least 5 articles

D. *Most Cited Works*

Table 2 shows the studies with more than 100 citations after book citations and self-citations are removed. Thakor [41], which ranked first and received 469 citations, examined the interaction between financial technology (fintech) and banking and addressed innovations in payment systems (including cryptocurrencies), credit markets (especially peer-to-peer [P2P] lending) and the insurance sector. In second place is Huang and Liao's [42] study examining the acceptance of augmented reality interactive technologies (ARIT) by users and the impact of this acceptance on sustainable relationship behaviours, with 275 citations. In third place is the study of Bourlakis et al. [43], which examines the evolution of retailing from traditional to electronic and metaverse retailing with 149 citations.

When the studies in Table 2 are analysed, it can be seen that the metaverse and digital technologies are fundamentally transforming individuals' social interactions, management processes and financial ecosystems. Virtual reality-based social interactions can improve users' interaction quality by providing a more intense sensory experience compared to traditional internet environments [44]. However, the effectiveness of these interactions is determined by contextual factors and mediating variables. While the proliferation of digital technologies enables the development of strategies based on data utilisation, it also creates new tensions around individual privacy [45]. Efforts to protect consumers' personal data and regulatory frameworks shape firms' data policies, and this process is directly related to consumer awareness and firm transparency. Centralised and decentralised governance models also play an important role in this transformation, and the balance between blockchain-based decentralised platforms and semi-centralised models is considered a critical factor for the sustainability of platforms [46].

TABLE II: STUDIES WITH MORE THAN 100 CITATIONS*

Article	n
Thakor, A. V. (2020). Fintech and banking: What do we know?. *Journal of financial intermediation*, *41*, 100833.	469
Huang, T. L., & Liao, S. (2015). A model of acceptance of augmented-reality interactive technology: the moderating role of cognitive innovativeness. *Electronic Commerce Research*, *15*, 269-295.	275
Bourlakis, M., Papagiannidis, S., & Li, F. (2009). Retail spatial evolution: paving the way from traditional to metaverse retailing. *Electronic commerce research*, *9*, 135-148.	149
Chen, Y., Richter, J. I., & Patel, P. C. (2021). Decentralised governance of digital platforms. *Journal of Management*, *47*(5), 1305-1337.	139
Quach, S., Thaichon, P., Martin, K. D., Weaven, S., & Palmatier, R. W. (2022). Digital technologies: tensions in privacy and data. *Journal of the Academy of Marketing Science*, *50*(6), 1299-1323.	135
Hennig-Thurau, T., Aliman, D. N., Herting, A. M., Cziehso, G. P., Linder, M., & Kübler, R. V. (2023). Social interactions in the metaverse: Framework, initial evidence, and research roadmap. *Journal of the Academy of Marketing Science*, *51*(4), 889-913.	132
Vidal-Tomás, D. (2022). The new crypto niche: NFTs, play-to-earn, and metaverse tokens. *Finance research letters*, *47*, 102742.	121
Allen, F., Gu, X., & Jagtiani, J. (2022). Fintech, cryptocurrencies, and CBDC: Financial structural transformation in China. *Journal of International Money and Finance*, *124*, 102625.	112

*: Self-citations and book citations are excluded.

The governance of digital platforms affects the transformation of not only governance structures but also sectors. The retail sector is developing new spatial dynamics by evolving from traditional and online retailing to metaverse-based retailing [43]. Augmented reality has become an important factor shaping consumer behaviour, and it is seen that consumers with high cognitive innovativeness focus on factors such as utility, aesthetics and service excellence in using these technologies [42]. Financial technologies are also developing in interaction with traditional financial structures by offering innovations in banking and payment systems [41]. Crypto-assets and decentralised finance are becoming increasingly critical in the global economy, especially central bank digital currencies (CBDCs) are accelerating the transformation of financial systems [47]. In the gaming industry, metaverse and win-win systems offer attractive opportunities for investors, while at the same time increasing the risk of speculation [48, 49].

E. Keyword Analysis

Table 3 shows the most frequently used keywords in the authors' works. According to the data in the table, *Blockchain* stands out among the most frequently used keywords with 113 uses and 156 total link strength, followed by *Metaverse* (140 link strength) with 116 uses. *Cryptocurrency* and *Virtual Reality* rank first in terms of link strength with 48 and 36 uses respectively. Other important terms include *NFT*, *Artificial Intelligence*, *Augmented Reality*, *DeFi*, *Bitcoin* and *Technology*.

TABLE III. TOP 10 MOST USED KEYWORDS BY TOTAL LINK STRENGTH

#	Keyword	n	Total Link Strength
1	Blockchain	113	156
2	Metaverse	116	140
3	Cryptocurrency	48	74
4	Virtual Reality	36	64
5	NFT	28	58
6	Artificial Intelligence	32	50
7	Augmented Reality	17	44
8	DeFi	13	36
9	Bitcoin	26	35
10	Technology	19	35

Figure 6 shows the network map of keywords. Based on map of keywords, following analysis can be made:

Yellow Theme: “Blockchain Technology, Banking and Technology Adoption” This color group includes concepts such as ‘digitalization’, ‘blockchain technology’, ‘banking’, ‘technology adoption’ and ‘decentralization’. Here, the adoption of decentralized blockchain structures with the digitalization process of the financial sector (especially banking) is emphasized. How digital financial environments that replace physical transactions are shaped by decentralized models and how this process contributes to the metaverse economy can be examined under this theme.

Green Theme: “Socio-Technical Dimensions of the Metaverse” This color group highlights the concepts of ‘metaverse’, ‘virtual reality’, ‘artificial intelligence’, ‘digital marketing’, ‘technology acceptance’, ‘privacy’, ‘trust’, ‘big data’ and ‘consumer behavior’. Drawing attention to both the technological and societal implications of the metaverse ecosystem, this theme will explore how elements such as privacy, trust and big data management will be shaped within the metaverse.

Red Theme: “Blockchain, Cryptocurrencies and Decentralized Finance” In this cluster, concepts such as ‘cryptocurrency’, ‘bitcoin’, ‘NFTs’, ‘smart contracts’, ‘web3’, ‘decentralized finance (DeFi)’ and ‘digital assets’ come to the fore. This theme particularly highlights blockchain-based financial instruments, the potential of NFTs to change ownership processes, and how decentralized finance (DeFi) is shaping new investment and business models. The transfer of value through cryptoassets is expected to play an important role in the future vision of the metaverse economy.

Blue Theme: "Digital Transformation and Artificial Intelligence at the Macro Level" Concepts such as 'artificial intelligence (AI)', 'economic growth', 'bibliometric analysis', 'smart city', 'digital transformation' and 'digital economy' feature heavily in this color group. The focus here is on the impact of technological developments on economic growth, smart city applications supported by artificial intelligence and the transformation of the digital economy in general. The evolution of the metaverse economy from physical to digital can be considered as part of this macro-level transformation.

Purple Theme: "Innovation, Governance and Marketing in the Metaverse" This cluster is dominated by concepts such as 'innovation', 'marketing', 'virtual worlds', 'ethics', 'governance', 'accountability' and 'extended reality'. Innovation, marketing strategies and ethics in the Metaverse and similar virtual worlds fall under this heading. Governance and accountability emphasize not only the economic but also the social responsibility dimension of technological developments.

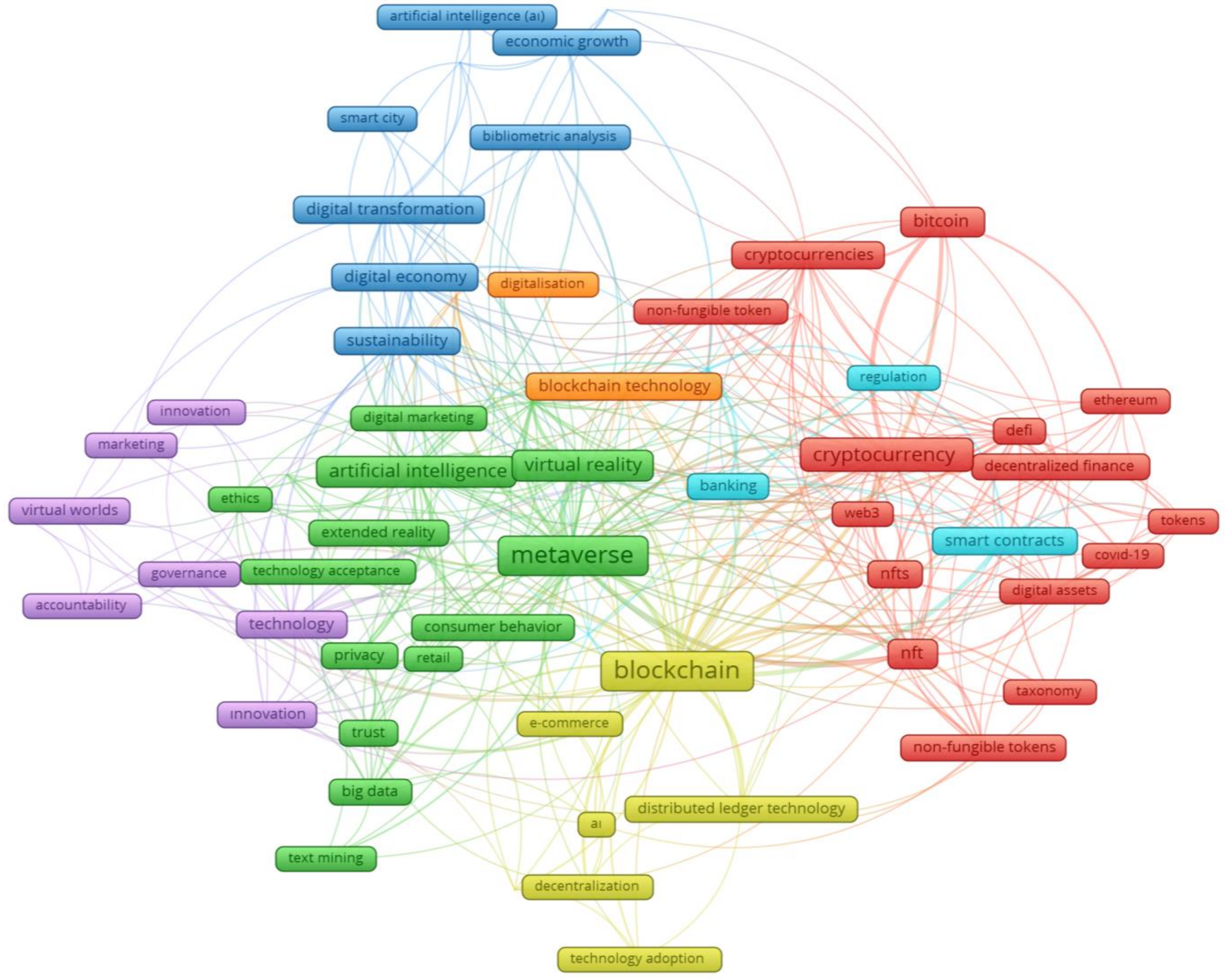


FIGURE V: NETWORK MAP OF KEYWORDS*

*: Keywords used at least 5 times are included.

V. DISCUSSION AND CONCLUSION

This study examines the digital transformation created by the metaverse economy through bibliometric analysis. The findings reveal that the metaverse ecosystem is growing rapidly, with research centred around innovative technologies such as blockchain, NFT and digital transformation being at the forefront. This observation coincides with the findings of Türkmen and Sürmeli [3] on the acceleration of metaverse studies in recent years and the acceleration of digital transformation, especially with the pandemic process. Similarly, Ding et al. [4] and Catherine et al. [5] state that technologies such as blockchain, NFT and virtual reality have recently created new opportunities in the fields of entrepreneurship and investment. Therefore, the increasing awareness of these technological innovations can be directly observed in bibliometric aggregation.

At the global level, it is seen that countries such as the UK, China and the USA are the leaders in academic production in this field, and the metaverse economy offers important opportunities for interdisciplinary cooperation and innovation. The fact that the UK, China and the USA are in the leading position shows that despite the decentralised structure of the metaverse economy, countries that have a say in the global economy also stand out in this field [2, 35]. In particular, the fact that the UK's academic institutions are in the top ten seems to be related to the relatively high level of interaction between mainstream banking, fintech initiatives and the digital technology ecosystem in this country. Moreover, Koohang et al. [7] emphasised that large-scale universities play a leading role in developing metaverse-based projects, especially in sectors such as retail, marketing, finance and education.

Keyword analyses show that the economic structures emerging from the convergence of digital and physical worlds are not only transforming user experiences, but also leading to radical changes in business models and value creation processes. The Metaverse is accelerating the evolution towards a new model of economy and social interaction, especially centred on digital assets (NFT, cryptocurrencies, DeFi) [16, 5]. However, technological infrastructure, data security, and the uncertainty of the regulatory framework are cited among the main challenges facing the metaverse economy [34]. In addition, the digital divide, inequality and possible transformations in labour markets are topics that research should focus on [20, 19]. In the face of sectoral impacts, opportunities and challenges, new research questions and collaborations are expected to emerge both at the micro level (business models, value creation mechanisms) and at the macro level (political-economic governance, income distribution, employment).

From a policy perspective, governments and regulatory bodies must establish clear guidelines on digital asset ownership, taxation, and intellectual property rights within the Metaverse Economy. Furthermore, ensuring financial inclusion and reducing digital divides should be key priorities to prevent economic inequalities from being exacerbated by metaverse-based economies. Policymakers should also focus on cybersecurity regulations to protect digital identities and assets. Data privacy laws must be adapted to virtual environments where user interactions and transactions occur on decentralised platforms. Additionally, fostering public-private partnerships for infrastructure development can support the widespread adoption of Metaverse technologies while maintaining ethical governance.

In conclusion, in line with the findings obtained, it is possible to say that metaverse economy studies are attracting more and more attention every year. The academic, commercial and social dimensions of the metaverse ecosystem will continue to be shaped by innovative technologies such as AR/VR, blockchain, NFT and artificial intelligence.

Funding

This research did not receive any outside funding or support. The authors report no involvement in the research by the sponsor that could have influenced the outcome of this work.

Acknowledgement

None.

Authors` Contributions

All authors have participated in drafting the manuscript. All authors read and approved the final version of the manuscript.

Conflict Of Interest

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Data Availability

The data supporting the findings of this study are available upon request from the authors

Ethical Statement

In this article, the principles of scientific research and publication ethics were followed. This study did not involve human or animal subjects and did not require additional ethics committee approval.

Declaration of AI Usage

No AI tools were used in the creation of this manuscript.

References

[1] Şanlısoy, S. & Çiloğlu, T. (2024). Two Sides of the Medallion in the Global Workforce as the Metaverse Evolves: New Job Opportunities and Technological Unemployment. In O. Meçik (Ed.), *Reskilling the Workforce for Technological Advancement* (pp. 111-140). IGI Global Scientific Publishing. https://doi.org/10.4018/979-8-3693-0612-3.ch006

[2] Egliston, B., & Carter, M. (2024). 'The metaverse and how we'll build it': The political economy of Meta's Reality Labs. New Media & Society, 26(8), 4336-4360. https://doi.org/10.1177/14614448221119785

[3] Türkmen, N. C., & Sürmeli, D. (2024). The Metaverse Virtual Economy: A Comprehensive Overview. *MANAS Sosyal Araştırmalar Dergisi, 13*(4), 1320-1335. https://doi.org/10.33206/mjss.1350087

[4] Ding, Y., Huang, W., Liang, H., Wang, Y., Yang, C., & Wang, H. (2024). A Fast Cross‐Chain Protocol Based on Trusted Notary Group for Metaverse. *International Journal of Network Management*, e2302. https://doi.org/10.1002/nem.2302

[5] Catherine, S., Rani, M. N., & Suresh, N. V. (2024). The Metaverse Economy: Transforming Money With Digital Currency. In B. Singla, K. Shalender, & N. Singh (Eds.), *Creator's Economy in Metaverse Platforms: Empowering Stakeholders Through Omnichannel Approach* (pp. 202-209). IGI Global Scientific Publishing. DOI: 10.4018/979-8-3693-3358-7.ch012

[6] Mancuso, I., Petruzzelli, A. M., & Panniello, U. (2023). Digital business model innovation in metaverse: How to approach virtual economy opportunities. Information Processing & Management, 60(5), 103457. https://doi.org/10.1016/j.ipm.2023.103457

[7] Koohang, A., Nord, J. H., Ooi, K. B., Tan, G. W. H., Al-Emran, M., Aw, E. C. X., ... & Wong, L. W. (2023). Shaping the metaverse into reality: a holistic multidisciplinary understanding of opportunities, challenges, and avenues for future investigation. Journal of Computer Information Systems, 63(3), 735-765.

[8] Saridakis, G., Khan, Z., Knight, G., Idris, B., Mitra, J., & Khan, H. (2024). A Look into the Future: The Impact of Metaverse on Traditional Theories and Thinking in International Business.

Management International Review, 64(4), 597-632. https://doi.org/10.1007/s11575-024-00550-8

[9] Curtis, C., & Brolan, C. E. (2023). Health care in the metaverse. *Medical Journal of Australia, 218*(1), 46-46.

[10] Gadalla, E., Keeling, K., & Abosag, I. (2013). Metaverse-retail service quality: A future framework for retail service quality in the 3D internet. Journal of Marketing Management, 29(13-14), 1493-1517.

[11] Razzaq, A., Zhang, T., Numair, M., Alreshidi, A., Jing, C., Aljaloud, A., Ghayyur, S. A. K., Ahmed, S., & Qurat Ul Ain, M. (2024). Transforming academic assessment: The metaverse‐backed Web 3 secure exam system. *Computer Applications in Engineering Education, 32*(1), e22797. https://doi.org/10.1002/cae.22797

[12] Ju, A. (2007). Students Get a'second life' in first'metanomics' course. Retrieved November, 1, 2007.

[13] Ball, M. (2022). *The metaverse: and how it will revolutionize everything*. Liveright Publishing.

[14] Tapscott, D. (2022). *How to build the digital economic system of the Metaverse.*

[15] Yadav, M., Singh, P., & Baral, S. K. (2024). Exploring the Synergy of Blockchain Technology and the Metaverse. In *Green Metaverse for Greener Economies* (pp. 306-320). CRC Press.

[16] Bao, W., Hudders, L., Yu, S., & Beuckels, E. (2024). Virtual luxury in the metaverse: NFT-enabled value recreation in luxury brands. *International Journal of Research in Marketing*. Doi : 10.1016/j.ijresmar.2024.01.002.

[17] Yazici, A. M., Özkan, A., Özkan, H. (2024). Meta: XR-AR-MR and Mirror World Technologies Business Impact of Metaverse. Journal of Metaverse. 4(1), 21-32. https://doi.org/10.57019/jmv.1344489

[18] Damaševičius, R. (2023). From E-commerce to V-commerce: Understanding the Impact of Virtual Reality and Metaverse on Economic Activities. *Journal of Information Economics, 1*(3), 55-79. doi: 10.58567/jie01030005

[19] Turner, C. (2023). The Metaverse: Virtual metaphysics, virtual governance, and virtual abundance. *Philosophy & Technology, 36*(4), 67. https://doi.org/10.1007/s13347-023-00666-z

[20] Zhou, Q., Wang, B., & Mayer, I. (2024). Understanding the social construction of the metaverse with Q methodology. *Technological Forecasting and Social Change, 208*, 123716. https://doi.org/10.1016/j.techfore.2024.123716

[21] Fuchs, B., & Thurner, S. (2014). Behavioral and network origins of wealth inequality: Insights from a virtual world. PloS one, 9(8), e103503. https://doi.org/10.1371/journal.pone.0103503

[22] Arakji, R. Y., & Lang, K. R. (2008). Avatar business value analysis: a method for the evaluation of business value creation in virtual commerce. *Journal of Economic Commerce Research*, *9*(3), 207-218.

[23] Calandra, D., Sadraei, R., Jafari-Sadeghi, V., & Biancone, P. (2023). Metaverse meets digital entrepreneurship: A practitioner-based qualitative synthesis. *International Journal of Entrepreneurial Behaviour & Research*. https://doi.org/10.1108/IJEBR-01-2023-0041

[24] Riva, G., Villani, D., & Wiederhold, B. K. (2022). Humane Metaverse: Opportunities and Challenges Towards the Development of a Humane-Centered Metaverse. *Cyberpsychology, Behavior, and Social Networking*. https://doi.org/10.1089/cyber.2022.29250.cfp

[25] Lin, H., Wan, S., Gan, W., Chen, J., & Chao, H. C. (2022, December). Metaverse in education: Vision, opportunities, and challenges. In *2022 IEEE International Conference on Big Data (Big Data)* (pp. 2857-2866). IEEE. DOI: 10.1109/BigData55660.2022.10021004

[26] Wang, G., Badal, A., Jia, X., Maltz, J. S., Mueller, K., Myers, K. J., ... & Zeng, R. (2022). Development of metaverse for intelligent healthcare. *Nature machine intelligence, 4*(11), 922-929. https://doi.org/10.1038/s42256-022-00549-6

[27] Kataria, S., Kedia, A. K., & Ravindran, V. (2023). Metaverse: Evolving role in healthcare delivery and implications. *Journal of the Royal College of Physicians of Edinburgh, 53*(3), 186-191. https://doi.org/10.1177/14782715231189900

[28] Hasei, J., Ishida, H., Katayama, H., Maeda, N., Nagano, A., Ochi, M., ... & Ozaki, T. (2024). Utilizing the metaverse to provide innovative psychosocial support for pediatric, adolescent, and young adult patients with rare cancer. *Cancers, 16*(15), 2617. https://doi.org/10.3390/cancers16152617

[29] Dohler, M., Kim, Y. G., Franco, M. G., & West, T. (2023). Making the MetAverse A Reality: Challenges And Opportunities. *IEEE Communications Magazine, 61*(9), 14-15. DOI: 10.1109/MCOM.2023.10268119

[30] Leshkevich, T. G. (2024). Metaverse as a Macroshift of Modern Culture. VOPROSY FILOSOFII, (4).

[31] Florido-Benítez, L. (2024). Metaverse cannot be an extra marketing immersive tool to increase sales in tourism cities. International Journal of Tourism Cities, 10(3), 974-994. DOI 10.1108/IJTC-01-2024-0001

[32] Zhao, N., & You, F. (2023). The growing metaverse sector can reduce greenhouse gas emissions by 10 Gt CO 2 e in the united states by 2050. *Energy & Environmental Science, 16*(6), 2382-2397. DOI https://doi.org/10.1039/D3EE00081H

[33] Go, H., & Kang, M. (2023). Metaverse tourism for sustainable tourism development: Tourism agenda 2030. Tourism Review, 78(2), 381-394. https://doi.org/10.1108/TR-02-2022-0102

[34] Donvito, R., Acuti, D., & Song, S. (2024). Fashion and the metaverse: Implications for consumers and firms. *Journal of Global Fashion Marketing, 15*(1), 1-5. https://doi.org/10.1080/20932685.2023.2293290

[35] Castronova, E., Williams, D., Shen, C., Ratan, R., Xiong, L., Huang, Y., & Keegan, B. (2009). As real as real? Macroeconomic behavior in a large-scale virtual world. *New Media & Society, 11*(5), 685-707. https://doi.org/10.1177/1461444809105346

[36] Cai, W., Zhao, J., Gui, X., Msahli, M., & Leung, V. C. (2023). Guest Editorial Special Issue on Social Studies, Human Factors, and Applications in Metaverse. *IEEE Transactions on Computational Social Systems, 10*(5), 2160-2164. doi: 10.1109/TCSS.2023.3313199

[37] Weking, J., Desouza, K. C., Fielt, E., & Kowalkiewicz, M. (2023). Metaverse-enabled entrepreneurship. *Journal of Business Venturing Insights, 19*, e00375. https://doi.org/10.1016/j.jbvi.2023.e00375

[38] Lim, C., Ratan, R., Foxman, M., Meshi, D., Liu, H., Hales, G. E., & Lei, Y. S. (2024). An Avatar's worth in the metaverse workplace: Assessing predictors of avatar customization valuation. Computers in Human Behavior, 158, 108309. https://doi.org/10.1016/j.chb.2024.108309

[39] Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. Journal of Business Research, 133, 285–296. https://doi.org/10.1016/j.jbusres.2021.04.070

[40] Van Eck, N. J. & Waltman, L. (2022). VOSviewer Manual. https://tinyurl.com/mywjrs9b

[41] Thakor, A. V. (2020). Fintech and banking: What do we know?. *Journal of financial intermediation, 41*, 100833. https://doi.org/10.1016/j.jfi.2019.100833

[42] Huang, T. L., & Liao, S. (2015). A model of acceptance of augmented-reality interactive technology: the moderating role of cognitive innovativeness. Electronic Commerce Research, 15, 269-295. DOI 10.1007/s10660-014-9163-2

[43] Bourlakis, M., Papagiannidis, S., & Li, F. (2009). Retail spatial evolution: paving the way from traditional to metaverse retailing.

Electronic commerce research, 9, 135-148. DOI 10.1007/s10660-009-9030-8

[44] Hennig-Thurau, T., Aliman, D. N., Herting, A. M., Cziehso, G. P., Linder, M., & Kübler, R. V. (2023). Social interactions in the metaverse: Framework, initial evidence, and research roadmap. Journal of the Academy of Marketing Science, 51(4), 889-913. https://doi.org/10.1007/s11747-022-00908-0

[45] Quach, S., Thaichon, P., Martin, K. D., Weaven, S., & Palmatier, R. W. (2022). Digital technologies: tensions in privacy and data. Journal of the Academy of Marketing Science, 50(6), 1299-1323. https://doi.org/10.1007/s11747-022-00845-y

[46] Chen, Y., Richter, J. I., & Patel, P. C. (2021). Decentralized governance of digital platforms. Journal of Management, 47(5), 1305-1337. https://doi.org/10.1177/0149206320916755

[47] Allen, F., Gu, X., & Jagtiani, J. (2022). Fintech, cryptocurrencies, and CBDC: Financial structural transformation in China. *Journal of International Money and Finance,* 124, 102625. https://doi.org/10.1016/j.jimonfin.2022.102625

[48] Vidal-Tomás, D. (2022). The new crypto niche: NFTs, play-to-earn, and metaverse tokens. *Finance research letters, 47*, 102742. https://doi.org/10.1016/j.frl.2022.102742

[49] Katterbauer, K., Syed, H., & Cleenewerck, L. (2022). Financial cybercrime in the Islamic Finance Metaverse. Journal of Metaverse, 2(2), 56-61. https://doi.org/10.57019/jmv.1108783

APPENDIX 1. SCOPUS SEARCH PARAMETER

ALL (metaverse OR "metaverse economy" OR "metaverse economics" OR "blockchain economy" OR "blockchain economics") AND (LIMIT-TO (SUBJAREA , "ECON")) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re") OR LIMIT-TO (DOCTYPE , "cp")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (EXACTKEYWORD , "Blockchain") OR LIMIT-TO (EXACTKEYWORD , "Metaverse") OR LIMIT-TO (EXACTKEYWORD , "Cryptocurrency") OR LIMIT-TO (EXACTKEYWORD , "Virtual Reality") OR LIMIT-TO (EXACTKEYWORD , "Artificial Intelligence") OR LIMIT-TO (EXACTKEYWORD , "NFT") OR LIMIT-TO (EXACTKEYWORD , "Bitcoin") OR LIMIT-TO (EXACTKEYWORD , "Digital Economy") OR LIMIT-TO (EXACTKEYWORD , "Augmented Reality") OR LIMIT-TO (EXACTKEYWORD , "Blockchain Technology") OR LIMIT-TO (EXACTKEYWORD , "Cryptocurrencies") OR LIMIT-TO (EXACTKEYWORD , "Artificial Intelligence (AI)") OR LIMIT-TO (EXACTKEYWORD , "Augmented Reality (AR)") OR LIMIT-TO (EXACTKEYWORD , "Banking") OR LIMIT-TO (EXACTKEYWORD , "Big Data") OR LIMIT-TO (EXACTKEYWORD , "Block-chain") OR LIMIT-TO (EXACTKEYWORD , "Decentralised") OR LIMIT-TO (EXACTKEYWORD , "Decentralisation") OR LIMIT-TO (EXACTKEYWORD , "Decentralised Finance") OR LIMIT-TO (EXACTKEYWORD , "Decentralised Finance (DeFi)") OR LIMIT-TO (EXACTKEYWORD , "Decision Making") OR LIMIT-TO (EXACTKEYWORD , "Digital Currencies") OR LIMIT-TO (EXACTKEYWORD , "Digital Assets") OR LIMIT-TO (EXACTKEYWORD , "Digital Finance") OR LIMIT-TO (EXACTKEYWORD , "Digital Marketing") OR LIMIT-TO (EXACTKEYWORD , "Digital Technologies") OR LIMIT-TO (EXACTKEYWORD , "Digital Transformation") OR LIMIT-TO (EXACTKEYWORD , "Digitalisation") OR LIMIT-TO (EXACTKEYWORD , "Digitization") OR LIMIT-TO (EXACTKEYWORD , "Economic Analysis") OR LIMIT-TO (EXACTKEYWORD , "Economic And Social Effects") OR LIMIT-TO (EXACTKEYWORD , "Economic Development") OR LIMIT-TO (EXACTKEYWORD , "Economic Growth") OR LIMIT-TO (EXACTKEYWORD , "Efficiency") OR LIMIT-TO (EXACTKEYWORD , "Ethereum") OR LIMIT-TO (EXACTKEYWORD , "Explainable Artificial Intelligence") OR LIMIT-TO (EXACTKEYWORD , "Extended Reality") OR LIMIT-TO (EXACTKEYWORD , "Finance") OR LIMIT-TO (EXACTKEYWORD , "Financial Inclusion") OR LIMIT-TO (EXACTKEYWORD , "Financial Literacy") OR LIMIT-TO (EXACTKEYWORD , "Financial Market") OR LIMIT-TO (EXACTKEYWORD , "Financial Performance") OR LIMIT-TO (EXACTKEYWORD , "Financial Markets") OR LIMIT-TO (EXACTKEYWORD , "Fintech") OR LIMIT-TO (EXACTKEYWORD , "Metaverses") OR LIMIT-TO (EXACTKEYWORD , "Machine Learning") OR LIMIT-TO (EXACTKEYWORD , "Internet Of Things") OR LIMIT-TO (EXACTKEYWORD , "Innovation") OR LIMIT-TO (EXACTKEYWORD , "Information And Communication Technology") OR LIMIT-TO (EXACTKEYWORD , "Governance") OR LIMIT-TO (EXACTKEYWORD , "Governance Approach") OR LIMIT-TO (EXACTKEYWORD , "Green Economy") OR LIMIT-TO (EXACTKEYWORD , "NFTs") OR LIMIT-TO (EXACTKEYWORD , "Natural Language Processing") OR LIMIT-TO (EXACTKEYWORD , "Non-fungible Token") OR LIMIT-TO (EXACTKEYWORD , "Non-fungible Tokens") OR LIMIT-TO (EXACTKEYWORD , "Non-fungible Tokens (NFTs)") OR LIMIT-TO (EXACTKEYWORD , "Smart Contracts") OR LIMIT-TO (EXACTKEYWORD , "Smart Contract") OR LIMIT-TO (EXACTKEYWORD , "Smart City") OR LIMIT-TO (EXACTKEYWORD , "Second Life") OR LIMIT-TO (EXACTKEYWORD , "Supply Chain Management") OR LIMIT-TO (EXACTKEYWORD , "Supply Chain") OR LIMIT-TO (EXACTKEYWORD , "Supply Chains") OR LIMIT-TO (EXACTKEYWORD , "Sustainability") OR LIMIT-TO (EXACTKEYWORD , "Sustainable Development") OR LIMIT-TO (EXACTKEYWORD , "Taxation") OR LIMIT-TO (EXACTKEYWORD , "Taxonomy") OR LIMIT-TO (EXACTKEYWORD , "Technological Development") OR LIMIT-TO (EXACTKEYWORD , "Technological Development") OR LIMIT-TO (EXACTKEYWORD , "Technological Innovation") OR LIMIT-TO (EXACTKEYWORD , "Technology") OR LIMIT-TO (EXACTKEYWORD , "Technology Acceptance") OR LIMIT-TO (EXACTKEYWORD , "Technology Acceptance Model") OR LIMIT-TO (EXACTKEYWORD , "Technology Adoption") OR LIMIT-TO (EXACTKEYWORD , "Text Mining") OR LIMIT-TO (EXACTKEYWORD , "Tokenomics") OR LIMIT-TO (EXACTKEYWORD , "Tokens") OR LIMIT-TO (EXACTKEYWORD , "Virtual World") OR LIMIT-TO (EXACTKEYWORD , "Virtual Worlds") OR LIMIT-TO (EXACTKEYWORD , "Web3") OR LIMIT-TO (EXACTKEYWORD , "XR"))

Journal of Metaverse
Research Article
Received: 2024-11-11 | **Reviewing:** 2024-11-23 & 2025-03-07 | **Accepted:** 2025-03-09 | **Online:** 2025-03-09 | **Issue Date:** 2025-06-30
Year:2025, **Volume:**5, **Issue:**1, **Pages:**38-50, **Doi:** 10.57019/jmv.1582149

A Bibliometric Analysis of Metaverse: Mapping, Visualizing and Future Research Trends

Saad G. YASEEN
Al-Zaytoonah University of Jordan
Amman, Jordan
saad.yaseen@zuj.edu.jo
0000-0002-3079-9410

Ayman Abdalmajeed ALSMADI
Al Zaytoonah University of Jordan
Amman, Jordan
ayman.smadi@zuj.edu.jo
0000-0003-4663-8424
(Corresponding Author)

Shorouq F. ELETTER
Al Ain University
Abu Dhabi, United Arab Emirates
shorouq.eletter@aau.ac.ae
0000-0002-5584-8899

Abstract— **Metaverse merges diverse digital technologies such as Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), Internet of Things (IoT) sensing technology, Three-dimensional (3D), Extended Reality (XR), and modeling. This research aims to present a bibliometric analysis for visualizing and mapping Metaverse research. In particular, 2673 research articles listed in the Scopus database between the years 2000 and 2023 were analyzed. The knowledge visualization and mapping based on VOS viewer and R studio present the current research status and keywords analysis. This research highlights newer insights into Metaverse applications across various business domains. The findings suggest that the metaverse is highly inclusive. The majority of industries and businesses have adopted several metaverse applications. The present state of the Metaverse literature justifies that Metaverse deep learning, Metaverse blockchain, and cyber-human interaction is a rapidly evolving research domain that engages a set of interconnected fields, which include the Internet of Things (IoT), virtual space, mixed reality and digital twin.**

Keywords— Bibliometric analysis, Metaverse, visualizing, Virtual Reality (VR), Augmented Reality (AR), Three dimensional (3D), Thematic (Tm)

I. INTRODUCTION

Metaverse technology integrates Virtual Reality (VR), Augmented Reality (AR), Three-dimensional (3D), and users-digital technology interactions within digital space [1-2]. The term Metaverse first appeared in Neal Stephenson's cyberpunk novel Snow Crash, and it was assumed to be the Internet of the future [3-4]. Since then, Google, Facebook, and Microsoft have been developing a plethora of Metaverse technology [5].

The terms VR, AR, XR and DT, which stand for Virtual Reality, Augmented Reality, Extended Reality, and Digital Twin, respectively, are interconnected with the Metaverse but different in terms of their scope and applicability. Augmented Reality covers digital elements in the physical world, which thereby enhances real-world interactive experiences [6]. Virtual Reality generates deeply immersive digital environments, capable of detaching the users from their present physical environment [7]. Extended Reality indicates an umbrella term encircling AR, VR, and MR, offering a range of captivating experiences. On the other hand, Digital Twin portrays a virtual replica of physical systems, which enables real-time synchronization of the data for simulations and monitoring. Metaverse combines these technologies into a durable, reliable and highly interactive digital space that works much more advanced than individual functionalities. Going beyond and broader than AR, VR, XR, or DT, Metaverse showcases a consistent, shared virtual world that combines real and virtual elements while supplementing diverse applications that include social interactions, education, commerce, and entertainment [8]. By integrating these technologies, Metaverse becomes a platform for complex and multiple user environments that are able to replicate or augment reality.

Recently, the term Metaverse technology has been used to clarify new emerging digital space that will be considered as the post-internet epoch [9]. Thus, the advent of Metaverse technology has received widespread attention due to its novelty as a new paradigm, technology, and mainstream research [10]. However, the existing literature is mostly interdisciplinary and conceptual, except for a few empirical studies [11]. Therefore, it is crucial to use visualization and quantitative tools such as bibliometric analysis for mapping the current research state and assuming a robust map to accommodate potential future research gaps. Researchers also used Bibliometric analysis to decrease the bias in the literature review, clarify emerging trends, explore the intellectual framework of the knowledge domain, and manipulate big scientific data and large volumes of published sources [12].

Furthermore, bibliometric analysis is beneficial for mapping the accumulative explicit knowledge and creating added value from large volumes of published scientific sources using both objective and rigorous tools [13]. This research aims to investigate the present and future research trends of the Metaverse technology by using VOS viewer and RStudio software and is based on 2673 documents spanning the years 2000-2023. The researchers analyzed the metadata of the studies obtained from Elsevier Scopus. In particular, this study introduces a bibliometric analysis of 'Metaverse' research in the literature and specifies existing research gaps. A research trends analysis was performed to investigate the development of the 'Metaverse' and its applications in different business settings.

This paper addresses the following questions:

Question 1: What are the most influential and critical features of Metaverse literature and emerging future research directors?

Question 2: What are the challenges and opportunities of 'Metaverse' research?

Cite (APA): Yaseen, S.G., Alsmadi, A.A., Eletter, S.F. (2025). A Bibliometric Analysis of Metaverse: Mapping, Visualizing and Future Research Trends. *Journal of Metaverse*. *5*(1), 38-50. **Doi:** 10.57019/jmv.1582149

II. Literature Review

The advent of smart digital technologies and artificial intelligence has facilitated the development of a digitally coexisting and emerging extended physical (real) and virtual world [14-15]. The term "Metaverse" is derived from the meta and verse, the term meta finds its deep in roots in philosophy connoting transcendence [11, 16], and the word "universe" implies a physical world. “Metaverse” traces its origins to Neal Stephenson's 1992 novel "Snow Crash", where people were engaged in virtual world populated by digital avatars or digital characters [4].

Metaverse technology creates immersive engagement where users participate in various activities and share their intellectual assets and knowledge using 3D tools [17]. Thus, Metaverse can be recognized as a digital replication of the real world or a digital mirror of the world where the multi-user realm combines Augmented Reality (AR), Virtual Reality (VR) or Extended Reality (XR) to create multi-sensory interactions between users and their physical and mirror-worlds [18]. The Metaverse technology is enormous in that it has crucial advantages, and has many applications which include marketing [19], blockchain [11], Healthcare, telemedicine, medicine mental health and physical health [3], education [5], gamification [3, 20], advertising [21] and artificial intelligence [22].

In the healthcare sector, the metaverse enables virtual consultations, allowing remote access to medical checkups or mental health therapies with immersive 3D environment experience [3, 23]. In the education sector, highly immersive learning experiences through virtual classrooms can be created using the ‘Metaverse’ helping students interact with real-life simulations and immersive classroom environments [24]. In the blockchain field, Metaverse supports decentralized platforms to enable secure transactions and to utilize non-fungible tokens (NFTs), thereby improving accessibility and trust in digital economies [11, 25].

All major businesses and industries, including manufacturing, services, social networking, smart governments, smart cities, gaming, hospitality, tourism and others, have embraced Metaverse applications [26]. In recent years, the Metaverse has been the most trending technology in digital technology [27]. According to Facebook and Microsoft, Metaverse is a digital space that replicates and covers the digital representation of users and things [28]. The early adopters of this immersive technology were gaming, entertainment, cloud computing and social media business models [17]. As per [22], the Metaverse space depicts an immersive environment where people live, work and interact between the real world and the Metaverse. In addition, the Metaverse offers an excellent platform due to its interactive and pure-mixed reality that allows users to engage in real-time both in the physical and digital world [25].

Metaverse technology has its applications in various domains that include gamification [29], online shopping [30], e-marketing [31], education [22], cryptocurrency [32], web or social media [33], blockchain [34], and brand management [35].

Although it constitutes a parallel or extended virtual world, Metaverse technology creates an immersive experience that makes individuals feel as if they are inhabiting a real-world environment [11]. According to [18], the Metaverse space implies eight components, namely: identity, users, immersion, diversification anywhere, low latency, economic systems, civilization [14] while [28] assume three major features of the Metaverse: blending real (physical) and virtual world; it facilitates social interactions, among virtual users, entities and virtual markets [36]. Consequently, the Metaverse space has revolutionized our experiences and virtualized each activity by fully crafted Virtual Reality or Augmented Reality enhanced by a variety of immersive technologies that shape the future interaction between human behavior and these cutting-edge technologies. The Metaverse is now considered the potential solution that amalgamates all cutting-edge technologies in the world context [37].

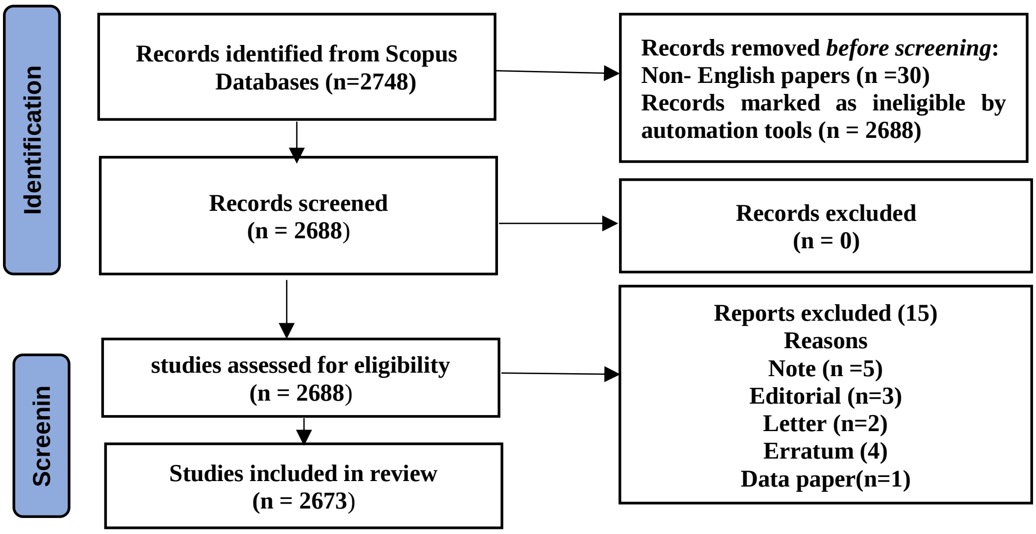


Figure I. “PRISMA Framework”

III. Research Methodology

VOS viewer provides distance-based visualization of the bibliometric network. It's especially suitable for visualizing large networks [38]. The bibliometric analysis is applied to express the bibliometric structure, which shows interrelations between constituents of the study in the field of Metaverse. The scope of the study is quite detailed to allow for bibliometric analysis. If the papers are in the hundreds (⩽500), then this research field can be assumed to be wholesome enough for conducting bibliometric mapping.

The PRISMA model, developed by [39] supported the methodological framework for conducting a meta-review. Figure (1) below illustrates bibliometric analysis and review development through identification, screening, and inclusion of documents.

A. *Data Selection Strategy*

This study uses convenience sampling and the Scopus database as the primary source. Researchers chose Scopus because it provides a comprehensive exploration of the social sciences and is popular for conducting diverse studies. Limited access to other databases, such as the SSCI (Social Science Citation Index and Science Citation Index Expanded) within the Web of Science collection, also influenced this choice.

B. *Data Collection and Analysis*

Data was collected from Elsevier Scopus. Bibliographic data was downloaded for all 2673 publications as illustrated in Table (1). In addition, the publications included in the bibliometric analysis covered the period of 2000 to 2023. The research figured out the applicable keywords and created search methods based on two keywords: Metaverse and Metaverse. Notably, research work increased modestly between the years 2000 and 2023. Retrieving bibliometric data, mapping bibliometric data, and research topic analysis were performed using visualization tools.

A co-word analysis was carried out since it helps to find the conceptual structure of the field under study, its research streams and research topic and to answer other research questions involved in this study [12]. The bibliometric analysis was done with VOS viewer software (version 1.6.17) and RStudio as followed by [40-43].

IV. Results and Discussion

The research on metaverse began in early 2000, which resulted in 2673 documents by 2023 published in Scopus, spanning across 1338 sources which include Journals, Books, etc.

TABLE I: PUBLICATIONS PROFILE

Description	Results
Timespan	2000:2023
Sources (Journals, Books, etc.)	1338
Documents	2673
Average years from publication	1.33
Average citations per document	7.988
Average citations per year per doc	2.969
References	105,998

Table 1 presents the annual distribution of Metaverse-related publications from the year 2000 to 2023. The numbers in the graph demonstrate a sharp spike in 2020.

The total number of documents that are Metaverse-related is 2673 from the year 2000 to 2023. The notable spike in publications post-2020 highlights the increasing academic and practical interest in Metaverse studies.

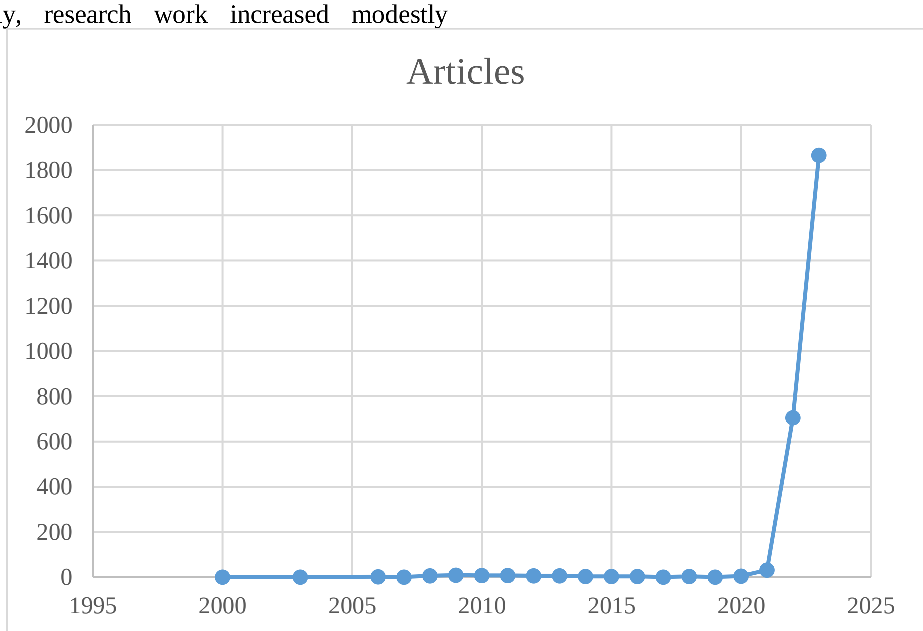


FIGURE 2. TRENDS IN METAVERSE RESEARCH PUBLICATIONS FROM 2000-2023 (EXTRACTED FROM SCOPUS DATABASE)

The rise in research on the Metaverse between 2000 and 2023, as represented in Figure 1, confirms the growing interest in digital technologies and their applications over the years. This rise aligns with an increased adoption of virtual and Augmented Reality, blockchain, and other similar immersive technologies, evidently after 2020 when the upward trend became more prominent. In the 1990s, foundational ideas like Neal Stephenson's ‘Snow Crash’ introduced the concept of

Metaverse. It emphasizes how industry adoption and technological advancements have modified scholarly interest over the past two decades.

Figure 2 indicates bibliometric data collected from the Elsevier Scopus database. The data includes 2673 documents that were published over the period from 2000 to 2023 and analyzed using VOS viewer and RStudio software.

A. Leading Countries, Institutions, Journals, and Authors

Figure 3 maps the top 10 authors who have published their research on Metaverse and related fields. Leading in this list is Niyato D, who has 52 documents, followed by Wang Y, who has 36 documents, and Li Y, who has 31 documents published. The number of publications gradually decreased after Chen Y secured 10th place with 22 publications. This ranking represents the prominent contributors towards research in the Metaverse, which is leading to the knowledge advancement in this field. This shows potential support in identifying potential collaborators for future research.

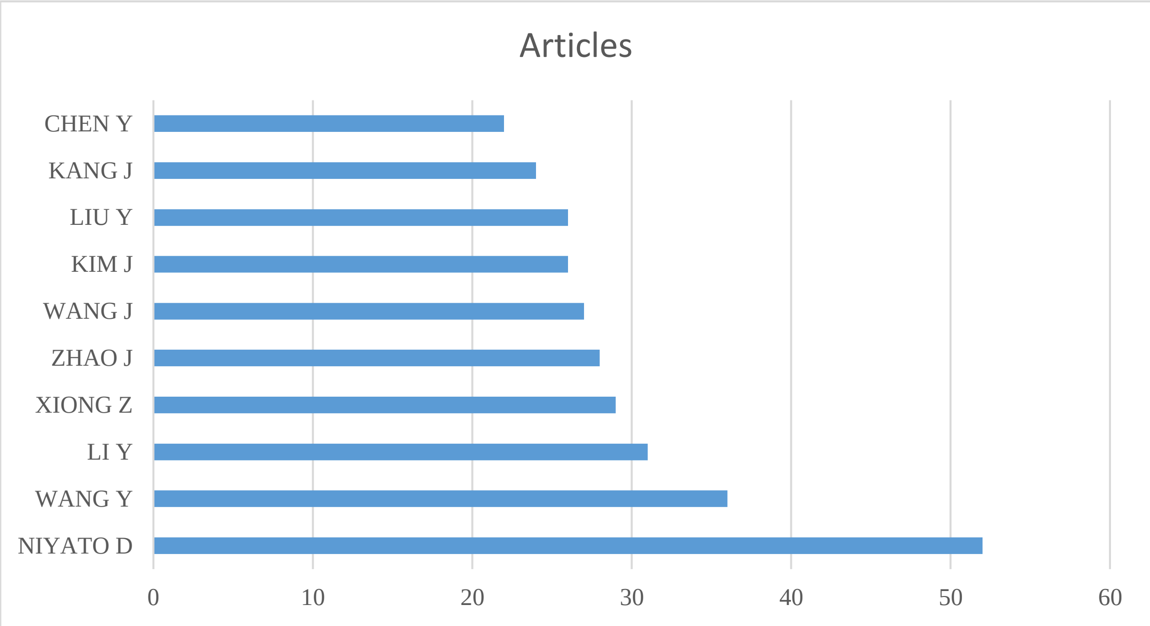


FIGURE 3. TOP 10 AUTHORS WHO HAVE PUBLISHED THEIR RESEARCH ON METAVERSE

Figure 4 highlights the countries of representation for the first authors from the top 20 contributors toward Metaverse research. The leading contributor is China with 2,351 publications, India with 1,026, and the USA with 895. This number steadily declines across the other countries, with France and Portugal contributing 85 and 82 publications, respectively. This country-wise distribution proves the global participation in Metaverse research, with a markable dominance from specific regions. Contributions from countries like China, India, and the USA contemplate their leadership and proactive participation in progressing Metaverse-related research and advancements in technology, especially in AI, digital infrastructure, and Virtual Reality. Thus, shows vital support for studies and practices of new emerging technologies in these countries.

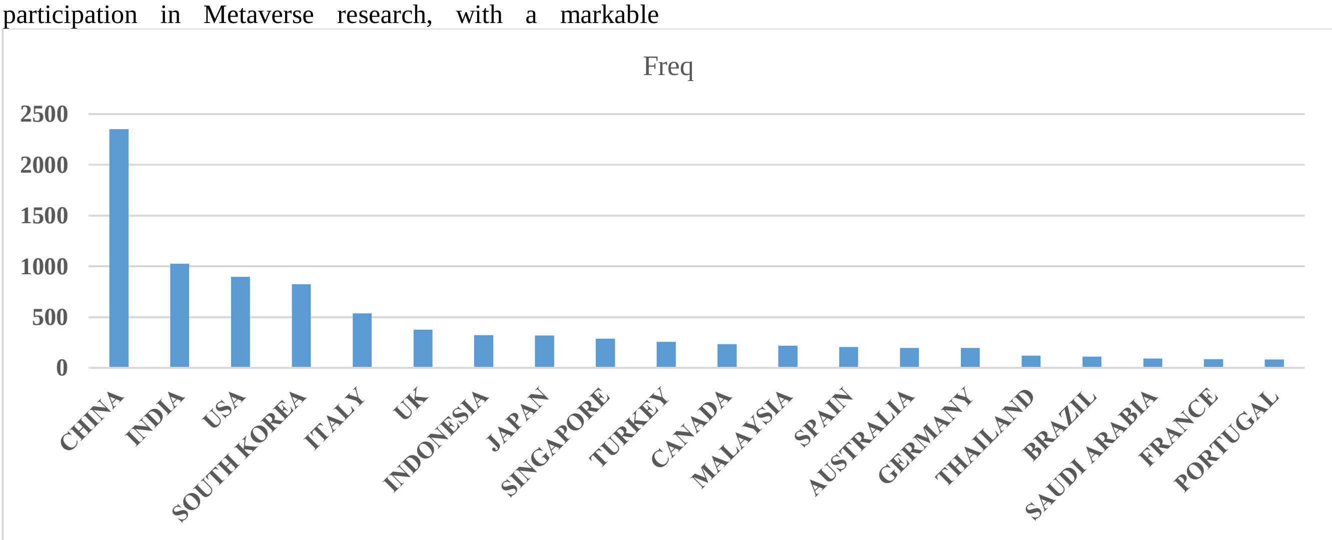


FIGURE 4. REPRESENTED COUNTRIES OF AUTHORS

Table 2 shows an overview of the top 10 most frequently affiliated institutions having 100 or fewer publications on Metaverse-related research. At the top of this list is Nanyang Technological University, with 100 publications, and Shanghai Jiao Tong University, with 48 publications, whereas Fudan is at the 10th position in the list showing 33 publications. It depicts diverse scholarly research engagement among the different institutions in this emerging field. This variation and diversity could be due to differences in focus areas of the research or research funding toward Metaverse-related research.

TABLE 2: AUTHOR-AFFILIATED INSTITUTIONS

Affiliations	Articles
Nanyang Technological University	100
Shanghai Jiao Tong University	48
Sun Yat-Sen University	46
The Hong Kong Polytechnic University	43
Sungkyunkwan University	42
Bina Nusantara University	39
Kyung Hee University	35
Tsinghua University	35
Zhongshan Hospital	34
Fudan University	33

Table 3 highlights the top 10 research publication sources for research in Metaverse. At the first position is "*The lecture notes in computer science"* with 77 publications, which includes the "lecture notes in bioinformatics" and "lecture notes in artificial intelligence", which is followed by "*International Conference on Metaverse Computing Networking and Applications Metacom 2023"* with 66 publications. Simultaneously, *the Review of Contemporary Philosophy* ranks 10th with 25 publications. This table depicts increasing academic interest and investment in utilizing and exploring Metaverse technology, its innovation and its advancement.

TABLE 3: TOP 10 RESEARCH PUBLICATION SOURCES

N	Sources	Articles
1	'Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)'	77
2	'Proceedings - 2023 IEEE International Conference on Metaverse Computing Networking and Applications Metacom 2023'	66
3	'ACM International Conference Proceeding Series'	57
4	'Lecture Notes in Networks and Systems	49
5	Studies in Big Data'	40
6	'IEEE Journal on Selected Areas in Communications'	35
7	IEEE Access	33
8	Journal of Metaverse	32
9	'Linguistic and Philosophical Investigations'	32
10	'Review of Contemporary Philosophy'	25

B. Citation Analysis

Table 4 represents the author impact analysis based on the number of citations. Kim J, published 15 researches, gained 1305 citations; whereas Kim Y-G published 2 documents and received 1304 citations, Park S.M, published 6 papers, received 1300 citations. And so on, Sigala M, has 4 publications, received 1001 citations, ranked tenth. Table 4 highlights the important role of the authors for producing a steady foundation, thereby guiding the progress and development of Metaverse-related research.

TABLE 4: AUTHOR IMPACT BASED ON NUMBER OF CITATIONS

Nu	Author	Documents	Citations
1	KIM J	15	1351
2	KIM Y-G	3	1305
3	PARK S-M	2	1304
4	BUHALIS D	6	1300
5	DWIVEDI YK	14	1151
6	HUGHES L	7	1076
7	RAMAN R	5	1030
8	DUTOT V	4	1028
9	PANDEY N	4	1028
10	SIGALA M	4	1001

Table 4 reveals the top 10 author contributions to Metaverse research in terms of the number of citations.

Moreover, understanding citation patterns elucidates major areas of research that are forming, where blockchain, deep learning, and cyber-human interaction are developing to be prominent fields. These domains have robust co-citation linkages that serve as the backbone of Metaverse-related developments. Nonetheless, there is a conspicuous lack of empirical studies in using these technologies within business and industry contexts. On another note, these studies are dominated by China, the USA, and India, with little input from the newer economies. Redressing this situation will require more collaboration across regions. In addition, broadening the methodological spectrum by including qualitative and experimental research will allow for an in-depth understanding of user experiences and the application of the Metaverse in real-world scenarios.

C. Mapping Networks and Content

Mapping networks and content includes visualizing relationships between entities and content structure, like topics, themes, or ideas [44]. In network mapping, nodes represent entities like individuals, organizations, or concepts, while edges like collaborations or interactions visualize their relationships. In content mapping, the nodes represent information like themes or ideas, and edges illustrate their connections and hierarchy [45]. This section deliberates co-citation analysis, bibliographic coupling, thematic evolution, keyword patterns, and hierarchy clustering for identifying existing research fields and guiding future research.

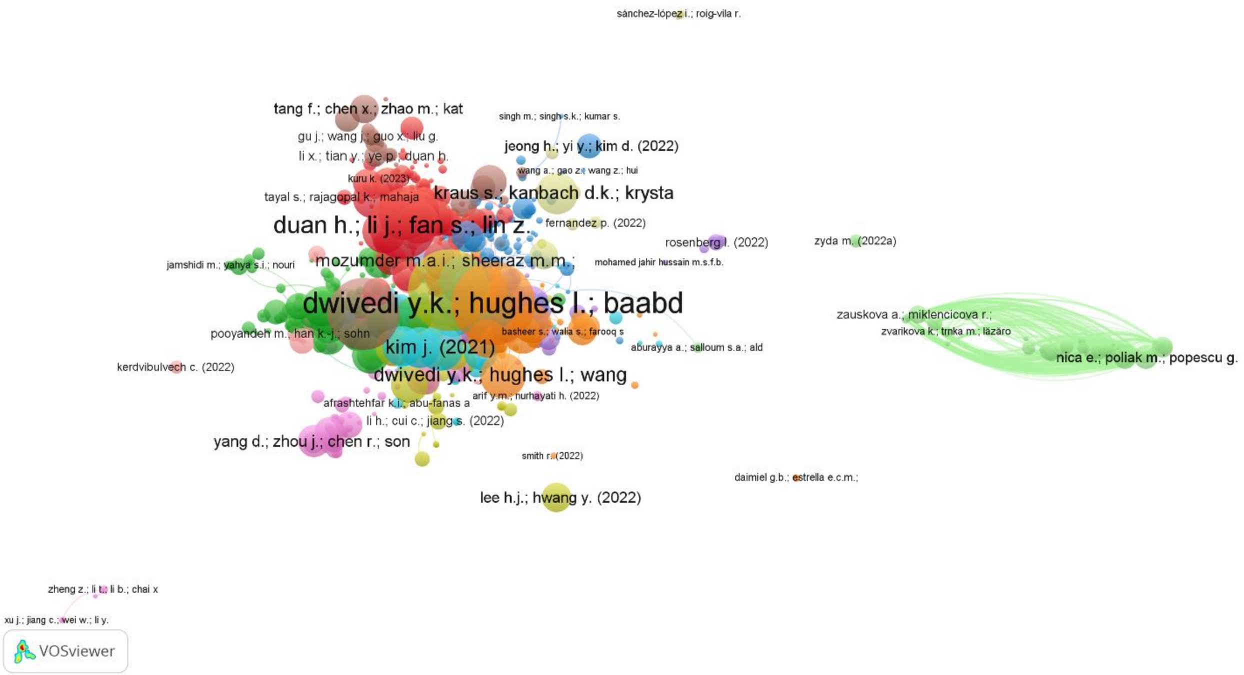


FIGURE 5. BIBLIOGRAPHIC COUPLING OF DOCUMENTS

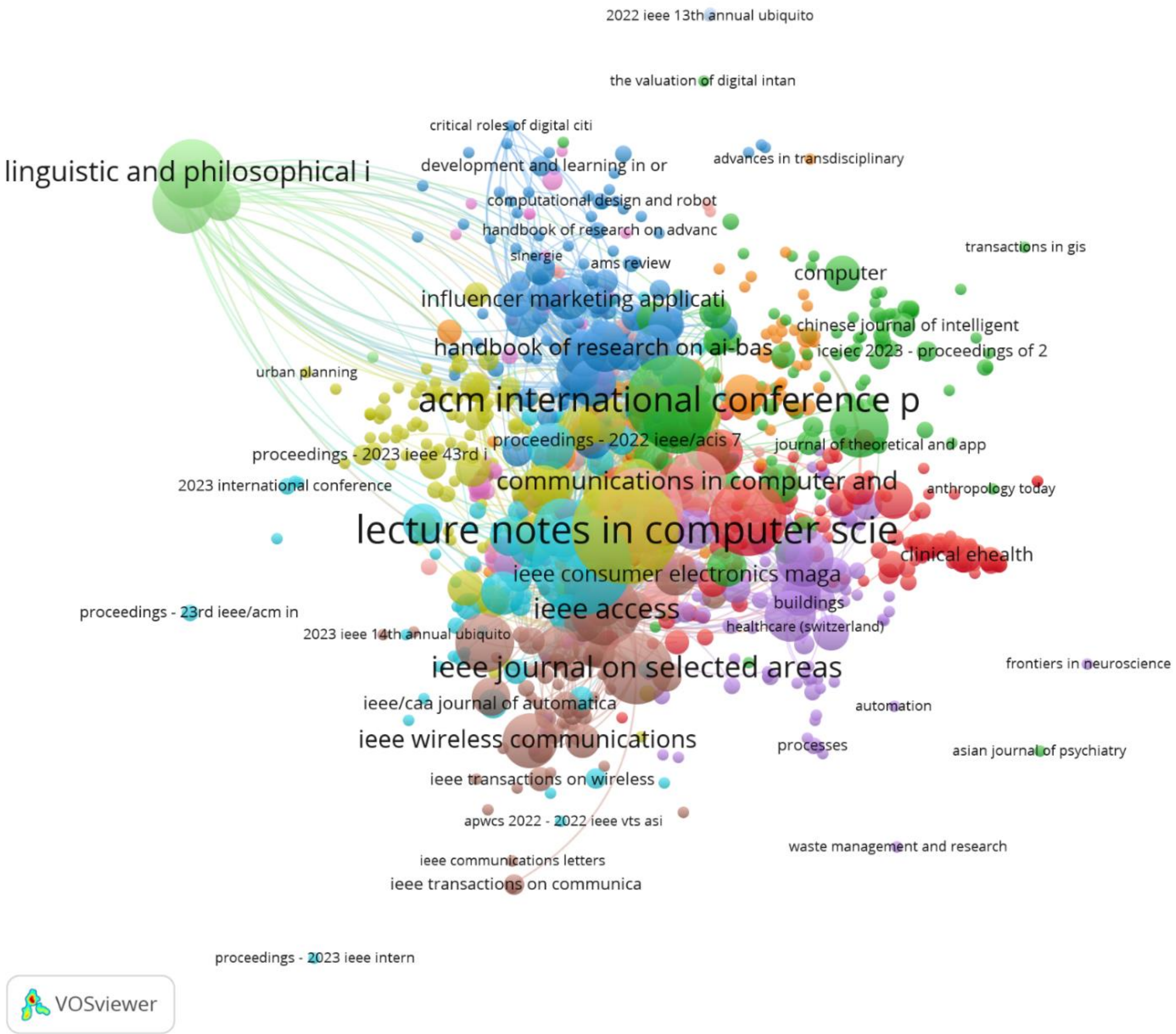


FIGURE 6. BIBLIOGRAPHIC COUPLING OF SOURCES

1) Bibliographic coupling

Figure 5 represents the bibliographic coupling of Metaverse research based on the methodology of [46] Bibliographic coupling categorizes pairs of documents that cite the same third paper to detect research structures and the evolution of interests across time and disciplines. Among the most co-cited works, the paper by [47] stands out as the most influential, followed by the study by [48]. Such analysis pinpoints the most co-cited papers, highlights vital contributions and their connections, and offers researchers a roadmap to understand dominant themes and identify gaps for future exploration.

Figure 6 shows the distribution of sources, where the color of each node reflects the citation relationships within the analysis, with a limit of five citations per document. Based on the model by [40], such an approach highlights the most significant citation networks. 'Lecture Notes in Computer Sciences' series, along with its subseries 'Lecture Notes in Bioinformatics' and 'Lecture Notes in Artificial Intelligence' stand out in the yellow cluster, marking it as a top journal in Metaverse research. Followed by the 'Proceedings of the 2023 IEEE International Conference on Metaverse Computing, Networking, and Applications', placed in the brown cluster, shows sturdy linking with the 'Journal of Communications in Computer and Information Science' in the red cluster, whereas, 'Journal of Studies in Big Data' in the brown-orange cluster. The variation of clusters suggests that this research field attracts the attention of various academic disciplines, which reflects the interdisciplinary nature of Metaverse studies. The connections between these journals show a growing interest in exploring the Metaverse from varied research perspectives.

2) Co-citation

Co-citation analysis involves enabling the characterization of research streams based on the bond of relationships between the documents, recognizing pairs of authors that cite the same source [47]. This study used at least five citations per document and five diverse clusters for the analysis. The green and purple clusters exhibit weaker connections with the red, blue, and light blue clusters. Conversely, the red and blue clusters demonstrate a strong interrelationship, depicted in Figure 7.

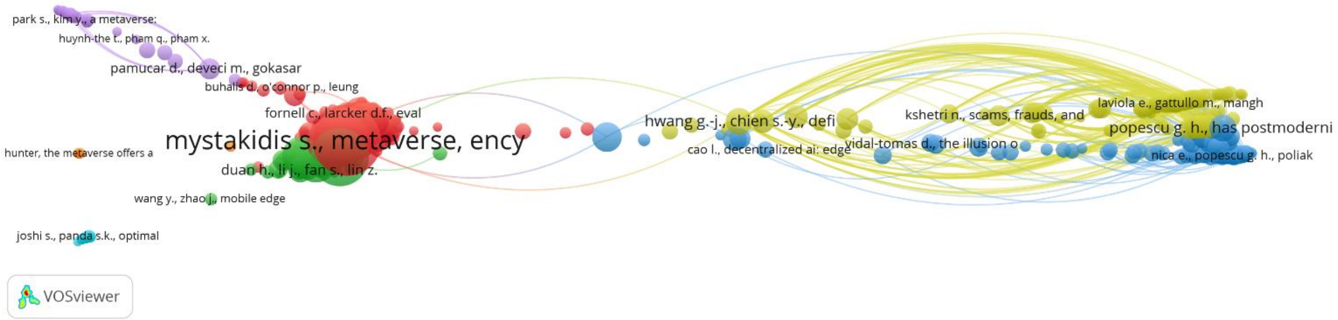


FIGURE 7. CO-CITATION OF REFERENCES

3) Keywords

Keywords can reflect the current trends and research structure of the metaverse. The co-occurrence frequency of keywords is represented by the link strength. The higher the value, the stronger the link. Keyword analysis presents the five occurrences in Figure 8. The analysis of five clusters is identified and reflects our research streams. Metaverse research encapsulates five research fields: Red color represents artificial intelligence, Generative AI, ChatGPT, robotics, medical education, healthcare, telemedicine, personalized medicine, surgical training, and other AI-metaverse applications in medicine. The light green color puts great emphasis on Augmented Reality, mixed reality, virtual community, immersive metaverse technology, innovation, and applications in marketing and education. Blue cluster pertains to the blockchain, 3-D modeling, engineering education, virtual space, arts computing, and higher education. The dark green cluster focuses on deep learning human-centric AI, edge computing, wireless communications, resource allocation and management, games, quality of services and benchmarking. While research in the orange cluster pays attention to the Internet of Things and collaboration. Although the clusters inter-connection can be assessed in the following two ways, the first is cluster overlap and second is the inter-cluster links. The two methods show the relationships and connections between different research themes.

Thematic classification based on the bibliometric mapping identifies some of the mainstream of Metaverse research. The main research streams are presented in Figure 9.

Figure 8 illustrates a two-dimensional matrix, themes are plotted according to their density rank values and centrality. As a result, we can find four kinds of themes:

It is relevant to mention that visualizing thematic clusters has gained awareness in bibliometric analysis. To achieve this end, we employ a thematic evolution map using the software R-studio. The quadrants in Figure 8 are as per the Cobo et al. (2024) classification. The quadrants are as follows:

Lower Right Quadrant (Basic Themes): Themes in the lower-right quadrant are important for research but not yet developed: Metaverse and Blockchain. Although these topics are less developed, they are still in the embryonic stage. According to this group, metaverse and blockchain technologies are considered basic themes to the Metaverse research

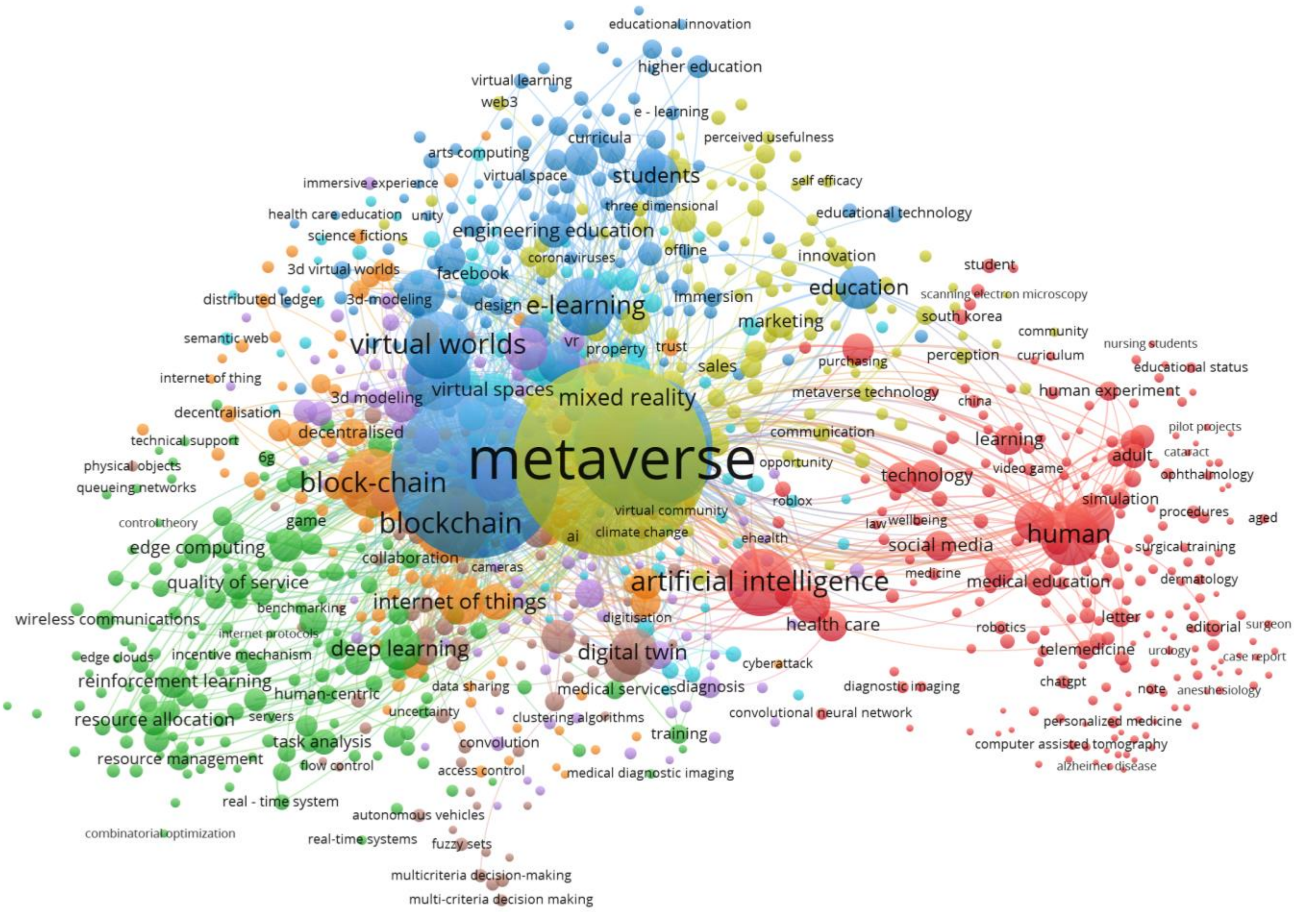


FIGURE 8. CO-OCCURRENCE OF THE KEYWORDS

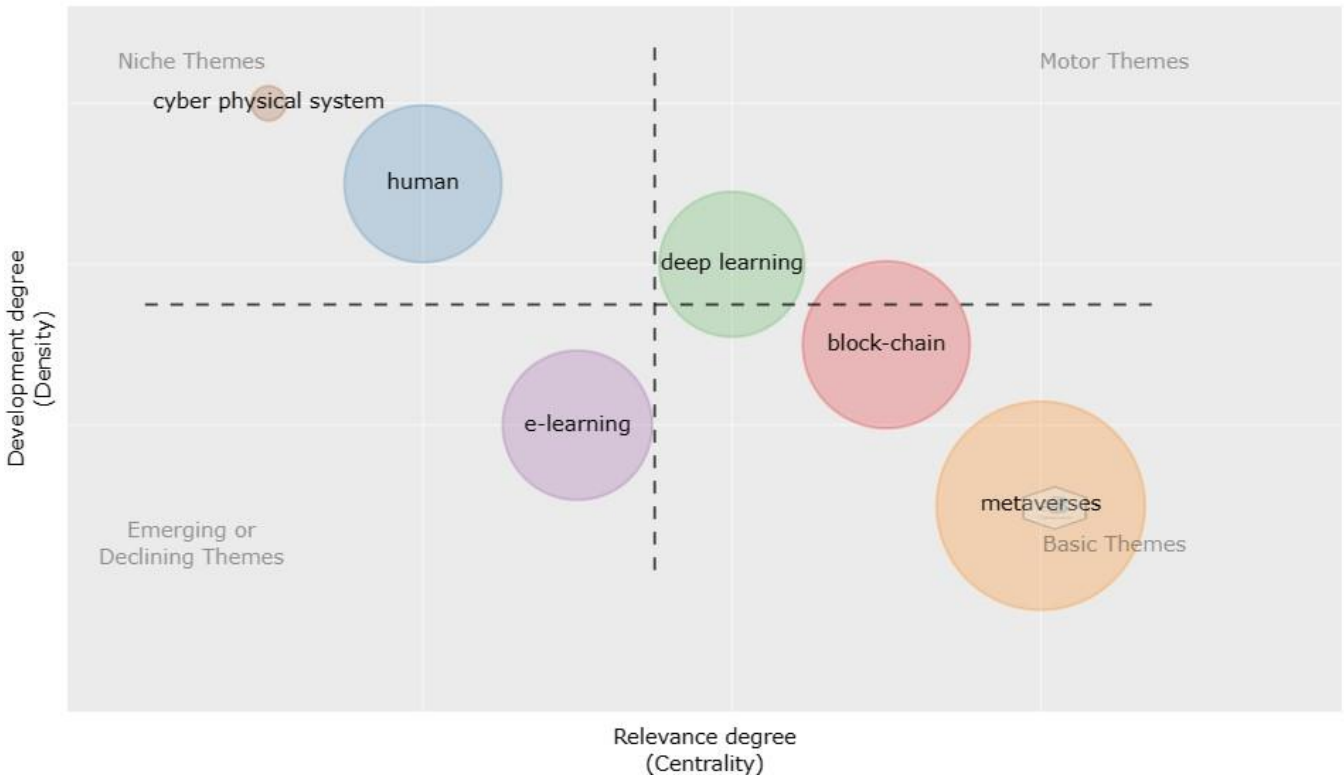


FIGURE 9. THEMATIC EVALUATION

Lower Left Quadrant: Themes in the lower-left quadrant (declining or emerging themes), e-learning, assumes a weak and marginal theme. Namely, e-learning has low centrality and low density, which represents either disappearing or emerging themes in the metaverse domain research.

Upper Right Quadrant: (Motor Themes) Themes in the upper-right quadrant are important and well-developed contributions in the field of the metaverse. Deep learning is an excellent brand of AI and generative AI.

Upper Left Quadrant: (Niche themes) Themes in the upper-left quadrant are cyber-physical systems and have well-developed themes. They reflected highly developed subjects in terms of internal links but unimportant or weak external ties with other fields [49]. Consequently, motor themes, i.e., high centrality and high density and basic themes (low density and high centrality) that represent deep learning blockchain and metaverse reflect red cluster, blue cluster, and dark green cluster in the co-occurrence visualization network. In addition, it can be seen that deep learning and blockchain are relatively accompanied in the middle of the matrix. The most impressive themes and clusters are deep learning, blockchain and metaverse.

V. Future Research Streams

Bibliometric mapping and analysis revealed that the Metaverse has received wide attention in recent years. As an Al-based emerging technology, the Metaverse space offers fully immersive applied paradigms, business models, and innovative products and services. It can provide a creative platform to the needs of entrepreneurs and users. However, based on the current intellectual structure state of the Metaverse literature, the impact of the Metaverse in the realm of business application remains unclear.

There are limited applied and empirical studies of the Metaverse in business and industry, especially in emerging development countries. As Figure (9) shows, the basic themes are Metaverse and Blockchain technology. The catalyst or driver is deep learning, while the niche theme is the interaction between human cyberspace. White e-learning is located in the lower left of the matrix, assumed weak of the Metaverse research. Consequently, their themes identify possible research gaps that must be addressed in the future. Additionally, more applied research is needed in the fields of deep learning, blockchain, FinTech, Metaverse learning, and cyber-human interactions and other emerging fields in the Metaverse economy. The dynamic involvement between users and digital environments can be termed as cyber-human interactions. These cyber-human interactions highlight how immersive technologies, such as the Metaverse, facilitate multi-sensory exchanges and real-time interactions [50-52]. These may integrate virtual avatars, feedback mechanisms, and Augmented Reality to create more seamless transitions between physical and digital realities. It is also possible to describe "Deep Learning and Metaverse" as a method of using advanced neural networks for processing extensive data sets in the Metaverse that give life to intelligent virtual agents, personalized user experiences, and improved decision-making, among others [53-54]. In conclusion, we assume the following Metaverse research stream for the future:

Research stream 1: Metaverse and blockchain

One of the prime benefits of Metaverse in FinTech is its capability to create immersive digital space that supports blockchain technology in various settings, especially its major role in generating augmented simulations with real or extended reality

[55] It has dynamic potential to be an innovative and interactive space for applying blockchain in businesses. Nevertheless, there is still a lack of research in Metaverse blockchain technology even though the Metaverse platforms put to use blockchain and non-fungible tokens [11].

Research Stream 2: Metaverse and deep learning

The artificial intelligence revolution (Al), especially generative Al and deep learning algorithms, is contributing to the enhancement of the Metaverse. The advent of advanced Al tools, techniques and deep learning neural networks facilitates a novel integration between Al and Metaverse [56]. Consequently, future research is necessary to fill these research gaps, especially the generative AI offering novel potential for Metaverse research [57].

Research Stream 3: Cyber-human interactions

Although Metaverse is currently in its early stage, cyber-human interaction has been recognized as one of the important potential research issues. To create a sturdy platform for developing immersive Metaverse space, it is vital to examine the potential impact of the Metaverse technology and elucidate the powerful impact of the current digital technologies on the users. This research attempts to shed light on the pertinent requirements in the Metaverse application and its impact on society [58].

Research Stream 4: Metaverse learning

According to [59], various potential applications of the Metaverse in learning and education are evident. Indeed, Metaverse technology holds the influence and potential to drastically modify the way of E-learning paradigms. The Metaverse technology can offer rich life-like experiences and leverage immersive digital and smart tools in the learning process [60]. Thus, more research is needed that investigates industry 5.0, E-learning paradigms and Metaverse technology [61].

Research in the Metaverse's business considerations, ethics, and AI automation is currently deficient. Integrating blockchain technology with Metaverse economies, particularly in areas of secure, private, and governance-free transactions, needs more work. The application of deep learning technology in enhancing user experiences through AI avatars and behavioral prediction models is still at its infancy. As for cyber-human interaction, the studies should address access, the psychological impacts, and user acclimatization to virtual environments over time. There need to be more psychological, human-computer interaction, and ethics experts in order to design a sustainable, inclusive, and ethical Metaverse environment.

VI. Discussion And Conclusion

The current bibliometric analysis illuminates a burgeoning academic curiosity toward Metaverse technology. The analysis of the Metaverse presented in this research gives invaluable insights into the current research landscape in this innovative field. By analyzing a substantial number of publications from 2000 to 2023 using advanced bibliometric techniques, researchers have been able to map out the key technologies, research streams, and influential contributors within the Metaverse domain. The analysis revealed the interdisciplinary nature of Metaverse technology, encompassing Augmented Reality, Virtual Reality, blockchain, digital twin, internet of things (IoT), and learning systems. This diversity highlights the complexity and interconnectedness of technologies shaping the Metaverse, underscoring the need for collaborative and multidisciplinary research efforts in this area.

In addition, identifying top authors and key publications helps to understand who and what are driving the intellectual trends within Metaverse research, thus providing a sense of direction for knowledge production and critical reflections in the field. The thematic trends of metaverse research depicted four major research themes. Firstly, the basic themes offer foundational knowledge to the field of the Metaverse as an immersive technology and blockchain. Such technologies have generated paths for digital applications in various settings. The current metaverse blockchain applications are split between potential value, new added value and emerging technologies. Blockchain has been identified as one of the fundamental themes and technologies. The blockchain has its distinctive characteristics of transparency, decentralization, and immutability and it is a crucial technology to secure the privacy of users and the Metaverse digital content [59-60]. Thus, the question becomes: How should companies capitalize on the Metaverse technology now and in the near future? How can we prepare our companies to gain strategic advantage? How metaverse technologies shape business models. These questions need rigorous investigation in future research. Moreover, the metaverse blockchain domain reflects emerging value creation of a knowledge-intensive economy. There is a need to examine how blockchain technology leverages new business models in different industries.

The research findings revealed that deep learning is a motor theme that encompasses fields such as AI and Generative AI. It is imperative to examine AI-driven metaverse applications in healthcare, education, marketing, advertising, entertainment, gamification, social media and other dynamic knowledge domains. Further, research should also consider the implications of Generative AI – metaverse interaction. The current research identified two niche themes: cyber-physical systems and humans. These themes represent specialized fields in the metaverse knowledge domain. Building upon topics such as computer-human interaction, cyber-physical technology, privacy, trust, flow state, and digital humanism, the metaverse technology evolves around human-centric AI applications and the ethical and social implications of the responsible metaverse experiences. However, we observed e-learning as an emerging or declining theme (rather declining than emerging). E-learning posits a specific area of transitioning knowledge [61]. Note worthily, the Metaverse paradigm moves to the Generative AI-based immersive technologies, particularly deep learning, blockchain, Augmented Reality, internet of things, internet of everything, edge computing and cognitive computing.

Moreover, the metaverse as a technology relies very heavily on the integration of AI as well as other technologies into one platform, thus enabling people to create fully digital 3D environments that people can use AI for [62]. Since the metaverse consists of virtual worlds outside the physical and real world, AI is fundamental to its functioning as it augments every interaction by using sophisticated algorithms and a variety of collected data [8]. These technologies help the Metaverse provide interactions and simulations of the real world, thus allowing for both virtual and reality to be intertwined effortlessly.

AI algorithms are required to perform complex tasks, which include real-time processing of a 3D environment, enabling personalization, and even simulating intelligent behaviors within avatars and other objects in the digital space [63]. Furthermore, AI also aids in the advanced features that the metaverse possesses, such as natural language processing, machine learning, and a highly complicated and engaging user interaction experience.

In addition, the moral question behind the Metaverse involves fair access, digital inequality, and virtual economies that could be exploited [58]. Properly accounting for these concerns requires an inclusive and equitable framework. Data privacy is a crucial aspect, considering that immersive technologies are designed to gather huge amounts of user information from their behavior and biometric data, hence demanding comprehensive privacy laws and open data control systems. Lastly, beyond just technical functionality, the examination of user experience should be considered in terms of safety, accessibility and psychological health given the addictive and immersive nature of the Metaverse [64].

The alteration demonstrates the significance of creating holistic frameworks that guide Metaverse research beyond the mere technical boundary. While the relevance of deep learning and blockchain is undeniable, their regulation, ethics, and sociocultural aspects still remain largely unexamined. Investigating the adoption of Generative AI in Metaverse systems needs to be done in the context of trust, security, and information abuse. Moreover, the consequences of adopting the Metaverse on the workforce, digital skills, and broader economy are still not well understood. This research needs to include studies that look at the development of Metaverse technology over a significant period of time to be more useful. These considerations can help researchers and policymakers design a Metaverse that is innovative, responsible, and centered on user experience.

The bibliometric analysis of Metaverse research provides an insightful look into its multifaceted impact across various domains. The findings indicate that Metaverse technology, Virtual Reality (VR), integrating Augmented Reality (AR), and other digital innovations are revolutionizing various sectors that include healthcare, education, and entertainment. This research underscores the transformative potential of

Metaverse in creating experiences that are immersive and that enhance user engagement and learning opportunities. The analysis also highlights the burgeoning interest in the application of blockchain within the Metaverse, suggesting a promising future for secure and interactive digital environments. By mapping out these influences, the study not only elucidates the present state of Metaverse research but also discovers key areas for future exploration, promising significant advancements in both theoretical and practical applications.

VII. Implications And Limitations

From an academic point of view, this research presents a comprehensive bibliometric analysis on studies of the Metaverse that contributes to the body of academic literature as well as the business world and gives new insights into a rapidly changing field. Mapping and visualizing the intellectual structure of metaverse research from an academic perspective to determine major themes, key players, and emerging trends. The systematic search helps one understand just how interdisciplinary metaverse technology is since it cuts across domains such as artificial intelligence, Virtual Reality, and blockchain. These findings would build a strong foundation for future researchers who will hence save them in recognizing some of those gaps that need to be filled through further knowledge creation.

For marketing professionals in the business world, this study offers marketers practical applications where they can take advantage of the Metaverse in their marketing campaigns. It identifies game-changing technologies that could transform the way business works, thus giving practical tips on how companies can exploit this technology in creating innovative goods, services, or customer experiences. In addition, mentioning nascent trends like integration with blockchain as well as deep learning application within Metaverse would assist firms in taking up state-of-the-art solutions, thereby reinforcing competitive standing and promoting strategic development. This double influence demonstrates that the paper is a valuable resource that covers the whole spectrum, starting from academia to practitioners intended for using the potential transformational power of the Metaverse. However, similar to any explorative research design, the current research has a few limitations. First, the Scopus database, as the only prominent source for bibliometric analysis, was utilised. Utilizing Scopus and Web of Science ensures more inclusion and diversity. Second, constraints that are in relation to the selected timeframe and the scope of the keywords search may have an impact on the comprehensiveness of the collected data.

Acknowledgement

None.

Funding

This research did not receive any outside funding or support. The authors report no involvement in the research by the sponsor that could have influenced the outcome of this work.

Authors` Contributions

All authors have participated in drafting the manuscript. All authors read and approved the final version of the manuscript.

Conflict Of Interest

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Data Availability

The data supporting the findings of this study are available upon request from the authors.

Ethical Statement

In this article, the principles of scientific research and publication ethics were followed. This study did not involve human or animal subjects and did not require additional ethics committee approval.

Declaration of AI Usage

No AI tools were used in the creation of this manuscript.

References

[1] Lyu, Z., & Fridenfalk, M. (2023). Digital twins for building industrial metaverse. *Journal of Advanced Research, 66,* 31-38. https://doi.org/10.1016/j.jare.2023.11.019

[2] Kumar, A., Saudagar, A. K. J., Alkhathami, M., Alsamani, B., Khan, M. B., Hasanat, M. H. A., ... & Srinivasan, B. (2023). Gamified learning and assessment using ARCS with next-generation AIoMT integrated 3D animation and Virtual Reality simulation. *Electronics, 12*(4), 835.

[3] Wu, P., Chen, D., & Zhang, R. (2024). Topic prevalence and trends of Metaverse in healthcare: A bibliometric analysis. *Data Science and Management, 7*(2), 129-143.

[4] Stephenson, N. (1994). Snow crash. Penguin UK.

[5] Chanda, R. C., Vafaei-Zadeh, A., Hanifah, H., & Ramayah, T. (2023). Investigating factors influencing individual user's intention to adopt cloud computing: a hybrid approach using PLS-SEM and fsQCA. Kybernetes.

[6] Dargan, S., Bansal, S., Kumar, M., Mittal, A., & Kumar, K. (2023). Augmented Reality: A comprehensive review. *Archives of Computational Methods in Engineering, 30*(2), 1057-1080.

[7] Tham, J., Duin, A. H., Gee, L., Ernst, N., Abdelqader, B., & McGrath, M. (2018). Understanding Virtual Reality: Presence, embodiment, and professional practice. *IEEE Transactions on Professional Communication, 61*(2), 178-195.

[8] Uddin, M., Obaidat, M., Manickam, S., Laghari, S. U. A., Dandoush, A., Ullah, H., & Ullah, S. S. (2024). Exploring the convergence of Metaverse, Blockchain, and AI: A comprehensive survey of enabling technologies, applications, challenges, and future directions. *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery, 14*(6), e1556.

[9] Xu, X., Zou, G., Chen, L., & Zhou, T. (2022). Metaverse space ecological scene design based on multimedia digital technology. *Mobile Information Systems*, 2022.

[10] Wang, W. X., Zhou, F., WAN, Y. L., & NING, H. S. (2022). A survey of metaverse technology. *Chinese Journal of Engineering, 44*(4), 744-756.

[11] Casale-Brunet, S., Mattavelli, M., & Chiariglione, L. (2023). Exploring blockchain-based metaverses: Data collection and valuation of virtual lands using machine learning techniques. *Digital Business, 3*(2), 100068.

[12] Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W. M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of business research, 133*, 285-296.

[13] Chaudhuri, R., Chavan, G., Vadalkar, S., Vrontis, D., & Pereira, V. (2021). Two-decade bibliometric overview of publications in the Journal of Knowledge Management. *Journal of Knowledge Management, 25*(6), 1550-1574.

[14] Lu, H. P., Chang, Y. C., & Chen, C. S. (2024). How to trigger user's willingness to participate in the metaverse? An exploration of the significant factors of the metaverse. *Virtual Reality, 28*(2), 1-16.

[15] Arya, V., Sambyal, R., Sharma, A., & Dwivedi, Y. K. (2024). Brands are calling your AVATAR in Metaverse‐A study to explore XR‐based gamification marketing activities & consumer‐based brand equity in virtual world. *Journal of Consumer Behaviour, 23*(2), 556-585.

[16] Ritterbusch, G. D., & Teichmann, M. R. (2023). Defining the metaverse: A systematic literature review. *IEEE Access, 11*, 12368-12377.

[17] Misa, A., Melenciuc, M., Pădurariu, I., & Văduva, C. (2022). Metaverse Engagement Metrics, Workplace Monitoring and Tracking Systems, Behavioral Predictive Analytics in Immersive 3D Virtual Reality Environments. *Psychosociological Issues in Human Resource Management, 10*(2), 103-118.

[18] Kim, D. Y., Lee, H. K., & Chung, K. (2023). Avatar-mediated experience in the metaverse: The impact of avatar realism on user-avatar relationship. *Journal of Retailing and Consumer Services, 73*, 103382.

[19] Yang, H., Cho, Y. and Han, S.-Y. (2024), "Understanding user perceptions toward marketing in the metaverse", *Kybernetes*, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/K-08-2023-1524

[20] Fernández-Ruano, M. L., Frías-Jamilena, D. M., Polo-Peña, A. I., & Peco-Torres, F. (2022). The use of gamification in environmental interpretation and its effect on customer-based destination brand equity: the moderating role of psychological distance. *Journal of Destination Marketing & Management, 23*, 100677.

[21] Kim, J. (2021). Advertising in the metaverse: Research agenda. Journal of Interactive Advertising, 21(3), 141-144.

[22] Singh, S., Singh, G., & Dhir, S. (2024). Impact of digital marketing on the competitiveness of the restaurant industry. *Journal of Foodservice Business Research, 27*(2), 109-137.

[23] Jasen, S. (2022). Applicability of CAD/CAM Technology in Orthodontics. *Digital Economy, Business Analytics, and Big Data Analytics Applications*, 69-76.

[24] SS. F. Eletter, G. A. Elrefae, S. G. Yaseen and A. R. Alshehadeh, "Using Monte Carlo Simulation for Real Estate Price Valuation," 2024 25th International Arab Conference on Information Technology (ACIT), Zarqa, Jordan, 2024, pp. 1-4, doi: 10.1109/ACIT62805.2024.10876955.

[25] Alhalaybeh, A., & Althunibat, A. (2023, August). Measuring Acceptance of Adoption Metaverse in eLearning by Using TAM Model. In 2023 International Conference on Information Technology (ICIT) (pp. 361-366). IEEE.

[26] Yao, X., Ma, N., Zhang, J., Wang, K., Yang, E., & Faccio, M. (2024). Enhancing wisdom manufacturing as industrial metaverse for industry and society 5.0. *Journal of Intelligent Manufacturing, 35*(1), 235-255.

[27] Buhalis, D., Leung, D., & Lin, M. (2023). Metaverse as a disruptive technology revolutionising tourism management and marketing. Tourism Management, 97, 104724.

[28] Kraus, S., Kanbach, D. K., Krysta, P. M., Steinhoff, M. M., & Tomini, N. (2022). Facebook and the creation of the metaverse: radical business model innovation or incremental transformation?. *International Journal of Entrepreneurial Behavior & Research, 28*(9), 52-77.

[29] Zhang, X., Clarke, C. L., & Rhynas, S. J. (2020). A thematic analysis of Chinese people with dementia and family caregivers' experiences of home care in China. *Dementia, 19*(8), 2821-2835.

[30] Zhang, L., Anjum, M. A., & Wang, Y. (2024). The impact of trust-building mechanisms on purchase intention towards metaverse shopping: the moderating role of age. *International Journal of Human–Computer Interaction, 40*(12), 3185-3203.

[31] Wedel, M., Bigné, E., & Zhang, J. (2020). Virtual and Augmented Reality: Advancing research in consumer marketing. International *Journal of Research in Marketing, 37*(3), 443-465.

[32] Pernice, I. G., & Scott, B. (2021). Cryptocurrency. *Internet policy review, 10*(2).

[33] Malik, N., Appel, G., & Luo, L. (2023). Blockchain technology for creative industries: Current state and research opportunities. International *Journal of Research in Marketing, 40*(1), 38-48.

[34] Sharma, M., Luthra, S., Joshi, S., & Kumar, A. (2022). Developing a framework for enhancing survivability of sustainable supply chains during and post-COVID-19 pandemic. *International Journal of Logistics Research and Applications, 25*(4-5), 433-453.

[35] Lee, C. T., Ho, T. Y., & Xie, H. H. (2023). Building brand engagement in metaverse commerce: The role of branded non-fungible tokens (BNFTs). *Electronic Commerce Research and Applications, 58*, 101248.

[36] Dwivedi, Y. K., Hughes, L., Baabdullah, A. M., Ribeiro-Navarrete, S., Giannakis, M., Al-Debei, M. M., ... & Wamba, S. F. (2022). Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. International *Journal of Information Management, 66*, 102542.

[37] Flavián, C., Ibáñez-Sánchez, S., Orús, C., & Barta, S. (2024). The dark side of the metaverse: The role of gamification in event virtualization. *International Journal of Information Management, 75*, 102726.

[38] van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics, 84*(2), 523–538. https://doi.org/10.1007/s11192-009-0146-3.

[39] Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & PRISMA Group*, T. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Annals of internal medicine, 151*(4), 264-269.

[40] Paltrinieri, A., Hassan, M. K., Bahoo, S., & Khan, A. (2023). A bibliometric review of sukuk literature. *International Review of Economics & Finance, 86*, 897-918.

[41] Jaradat, Y., Alia, M., Masoud, M., Manasrah, A., Jebreil, I., Garaibeh, A., & Al-Arasi, S. (2022). A bibliometric analysis of the International Journal of Advances in Soft Computing and its Applications: Research influence and Contributions. *International Journal of Advances in Soft Computing & Its Applications, 14*(2), 186-184. http://dx.doi.org/10.15849/IJASCA.220720.12

[42] Alsmadi, A. A., Al-Gasaymeh, A., & Alrawashdeh, N. (2022). Purchasing Power Parity: A Bibliometric approach for the period of 1935-2021. *Calitatea, 23*(189), 260-269.

[43] Alrawashdeh, N., Alsmadi, A. A., & Al-Gasaymeh, A. (2022). FinTech: a bibliometric analysis for the period of 2014-2021. *Calitatea, 23*(188), 176-188.

[44] Alnajem, M., Mostafa, M. M., & ElMelegy, A. R. (2021). Mapping the first decade of circular economy research: a bibliometric network analysis. *Journal of Industrial and Production Engineering, 38*(1), 29-50.

[45] Gan, Y. N., Li, D. D., Robinson, N., & Liu, J. P. (2022). Practical guidance on bibliometric analysis and mapping knowledge domains methodology–A summary. *European Journal of Integrative Medicine, 56*, 102203.

[46] Boyack, K. W., & Klavans, R. (2010). Co‐citation analysis, bibliographic coupling, and direct citation: Which citation approach represents the research front most accurately?. *Journal of the American Society for information Science and Technology, 61*(12), 2389-2404.

[47] Shiau, W. L., Dwivedi, Y. K., & Yang, H. S. (2017). Co-citation and cluster analyses of extant literature on social networks. International *Journal of Information Management, 37*(5), 390-399.

[48] Park, S., & Kim, S. (2022). Identifying world types to deliver gameful experiences for sustainable learning in the Metaverse. *Sustainability, 14*(3), 1361.

[49] Zhang, X., Gao, Z., Wang, Y., Zhang, X., & Wang, Y. Exploring the Impact of Gamification in Immersive Virtual Exhibitions: From User Experience Perspective. Available at SSRN 4681231. https://dx.doi.org/10.2139/ssrn.4681231

[50] Fadhel, M. A., Duhaim, A. M., Albahri, A. S., Al-Qaysi, Z. T., Aktham, M. A., Chyad, M. A., ... & Gu, Y. (2024). Navigating the metaverse: unraveling the impact of artificial intelligence—a comprehensive review and gap analysis. *Artificial Intelligence Review, 57*(10), 264.

[51] Jaradat, Y. M., Zerek, A. R., Masoud, M. Z., Manasrah, A. A., Abdaljlil, S. A., & Alheyasat, O. (2023, May). Analysis of the scientific publication of Libyan State: A bibliometric review. In 2023 IEEE 3rd International Maghreb Meeting of the Conference on Sciences and Techniques of Automatic Control and Computer Engineering (MI-STA) (pp. 382-386). IEEE.

[52] Chodakowska, E., Nazarko, J., Nazarko, Ł., & Rabayah, H. S. (2024). Solar Radiation Forecasting: A Systematic Meta-Review of Current Methods and Emerging Trends. *Energies, 17*(13), 3156.

[53] Himangi, P., & Singla, M. (2022). Investigating Role of Deep Learning in Metaverse. *International Journal of New Practices in Management and Engineering, 11*(01), 53-60.

[54] Alkasasbeh, H., Oudat, M.S., Abu-AlSondos, I. and Alhawamdeh, L. (2024), "Metaverse finance: shaping the future of Islamic fintech solutions in UAE", Journal of Islamic Marketing, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/JIMA-01-2024-0039.

[55] Kaur, N., Saha, S., Agarwal, V., & Gulati, S. (2023, February). Metaverse and fintech: Pathway for innovation and development. In 2023 3rd International Conference on Innovative Practices in Technology and Management (ICIPTM) (pp. 1-6). IEEE.

[56] Alhalaybeh, A., Alkhatib, A. A., Albustanji, R. N., Elmanaseer, S., Kanan, T., & Alsakarnah, R. (2023, August). Facilitating Metaverse Integration in Education via Extended Reality and the Internet of Things: AN OVERVIEW. In 2023 International Conference on Information Technology (ICIT) (pp. 38-42). IEEE.

[57] Alotaibi, O. (2024). Role of Artificial Intelligence in Enhancing Metaverse Gaming Experience and Human Interaction. *International Journal of Metaverse, 2*(1), 11-19.

[58] Benjamins, R., Rubio Viñuela, Y., & Alonso, C. (2023). Social and ethical challenges of the metaverse: Opening the debate. AI and Ethics, 3(3), 689-697.

[59] Aiolfi, S., & Luceri, B. (2024). See you on the Metaverse: A bibliometric expedition through the Metaverse landscape. Technological Forecasting and Social Change, 207, 123605.

[60] Gadekallu, T. R., Huynh-The, T., Wang, W., Yenduri, G., Ranaweera, P., Pham, Q. V., ... & Liyanage, M. (2022). Blockchain for the metaverse: A review. arXiv preprint arXiv:2203.09738.

[61] Lim, W. M., Kumar, S., & Donthu, N. (2024). How to combine and clean bibliometric data and use bibliometric tools synergistically: Guidelines using metaverse research. *Journal of Business Research, 182*, 114760.

[62] Huynh-The, T., Pham, Q. V., Pham, X. Q., Nguyen, T. T., Han, Z., & Kim, D. S. (2023). Artificial intelligence for the metaverse: A survey. *Engineering Applications of Artificial Intelligence, 117*, 105581.

[63] Soliman, M. M., Ahmed, E., Darwish, A., & Hassanien, A. E. (2024). Artificial intelligence powered Metaverse: analysis, challenges and future perspectives. *Artificial Intelligence Review, 57*(2), 36.

[64] Han, D. I. D., Bergs, Y., & Moorhouse, N. (2022). Virtual Reality consumer experience escapes: preparing for the metaverse. *Virtual Reality, 26*(4), 1443-1458.

Journal of Metaverse
Research Article
Received: 2024-09-09 | **Reviewing:** 2024-09-24 & 2025-03-08 | **Accepted:** 2025-03-10 | **Online:** 2025-03-12 | **Issue Date:** 2025-06-30
Year:2025, **Volume:**5, **Issue:**1, **Pages:**51-63, **Doi:** 10.57019/jmv.1546324

Shaping Virtual Retail: Identifying Key Influences in Metaverse Shopping with Fuzzy DEMATEL

Lekhika SHARMA
Department of Business Administration
National Institute of Technology
Kurukshetra, India
62210027@nitkkr.ac.in
0009-0008-3165-461X
(Corresponding Author)

Neeraj KAUSHIK
Department of Business Administration
National Institute of Technology
Kurukshetra, India
kaushik.neeraj@nitkkr.ac.in
0000-0003-2651-3448

***Abstract*—The Metaverse is significantly transforming e-commerce by providing immersive and interactive virtual shopping environments. This study explores the qualitative aspects and user interactions that shape customer experiences on Metaverse platforms. The research uses the Fuzzy DEMATEL (FDEMATEL) technique to identify and prioritize 11 key factors influencing digital shopping experiences, derived from literature and expert opinions. The FDEMATEL approach effectively examines causal relationships among these factors, reducing the bias associated with imprecise human judgments. The study reveals that flow, immersion, and ease of use are prominent factors, while informativeness, media richness, and risk are critical cause factors for successful retail platforms. These findings offer valuable insights for managers and platform developers to enhance Metaverse shopping experiences. The study uniquely identifies and analyzes the causal relationships of critical success factors, providing a comprehensive understanding that can drive the success of Metaverse retail environments.**

Keywords—Metaverse Shopping, MCDM, Fuzzy DEMATEL, Retail platform

I. INTRODUCTION

The metaverse represents a significant leap in the digital revolution and offers a persistent, immersive, and interactive future version of the Internet [1-3]. Metaverse platforms like Roblox Sandbox, decentraland, Zepeto, and Upland provide users with rich, engaging experiences that mirror real-world interactions and activities, seamlessly blending the virtual and physical realms. [4-6]. Among its most promising applications, Metaverse shopping is revolutionizing e-commerce, allowing consumers to purchase products for both their virtual avatars and real-world use, thereby offering a highly engaging and immersive retail experience [7-9].

This transformation has driven substantial market growth. By 2030, the Metaverse economy is projected to reach $936.57 billion, with the global Metaverse e-commerce market expected to expand by 37.91% to $210.3 billion [10, 11]. Major technology companies such as Meta, Microsoft, and Google, as well as various brands, from fashion giants such as Adidas, Gucci, Hermes, Nike, and Vans to other industry leaders such as Hyundai, Samsung, and Sunsilk, are actively investing in metaverse commerce, launching virtual storefronts and digital assets and digital assets to enhance customer engagement [12-14]. For instance, Vans, and Adidas launched their virtual retail space where users can explore and purchase digital fashion items (Figures I and II).

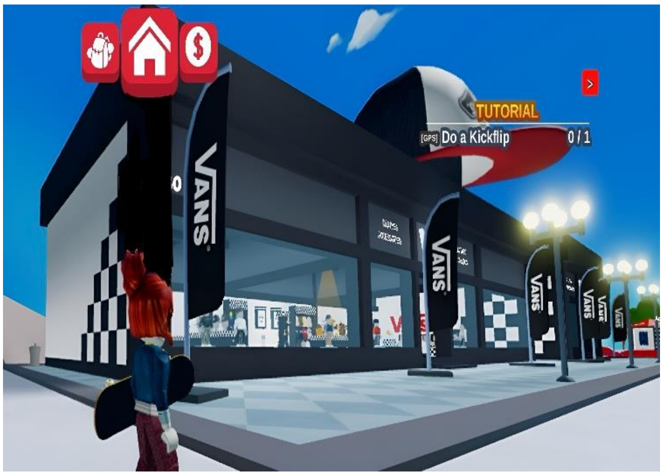


FIGURE I. VANS STORE IN THE METAVERSE [19]

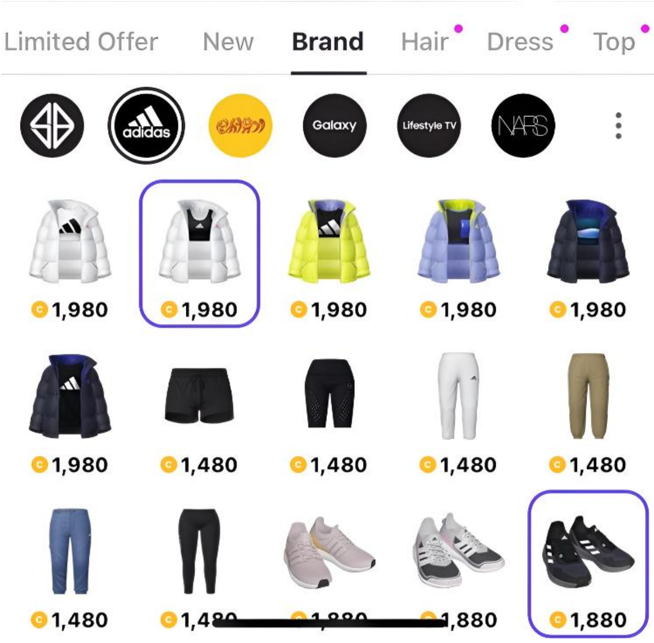


FIGURE II. VIRTUALLY WEARABLE PRODUCTS IN THE METAVERSE [20]

In addition, research suggests that consumer interest in buying goods related to Metaverse is increasing, with physical clothing being the most sought-after product category [15].

Cite (APA): Sharma, L., Kaushik, N. (2025). Shaping Virtual Retail: Identifying Key Influences in Metaverse Shopping with Fuzzy DEMATEL. *Journal of Metaverse*. *5*(1), 51-63. **Doi:** 10.57019/jmv.1546324

Despite these advancements, understanding the key factors influencing Metaverse shopping experiences remains a critical challenge due to the complex and interdependent nature of technological, behavioral, and experiential factors. Existing studies primarily focus on specific theoretical models such as technology adoption and consumer behavior frameworks, often from a customer-centric perspective [16-18].

Although these studies provide valuable insights, they lack a holistic approach that takes into account the interwoven relationships between multiple influencing factors. There is therefore an urgent need for a comprehensive method that not only identifies key determinants but also uncovers their cause-and-effect relationships and provides deeper insights into consumer behavior in this evolving environment. To address this gap, this study applies the Fuzzy Decision-Making Trial and Evaluation Laboratory (FDEMATEL), a method specifically designed to analyze interdependencies, identify causal relationships, and manage uncertainty in expert evaluations. Metaverse shopping involves multiple interacting factors, making it essential to prioritize key influences while understanding how they affect one another [21].

Although, DEMATEL has been widely applied across various business domains [22-25] and in contexts such as the automobile industries [26], climate issues [27], and marine machinery system [28]. Its application within the Metaverse context remains largely unexplored [29]. Moreover, recent studies have applied innovative decision-making approaches such as the spherical fuzzy decision-making method to prioritize sustainable business investments in the Metaverse [30]. However, these approaches have yet to receive adequate attention in metaverse shopping experiences.

To fill in these gaps, the study aims to address the following research questions are addressed in this study:

- What are the key factors driving the success of Metaverse shopping platforms?
- How do these factors interact with each other regarding cause-and-effect relationships?
- Which factors should be prioritized to enhance and improve the overall shopping experience in the Metaverse?

This study adds to the body of knowledge already available in the field and offers useful advice to developers and companies who want to improve customer adoption and engagement in the metaverse retail setting. The findings present significant theoretical and practical implications. Theoretically, it underscores the need to refine existing frameworks by incorporating context-specific variables related to the metaverse. Practically, it offers valuable guidelines for metaverse developers and content creators, enabling them to improve their offerings effectively.

II. LITERATURE REVIEW

This section examines the metaverse concept and how it affects shopping and retail. It investigates the influential factors in the context of successful online shopping experiences on metaverse platforms.

A. *Metaverse and Shopping*

The emergence of the metaverse, a synthesis of virtual, augmented, and physical realities, has profoundly transformed how we approach shopping and commerce [17]. It is anticipated that the metaverse will drastically alter how customers engage with the digital world and alter the retail industry. Customers will be able to move through immersive virtual environments and engage with other avatars, such as those of other customers and store employees, while frequently utilizing digital avatars of themselves [8,31-32]. Like e-commerce, retailers who are successful in creating a metaverse presence can reach a wider audience by enabling customers from far-off places to visit [33]. Thus, it is anticipated that the metaverse market will grow to a value of $800 billion by 2024, prompting retailers to contemplate how they can modify their business plans to remain competitive in the "virtual" retail space. As early adopters of this new retail landscape, some trailblazing stores have already started working with metaverse developers to create highly immersive and captivating shopping experiences that conflate the real and virtual worlds [14, 34-35].

The integration of the metaverse into the retail landscape offers numerous opportunities, but it also presents a complex array of challenges. Retailers need to maneuver through this complex terrain, balancing the potential benefits against the inherent uncertainties of this technological frontier [7, 36]. Understanding the factors that influence successful shopping experiences on metaverse platforms is crucial for effective integration. Consequently, it is crucial to identify these factors. The following factors have been found to contribute to positive metaverse platform shopping experiences.

B. *Factors Influencing Shopping on Metaverse Platforms*

After reviewing the literature on Metaverse shopping experiences, initially, a total of 20 variables were identified. These factors were then validated through expert opinion. Later, 9 variables were found to be redundant or encompassed by others, such as security, fraud being covered under the broader factor of risk, and aspects of fun and joy falling under enjoyment. As a result, a final set of 11 factors was selected for further analysis and exploration. The complete list of final factors has been provided in Table I.

- Ease of use (EU): According to [37], the attitude and behavioral intention towards using a specific technology are determined by two factors: perceived ease of use and perceived usefulness. EU implies that technology is more likely to be accepted when users perceive it as easy to use. In the context of the metaverse, many researchers have demonstrated the positive impact of ease of use on the acceptance of this platform across various fields, including education [38-39], healthcare [40], human resources [41], and banking [42]. A study by [43] showed that shopping on metaverse platforms can provide an experience comparable to or even better than traditional shopping. Specifically, by focusing on EU i.e. user-centered design principles like intuitive navigation, clear instructions, and seamless integration of augmented and virtual reality features, one can enhance user satisfaction and drive adoption of your platform.

- Enjoyment (EN): EN enhances users' experiences by providing positive interactions within the platform that lead to a sense of self-fulfillment [44]. Fun or enjoyment serves as intrinsic drivers of platform usage, contributing to users' internal motivations and desires to interact with the platform. These hedonic elements go beyond practical usefulness, enhancing user experiences and encouraging more in-depth interaction with the system. Past studies have indicated metaverse retailing as an evolution of traditional online channels, emphasizing heightened elements of EN [45]. The hedonic gratification strongly influences young consumers to explore the metaverse for shopping [46]. [9] similarly observed that EN positively influences consumer adoption of metaverse shopping platforms.
- Social Influence (SI): According to Social Influence Theory, SI emphasizes the impact of others' opinions and behaviors on an individual’s actions [47]. In the metaverse, social influence can affect users' decisions to shop based on recommendations, reviews, and social presence [48]. SI is not limited to instances where consumers actively interact with others but also in passive scenarios where other people are present physically but don't engage with the main consumer [32]. A study by [49] depicts SI has a positive impact on how useful people perceive the metaverse platform to be. Furthermore, satisfaction, usage intention, purchase intention, and word-of-mouth intention were all markedly elevated by SI of the metaverse platform [50].
- Informativeness (INF): Providing precise and thorough product information in the metaverse can improve user satisfaction and shopping decision-making [51]. The incorporation of INF within metaverse platforms significantly enhances customer experiences and contributes to their sustained usage over time [52-53]. In a study, [54] discovered that the metaverse attribute of informativeness has a major impact on the flow experience on the platforms, encouraging users to visit the destination physically and demonstrating the fundamentals of INF.
- Media Richness (MR): MR posits that communication effectiveness is enhanced by the richness of the media used [55]. In metaverse shopping, rich media (e.g., 3D product views, and virtual try-ons) can improve user engagement and satisfaction. Previous research has highlighted the positive impact of MR on ease of use and participation intention in the metaverse [56], while also indicating that MR in tourism content, particularly through virtual reality in the metaverse, significantly increases perceived usefulness and enjoyment [57]. In terms of retail, the richness of media in the metaverse cultivates cognitive and affective trust, subsequently shaping purchase intention toward metaverse shopping [58].
- Risk (RK): Perceived risks (RK) in online transactions (e.g., privacy, security, financial) can deter users [2, 9]. Past studies suggest that the RK negatively impacts the intention to shop on the platform [59], diminishing decision confidence and overall satisfaction with the shopping experience [60]. In terms of luxury shopping in the metaverse, reducing perceived risk improves results, as brands must effectively convey their aesthetics and ensure high-quality experiences [61-62].
- Technological Anxiety (TA): TA addresses users' apprehension or fear of using computers and technology [9]. High levels of technological anxiety can negatively impact users' willingness to shop in the metaverse, making it crucial to design user-friendly and supportive interfaces. Previous research indicates that TAs make consumers less likely to want to switch to metaverse platforms [63]. Hence, TA negatively influences consumers’ use of the metaverse platform [64].
- Immersion (IM): IM is one of the distinct features of the metaverse shopping platform. High levels of immersion in the metaverse can create a sense of presence, making the shopping experience more realistic and engaging [8]. Previous research has indicated that IM has a positive effect on the intention to use metaverse retail in a variety of sectors including banking [65], education [1] and commerce [66-67]. IM enhances the metaverse platform's shopping experiences positively [9].
- Flow (FL): Flow is a psychological state, where a person becomes fully absorbed and engaged in an activity, experiencing a sense of enjoyment, and focus [68]. Here, it refers to total absorption in the shopping process, which results in a smooth and pleasurable metaverse shopping experience [69]. In past literature, flow and immersion have been used interchangeably but both are different. Flow involves deep engagement and enjoyment in an activity, while immersion pertains to feeling enveloped by sensory experiences within a virtual environment [69]. The flow has a significant influence on consumers’ intention to purchase on the Metaverse platforms [4-70].
- Avatar's Self-Congruence (ASC): Self-Congruity Theory proposes that consumers prefer products that are congruent with their self-image [71]. In the metaverse, avatars that accurately represent users’ identities can enhance satisfaction and engagement [72]. Recent research also demonstrates that ASC has a positive impact on consumers' intentions to make purchases when using virtual marketplaces [73, 4].
- Synchronicity (SY): Media Synchronicity Theory proposed by [74], suggests that communication processes that are synchronous (real-time) can improve coordination and understanding. Synchronous interactions during metaverse shopping have a positive effect on customers' perceptions of brand trust, brand knowledge, and brand attachment [5]. These factors then influence the customers' active engagement with the brand and their propensity to purchase the product [31].

TABLE I. FACTORS AND THEIR REFERENCES

S.No	Factor	Definition	References
1	Ease of Use (EU)	The degree to which a user finds the metaverse shopping platform easy to navigate and use, including the intuitiveness of its interface and the simplicity of shopping tasks.	[75-76, 43]
2	Enjoyment (EN)	The extent to which users derive pleasure and satisfaction from their shopping experiences in the metaverse influences their engagement and likelihood of repeat visits.	[46, 9]
3	Social Influence (SI)	The impact of peer opinions, social networks, and community interactions on a user's shopping behavior and decisions within the metaverse environment.	[32, 50, 47, 77]
4	Informativeness (INF)	The quality, relevance, and comprehensiveness of the information provided about products and services within the metaverse, helping users make informed purchasing decisions.	[51-52, 54]
5	Media Richness (MR)	The degree to which the metaverse platform provides engaging and sensory-rich multimedia content, such as high-quality images, videos, and interactive elements.	[55, 58]
6	Risk (RK)	The perceived security and privacy concerns associated with shopping in the metaverse, including fears of data breaches, fraud, and the safety of personal information.	[61 -62, 78]
7	Technological Anxiety (TA)	The level of discomfort or apprehension users feel when interacting with new or complex technological features in the metaverse shopping platform.	[63, 9]
8	Immersion (IM)	The extent to which users feel absorbed and present in the virtual shopping environment, leads to a more engaging and realistic experience.	[79-80, 8]
9	Flow (FL)	The seamlessness and continuity of the user experience while shopping in the metaverse, are characterized by an effortless progression through different shopping activities.	[68-69, 81]
10	Avatar's Self-Congruence (ASC)	The alignment and representation of a user's real identity through their virtual avatar, contribute to a more personalized and relatable shopping experience.	[4, 72]
11	Synchronicity (SY)	The real-time responsiveness and interaction capabilities of the metaverse platform, allow for instant communication, updates, and feedback during the shopping experience.	[5,74]

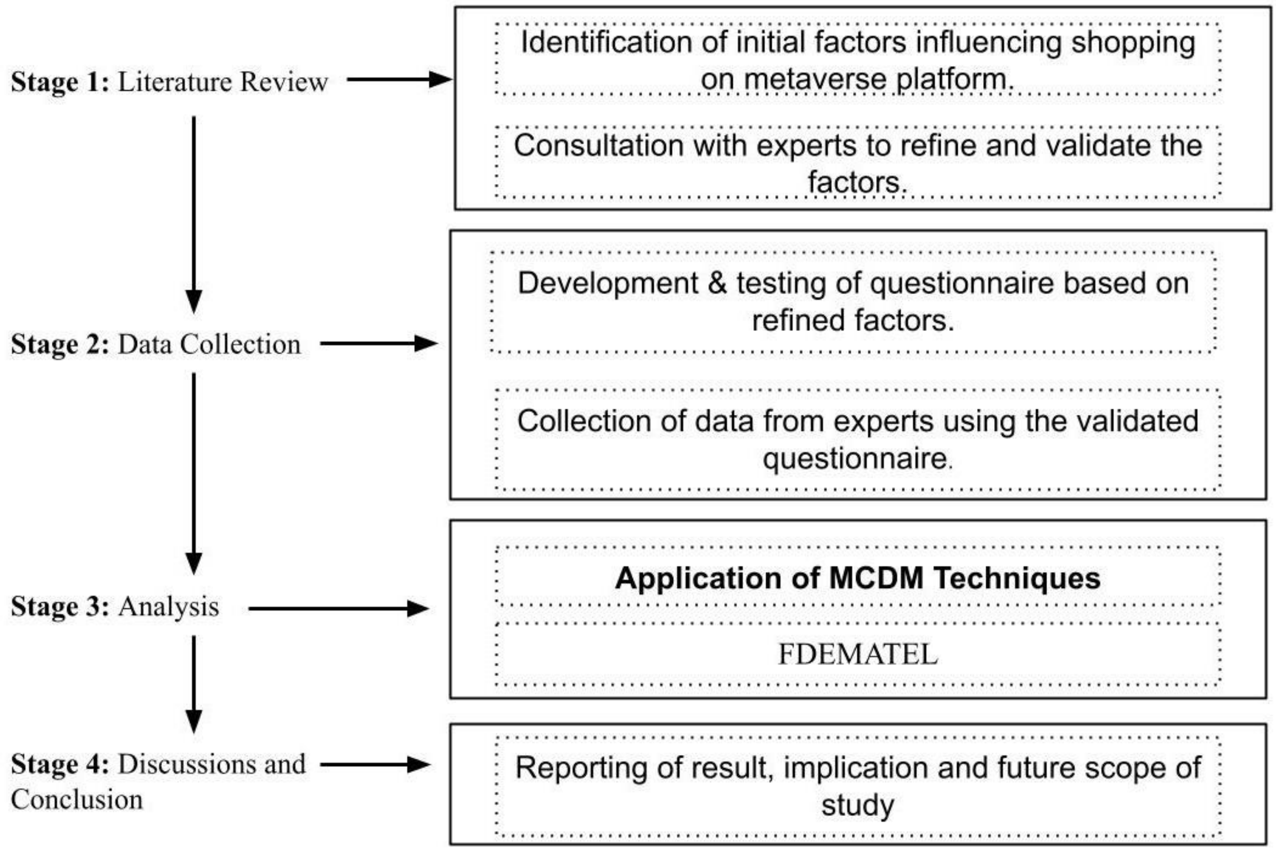


FIGURE III. APPLIED RESEARCH FRAMEWORK FOR THIS STUDY

III. RESEARCH METHODOLOGY

After finalizing the factors in section two factors linked to successful metaverse shopping experiences. However, it remains challenging to determine the importance and causal relationships among these factors. There is a lack of empirical evidence to comprehend the crucial factors. To address this, the FDEMATEL method is employed to provide a systematic and quantitative examination of the influencing factors. This section also discusses the expert data collection process and related methodologies used to identify and evaluate these factors. There are four steps involved in the entire analysis (See Figure III).

A. The Fuzzy DEMATEL Method

The Decision-Making Trial and Evaluation Laboratory (DEMATEL) method is a powerful analytical tool designed to analyze complex problems with intricate interrelationships [21]. DEMATEL is based on graph theory and matrix tools and uses expert knowledge to visually represent causal relationships between various factors, which makes it particularly valuable for structured decisions [23,24]. Despite its strengths, the traditional DEMATEL is based on clear numerical values and is therefore less effective in dealing with uncertainties when expert opinions are subjective. To address this, fuzzy logic is integrated into DEMATEL to accommodate imprecise expert judgments, improving the reliability of causal analysis [22, 23]

While various MCDM methods exist, not all are suitable for analyzing interdependent factors in Metaverse shopping. The Analytic Hierarchy Process (AHP) assumes independent criteria, limiting its applicability [82]. Although the Analytic Network Process (ANP) takes dependencies into account, it remains computationally complex and does not explicitly represent causal effects [83]. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) focuses on ranking alternatives but does not assess how factors influence each other, which limits their suitability for cause-and-effect analyses [84]. Similarly, interpretive structure modeling (ISM) identifies relationships between variables but does not quantify the strength of influence between them. In contrast, Fuzzy DEMATEL captures both the direction and intensity of causal effects and thus enables a deeper understanding of factor interactions [85].

Given these limitations, Fuzzy DEMATEL is the most suitable approach as it provides a structured evaluation of critical Metaverse shopping determinants. By incorporating fuzzy linguistic scales, it enhances the accuracy of causal diagrams and prioritization of influential factors, making it particularly effective for understanding the complex interplay of technology, user experience, and social influence in Metaverse shopping.

Step 1: Selecting the Team of Experts and the Fuzzy Linguistic Scale

To address the fuzziness in expert evaluations, the experts selected for the study came from academia, industry, and experienced users of metaverse platforms. The detailed list of experts is provided in Table II. The sample size was determined based on previous research, which suggests that a group of 10-15 experts is sufficient to obtain reliable results and achieve saturation in a homogeneous sample, particularly for the DEMATEL method [86]. This approach is in line with studies by [87] and [88], in which expert assessments were carried out with twelve and ten respondents, respectively. Given that similar studies have successfully used sample sizes within this range, a group of fifteen experts was considered adequate to ensure rigorous and reliable findings.

TABLE II. DEMOGRAPHIC PROFILE OF EXPERTS

Demographics	Category	Sample Size (N=15)	Percentage
Gender	Male	9	60
	Female	6	40
Age	21-30	3	20
	31-40	5	33
	41-50	5	33
	Above 50	2	14
Field	**Academia:**	11	73
	Retail	5	
	Immersive technologies	6	
	Industry:	4	27
	Retail	2	
	Immersive technologies	2	
Total Experience	Less than 5 years	4	27
	5-10 years	5	33
	Above 10 years	6	40

Each expert provided qualitative input on various factors influencing the adoption of metaverse shopping platforms. Their judgments regarding the mutual impact of identified factors were collected using a pairwise comparison matrix and linguistic variables. A five-point fuzzy linguistic scale was employed to enable experts to assess the interrelationships among the factors (Table III).

TABLE III. FUZZY LINGUISTIC SCALE ADOPTED FROM [21]

Linguistic Variable	Influence Score	Corresponding Triangular Fuzzy Numbers (TFNs)
No influence	0	(0, 0.1, 0.3)
Very low influence	1	(0.1, 0.3, 0.5)
Low influence	2	(0.3, 0.5, 0.7)
High influence	3	(0.5, 0.7, 0.9)
Very high influence	4	(0.7, 0.9, 1.0)

Step 2: De-fuzzifying the Triangular Fuzzy Numbers (TFNs) to a Crisp Value

A fuzzy aggregation method was applied to address the uncertainty in human judgment. The fuzzy linguistic data were converted into TFNs (Table IV), which were then defuzzified to obtain crisp values. This process involves several sub-steps:

Step 2.1: Standardization of Fuzzy Numbers

$$x_{ij}^{lk} = \frac{l_{ij}^{k} - \min l \le k \le K l_{ij}^{k}}{D_{\max\min}} \tag{1}$$

$$x_{ij}^{mk} = \frac{m_{ij}^{k} - \min l \le k \le K l_{ij}^{k}}{D_{\max\min}} \quad (2)$$

$$x_{ij}^{rk} = \frac{r_{ij}^{k} - \min l \le k \le k l_{ij}^{k}}{D_{\max\min}} \quad (3)$$

Where $D_{max\ min} = max\ r_{ij}^{k} - min\ l_{ij}^{k}$

These equations represent the standardization of the lower, middle, and upper values of the Triangular Fuzzy Numbers (TFNs). Each component ($x_{ij}^{lk}, x_{ij}^{mk}, x_{ij}^{rk}$) is obtained by normalizing the respective fuzzy values against the range $D_{max\ min}$. This step transforms the fuzzy data into a standardized form, facilitating further analysis while preserving the relative differences in the original fuzzy inputs.

Step 2.2: Calculate Left and Right Normalized Values

$$x_{ij}^{lsk} = \frac{x_{ij}^{mk}}{1 + x_{ij}^{mk} - x_{ij}^{lk}} \quad (4)$$

$$x_{ij}^{rsk} = \frac{x_{ij}^{rk}}{1 + x_{ij}^{rk} - x_{ij}^{mk}} \quad (5)$$

The left and right normalized values represent the proportions of the middle and upper fuzzy values relative to their spreads, indicating the skewness on both sides.

Step 2.3: Calculate the Total Normalized Value

$$x_{ij}^{k} = [x_{ij}^{lsk}(1 - x_{iy}^{lsk}) + x_{ij}^{rs\,k}][1 + x_{ij}^{lsk} - x_{ij}^{ls\,k}] \quad (6)$$

Here, it integrates both the left and right normalized values to produce a total normalized value. It combines the impact of left and right spreads to offer a comprehensive normalization of the TFN.

Step 2.4: Compute the Crisp Value

$$CV_{ij}^{k} = min\ l_{ij}^{k} + x_{ij}^{k} D_{max\ min} \quad (7)$$

This equation calculates the crisp value by adding the minimum lower fuzzy value to the product of the total normalized value and the range $D_{max\ min}$. This step converts the standardized fuzzy data into a single crisp value, suitable for analysis.

Step 3: Combined Scores and DEMATEL Analysis

In the last step, the combined crisp scores from all expert opinions were calculated (Table V), followed by DEMATEL analysis in R using the Dematel package. This facilitated the visualization and analysis of causal relationships, highlighting key factors influencing metaverse shopping experiences.

TABLE IV. TRIANGULAR FUZZY NUMBERS (TFNS)

	EU	EN	SI	INF	MR	RK	TA	IM	FL	ASC	SY
EU	1,1,1	0.3,0.5,0.7	0.5,0.7,0.9	0.3,0.5,0.7	0.5,0.7,0.9	0.3,0.5,0.7	0.7,0.9,1	0.3,0.5,0.7	0.3,0.5,0.7	0.3,0.5,0.7	0.3,0.5,0.7
EN	0.3,0.5,0.7	1,1,1	0.7,0.9,1	0.3,0.5,0.7	0.7,0.9,1	0.3,0.5,0.7	0.3,0.5,0.7	0.5,0.7,0.9	0.5,0.7,0.9	0.5,0.7,0.9	0.7,0.9,1
SI	0.5,0.7,0.9	0.7,0.9,1	1,1,1	0.5,0.7,0.9	0.3,0.5,0.7	0.3,0.5,0.7	0.3,0.5,0.7	0.7,0.9,1	0.3,0.5,0.7	0.3,0.5,0.7	0.3,0.5,0.7
INF	0.5,0.7,0.9	0.3,0.5,0.7	0.3,0.5,0.7	1,1,1	0.7,0.9,1	0.7,0.9,1	0.7,0.9,1	0.3,0.5,0.7	0.3,0.5,0.7	0.3,0.5,0.7	0.3,0.5,0.7
MR	0.3,0.5,0.7	0.7,0.9,1	0.3,0.5,0.7	0.7,0.9,1	1,1,1	0.3,0.5,0.7	0.3,0.5,0.7	0.7,0.9,1	0.7,0.9,1	0.7,0.9,1	0.7,0.9,1
RK	0.3,0.5,0.7	0.3,0.5,0.7	0.1,0.3,0.5	0.5,0.7,0.9	0.3,0.5,0.7	1,1,1	0.5,0.7,0.9	0.3,0.5,0.7	0.3,0.5,0.7	0.3,0.5,0.7	0.3,0.5,0.7
TA	0.1,0.3,0.5	0.3,0.5,0.7	0.5,0.7,0.9	0.5,0.7,0.9	0.3,0.5,0.7	0.3,0.5,0.7	1,1,1	0.3,0.5,0.7	0.3,0.5,0.7	0.3,0.5,0.7	0.3,0.5,0.7
IM	0.1,0.3,0.5	0.7,0.9,1	0.5,0.7,0.9	0.3,0.5,0.7	0.7,0.9,1	0.3,0.5,0.7	0.3,0.5,0.7	1,1,1	0.7,0.9,1	0.7,0.9,1	0.3,0.5,0.7
FL	0.1,0.3,0.5	0.7,0.9,1	0.3,0.5,0.7	0.3,0.5,0.7	0.7,0.9,1	0.3,0.5,0.7	0.3,0.5,0.7	0.7,0.9,1	1,1,1	0.5,0.7,0.9	0.3,0.5,0.7
ASC	0.1,0.3,0.5	0.7,0.9,1	0.5,0.7,0.9	0.3,0.5,0.7	0.7,0.9,1	0.3,0.5,0.7	0.3,0.5,0.7	0.7,0.9,1	0.7,0.9,1	1,1,1	0.3,0.5,0.7
SY	0.1,0.3,0.5	0.7,0.9,1	0.3,0.5,0.7	0.3,0.5,0.7	0.5,0.7,0.9	0.3,0.5,0.7	0.3,0.5,0.7	0.3,0.5,0.7	0.3,0.5,0.7	0.3,0.5,0.7	1,1,1

Note: Triangular Fuzzy Numbers (TFNs) derived from linguistic data provided by Expert 1

IV. RESULT

This study applied the Fuzzy DEMATEL (FDEMATEL) method to understand the factors influencing successful metaverse experiences, experts provided their insights on causal relationships between various attributes. These relationships were quantified by assessing the level of influence one attribute exerts on another. By taking the average (arithmetic mean) of these expert opinions which was normalized, we obtained an initial directed-relation matrix (Table V). Table VI presents the final total relation matrix, derived from the normalized relationships matrix through DEMATEL analysis in R. This analysis establishes a threshold of 0.368 to pinpoint the most impactful factors influencing successful metaverse experiences.

The analysis yields three major outcomes: identification of Prominent factors, determination of causal factors, and classification of effect factors, which are discussed below.

A. Prominent Factors

As given in Table VII, R+D represents the overall prominence of each factor. A higher value indicates a more significant role in the system which are as follows: FL> IM> EU> EN> MR> ASC> SY> TA> INF> SI> RK. It is evident that with R+D= 9.84, FL has the highest prominence, indicating that it is the most important factor in the platform and must be present for it to function properly overall. Close to it are IM and EU with 9.40 and 9.25 respectively, playing key roles in overall metaverse dynamics and significantly impacting user experience. Further, EN (8.81), MR (8.47), and ASC (8.43) also show high prominence, indicating their substantial influence on the platform's effectiveness and user satisfaction. These factors collectively highlight the critical elements that need to be prioritized to enhance user engagement and ensure a seamless and enriching experience in the digital environment.

TABLE V. INITIAL DIRECTED-RELATION MATRIX

	EU	EN	SI	INF	MR	RK	TA	IM	FL	ASC	SY
EU	0.800	0.533	0.178	0.312	0.332	0.258	0.429	0.509	0.507	0.256	0.428
EN	0.321	0.666	0.334	0.143	0.368	0.137	0.245	0.479	0.533	0.395	0.403
SI	0.122	0.196	0.777	0.167	0.122	0.200	0.189	0.173	0.185	0.220	0.226
INF	0.512	0.245	0.269	0.723	0.395	0.322	0.269	0.393	0.390	0.235	0.281
MR	0.472	0.516	0.271	0.300	0.754	0.281	0.266	0.480	0.495	0.406	0.440
RK	0.335	0.294	0.322	0.091	0.223	0.748	0.523	0.268	0.283	0.186	0.328
TA	0.361	0.281	0.284	0.078	0.185	0.363	0.722	0.369	0.393	0.300	0.231
IM	0.390	0.502	0.405	0.205	0.259	0.191	0.242	0.678	0.537	0.480	0.464
FL	0.469	0.531	0.414	0.234	0.332	0.181	0.216	0.543	0.707	0.456	0.431
ASC	0.385	0.433	0.382	0.156	0.275	0.207	0.217	0.515	0.529	0.748	0.360
SY	0.313	0.283	0.381	0.230	0.347	0.198	0.215	0.380	0.453	0.296	0.751

Note: Initial directed-relation matrix derived by averaging the normalized expert opinions.

TABLE VI. TOTAL RELATION MATRIX

	EU	EN	SI	INF	MR	RK	TA	IM	FL	ASC	SY
EU	0.554	0.512	0.378	0.279	0.374	0.295	0.379	0.529	0.550	0.402	0.472
EN	0.399	0.489	0.374	0.214	0.342	0.234	0.297	0.469	0.500	0.392	0.419
SI	0.209	0.233	0.343	0.139	0.171	0.163	0.181	0.239	0.252	0.217	0.233
INF	0.447	0.397	0.356	0.345	0.351	0.283	0.310	0.449	0.466	0.351	0.391
MR	0.495	0.521	0.411	0.284	0.475	0.307	0.349	0.536	0.561	0.447	0.487
RK	0.351	0.352	0.325	0.171	0.267	0.345	0.333	0.363	0.382	0.293	0.349
TA	0.361	0.355	0.319	0.170	0.261	0.261	0.373	0.391	0.412	0.324	0.331
IM	0.438	0.479	0.413	0.241	0.337	0.262	0.315	0.537	0.528	0.432	0.457
FL	0.472	0.503	0.428	0.257	0.366	0.270	0.321	0.527	0.582	0.441	0.466
ASC	0.426	0.454	0.398	0.224	0.331	0.259	0.302	0.492	0.514	0.480	0.423
SY	0.377	0.383	0.367	0.224	0.322	0.238	0.277	0.424	0.457	0.349	0.473

Note: The total relation matrix, obtained through DEMATEL analysis in R, identifies the strength of relationships between factors. A threshold of 0.368

TABLE VII. FINAL RESULT OF FDEMATEL ANALYSIS

	R	D	R+D (Importance)	R-D (Role)	Rank
EU	4.72	4.53	9.25	0.19	3
EN	4.13	4.68	8.81	-0.55	4
SI	2.38	4.11	6.49	-1.73	10
INF	4.15	2.55	6.69	1.6	9
MR	4.87	3.6	8.47	1.28	5
RK	3.53	2.92	6.45	0.61	11
TA	3.56	3.44	7	0.12	8
IM	4.44	4.96	9.4	-0.52	2
FL	4.63	5.2	9.84	-0.5`7	1
ASC	4.3	4.13	8.43	0.18	6
SY	3.89	4.5	8.39	-0.61	7

B. *Cause and Effect Factors*

In our analysis (Table VI), the highest cause factor is INF with a value of 1.6. Informativeness significantly enhances the system by providing valuable and relevant content, greatly increasing user engagement and satisfaction. Following closely is MR with a value of 1.28, which improves user satisfaction through a richer media experience. Other positive influencers include RK at 0.61, TA with a value of 0.12, and ASC at 0.18. EU with a value of 0.19 also positively influences the system by making it more user-friendly.

On the other hand, the highest effect factor is SI with a value of -1.73, indicating it is significantly impacted by other factors. EN, at -0.55, is influenced by various elements including EU and INF. IM at -0.52, FL at -0.57, and SY, with a value of -0.61, are influenced by a wide range of factors including EU and EN. Figure IV illustrates the cause-and-effect relationship between causal factors and their resulting factors.

Further, Figure V represents the factors based on their role and importance. The X-axis (R+D) represents the overall importance of each factor, while the Y-axis (R-D) distinguishes between influencing (cause) factors and influenced (effect) factors. It can be seen from the above diagram that the factors FL, IM, EN, and SY are the most important influenced factors while SI is the least. On the other hand, EU, MR & ASC are the important influencing factors while INF, RK, and TA are less important influencing factors.

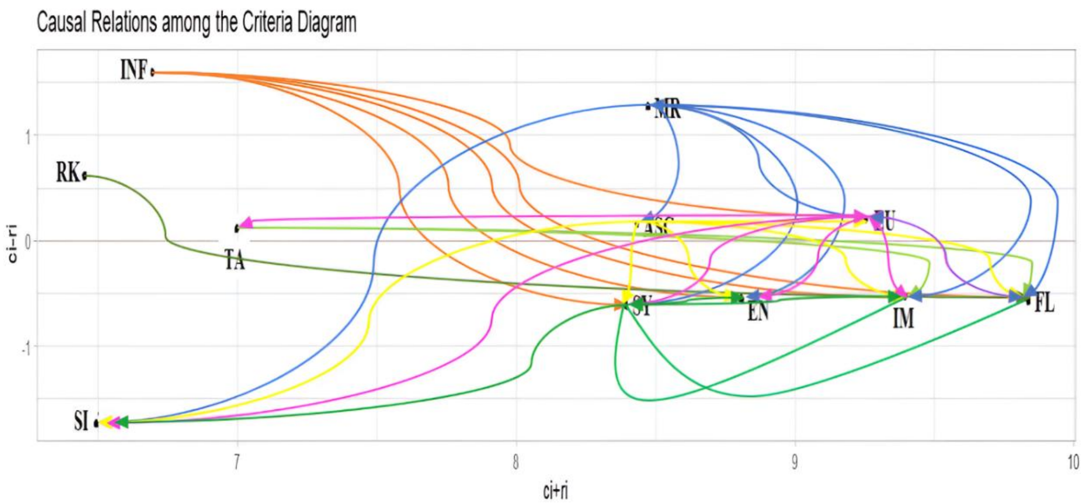


FIGURE IV. DIGRAPH OF CAUSAL RELATIONS AMONG THE FACTORS

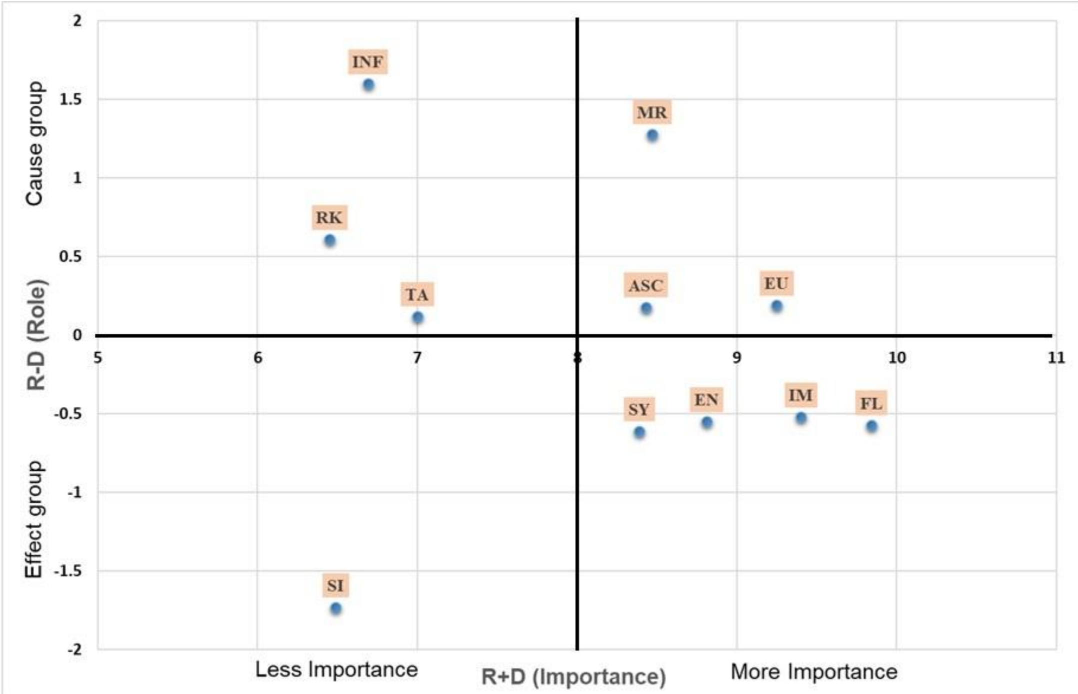


FIGURE V. REGIONS OF FACTORS OF THE METAVERSE PLATFORM

C. *Sensitivity Analysis*

The results may suffer from biases due to the varying backgrounds and levels of expertise of the experts selected for the study [23]. A sensitivity analysis was carried out to confirm the accuracy of the discovered cause-and-effect relationships. The findings of the sensitivity analysis indicate that the rankings of the factors are not significantly affected by modifications to the weights.

This stability shows that, despite possible expert biases, the rankings are not very sensitive to changes in the input data, suggesting that the findings are robust and reliable.

V. DISCUSSIONS

In our study, the most critical factor identified in the success of the metaverse shopping platform is INF. Informativeness influences ease of use, enjoyment, immersion, flow, and synchronicity because valuable and relevant content enhances user experience and engagement. However, it is not affected by any other factor, making it the most outcome-oriented variable due to its role as a key content quality metric. The findings are in line with earlier studies where informativeness (INF) is a significant factor in metaverse adoption [50]. The prominence of media richness (MR) in fostering immersive metaverse experiences also resonates with recent literature that underscores its importance in creating realistic virtual environments that engage users effectively [89].

Avatar self-congruence (ASC) was identified as another important factor influencing user satisfaction and engagement in the metaverse. This finding supports existing studies highlighting the role of avatar self-identity alignment in enhancing user experience and immersion [4, 90]. conversely, the influence of risk perceptions (RK) on user engagement suggests a nuanced understanding of how perceived risks can affect user intention and adoption within virtual platforms, in line with previous findings or theories that may emphasize other factors in virtual environment adoption [9, 62].

Synchronicity (SY) was found to enhance user experience through real-time interactions, consistent with literature emphasizing the importance of dynamic and responsive virtual environments [5]. Technological anxiety (TA) impacts attitudes toward shopping intention in the metaverse [9].

Overall, the study adds to the body of knowledge by offering empirical insights into the intricate interactions between variables affecting user engagement in metaverse retail settings. Future research could further explore these dynamics across different demographic and cultural contexts to enrich our understanding of user behavior and preferences in virtual retail settings.

VI. Implications

A. Theoretical Contribution

While traditional theoretical frameworks typically employ a standardized approach, the relationships among variables show significant changes when contextualized within the dynamics of the metaverse.

In traditional TAM, perceived ease of use (EU) is considered a key independent variable affecting both attitude and behavioural intention [75]. However, this study demonstrates that in the metaverse, EU is both influenced by and influences several key factors, including informativeness (INF), media richness (MR), immersion (IM), flow (FL), avatar self-congruence (ASC), and synchronicity (SY). This reciprocal relationship suggests that TAM should be extended to account for bidirectional influences rather than assuming the EU as a purely independent factor. This shift underscores the need for a more dynamic and interaction-based TAM model for the metaverse.

Similarly, HMSAM states that enjoyment (EN) is influenced by EU and affects immersion (IM) [91]. However, in the metaverse, EN not only influences EU and IM but is also shaped by them, forming a feedback loop rather than a unidirectional relationship. The immersive and engaging nature of the metaverse enhances user satisfaction and perceived ease of use, which, in turn, deepens immersion and further amplifies enjoyment. This study suggests that HMSAM should be extended to incorporate bidirectional interactions, as user engagement in the metaverse is driven by an ongoing reinforcement cycle rather than a linear process.

In Computer Anxiety Theory, technological anxiety (TA) is assumed to negatively impact ease of use (EU) [92]. However, this study finds that in the metaverse, EU reduces TA, meaning that as users find the platform easier to navigate, their anxiety decreases. This reversal challenges the traditional perspective and suggests that TA should be considered a dynamic factor that evolves with user experience, rather than a static barrier to adoption.

These findings indicate that traditional theoretical models require modifications when applied to the metaverse context. Instead of treating variables as static and unidirectional, models should be revised to accommodate bidirectional influences, dynamic relationships, and user-driven experiences. Future research should explore these extensions further to refine theoretical frameworks for understanding consumer behaviour in immersive digital environments.

B. Managerial Implications

The DEMATEL analysis provides a prioritized list of factors crucial for enhancing Metaverse shopping experiences, highlighting specific actions for developers and marketers according to their ranking.

Flow (FL) and immersion (IM) emerged as the most critical elements. Developers should focus on creating seamless and deeply engaging environments by optimizing user interfaces and utilizing advanced graphics and interactive elements. Ensuring seamless interactions will increase user satisfaction and engagement, adding to the fun and memorable nature of shopping. Ease of use (EU) ranks third in importance. Both developers and marketers must work together to simplify navigation, design intuitive controls, and provide clear instructions and helpful guides. A user-friendly interface will attract and retain more users, reducing frustration and encouraging repeat visits.

Enjoyment (EN), media richness (MR), and informativeness (INF) are also highly significant. Marketers should incorporate elements that enhance user enjoyment, such as rich media, comprehensive information, and immersive content, to create a more engaging and pleasurable shopping experience. By doing so, they can make the shopping process more entertaining and satisfying. Additionally, enhancing avatar self-congruence (ASC) is vital. Developers should allow users to create realistic avatars that closely resemble themselves, providing advanced customization options and accurate virtual try-on features. This increased realism will elevate users' enjoyment and satisfaction.

Synchronicity (SY) is important for maintaining user engagement. Developers should ensure real-time responses and interactions by implementing robust servers and efficient data handling to reduce lag and latency. Real-time interactions will prevent users from switching to other platforms due to frustration with delays. Addressing technological anxiety (TA) is also essential. Developers need to design platforms and devices that are user-friendly and require minimal technical knowledge. Providing user support and resources will help users feel more comfortable, making the platform more accessible to a broader audience.

Finally, mitigating overall risk (RK) is crucial for building user trust. To safeguard user information and financial transactions, developers and marketers need to put strict security measures in place and communicate these measures to users. A secure platform will reduce perceived risks, encourage more transactions, and foster a sense of safety and reliability. Efforts to increase system integration should also be made to ensure that various components of the Metaverse shopping platform work seamlessly together to provide a smooth and cohesive user experience. Developers and marketers can raise the standard and appeal of Metaverse shopping platforms considerably by concentrating on these aspects, which will increase user satisfaction and loyalty in the long run.

VII. Conclusion

In conclusion, this study employed the fuzzy DEMATEL method within the MCDM framework to systematically identify the key factors driving the success of metaverse shopping platforms. Addressing the first research question (RQ1), the factors were identified through a review of the literature and expert evaluations, ensuring a comprehensive and systematic approach to understanding the effectiveness of metaverse shopping platforms. Flow (FL), immersion (IM), and ease of use (EU) emerged as critical elements that enhance user experience, ensuring a seamless and engaging shopping journey. Additionally, enjoyment (EN), media richness (MR), and avatar self-congruence (ASC) were found to impact user adoption and satisfaction significantly.

Regarding the second research question (RQ2), the study analyzed the cause-and-effect relationships among these factors. Informativeness (INF) was identified as the most influential causal factor, which is crucial in enriching user engagement by providing valuable content. Media richness (MR) also acted as a key driver by enhancing the immersive quality of the digital shopping experience. Conversely, social influence (SI) emerged as the most affected factor, heavily influenced by other system elements. Enjoyment (EN), immersion (IM), and synchronicity (SY) were also classified as effect factors, highlighting their reliance on foundational drivers like informativeness and media richness.

Addressing the third research question (RQ3), the findings emphasize the need to prioritize flow (FL), immersion (IM), and ease of use (EU) to create a compelling metaverse shopping experience. Enhancing informativeness (INF) and media richness (MR) can further improve user engagement while mitigating risk (RK) and technological anxiety (TA) can foster greater user confidence.

Future research should explore other MCDM techniques such as Analytic Hierarchy Process (AHP) and Interpretive Structural Modeling (ISM), as well as additional context-specific variables related to the metaverse to further refine the theoretical framework. A deeper understanding of how these factors change over time and affect long-term user satisfaction and engagement may be obtained through longitudinal studies. Additionally, looking into how new technologies, like virtual reality and artificial intelligence, affect the factors mentioned above may provide important new information about how they might improve the metaverse experience. Finally, cross-cultural studies could reveal how these dynamics vary across different demographic and cultural contexts, providing a more comprehensive understanding of user behavior in the metaverse retail environment.

Acknowledgement

None.

Funding

This research did not receive any outside funding or support. The authors report no involvement in the research by the sponsor that could have influenced the outcome of this work.

Authors` Contributions

All authors have participated in drafting the manuscript. All authors read and approved the final version of the manuscript.

Conflict Of Interest

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Data Availability

The data supporting the findings of this study are available upon request from the authors.

Ethical Statement

In this article, the principles of scientific research and publication ethics were followed. This study did not involve human or animal subjects and did not require additional ethics committee approval.

Declaration of AI Usage

No AI tools were used in the creation of this manuscript.

References

[1] Alsamhi, M. H., Hawbani, A., Kumar, S., & Alsamhi, S. H. (2024). Multisensory Metaverse-6G: A New Paradigm of Commerce and Education. *IEEE Access. 12*, 75657-75677 https://doi.org/10.1109/ACCESS.2024.3392838

[2] Hajian, A., Daneshgar, S., Sadeghi R., K., Ojha, D., & Katiyar, G. (2024). From theory to practice: Empirical perspectives on the metaverse's potential. *Technological Forecasting and Social Change, 201* (April 2024), 123224. https://doi.org/10.1016/j.techfore.2024.123224

[3] Dwivedi, Y. K., Hughes, L., Baabdullah, A. M., Ribeiro-Navarrete, S., Giannakis, M., Al-Debei, M. M., Dennehy, D., Metri, B., Buhalis, D., Cheung, C. M. K., Conboy, K., Doyle, R., Dubey, R., Dutot, V., Felix, R., Goyal, D. P., Gustafsson, A., Hinsch, C., Jebabli, I., … Wamba, S. F. (2022). Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy. *International Journal of Information Management, 66*. https://doi.org/10.1016/j.ijinfomgt.2022.102542

[4] Park, J., & Kim, N. (2024). Examining self-congruence between user and avatar in purchasing behavior from the metaverse to the real world. *Journal of Global Fashion Marketing, 15*(1), 23–38. https://doi.org/10.1080/20932685.2023.2180768

[5] Payal, R., Sharma, N., & Dwivedi, Y. K. (2024). Unlocking the impact of brand engagement in the metaverse on Real-World purchase intentions: Analyzing Pre-Adoption behavior in a futuristic technology platform. *Electronic Commerce Research and Applications, 65*, 101381. https://doi.org/10.1016/j.elerap.2024.101381

[6] Bruni, R., Colamatteo, A., & Mladenović, D. (2023). How the metaverse influences marketing and competitive advantage of retailers: predictions and key marketing research priorities. *Electronic Commerce Research, 24*(2), 965–982. https://doi.org/10.1007/s10660-023-09779-1

[7] Yoon, S., & Nam, Y. (2024). Metaverse engagement and Korea travel intentions: Understanding affordances, presence, and place attachment among Brazilian ZEPETO users. *Journal of Destination Marketing & Management, 31*, 100865. https://doi.org/10.1016/j.jdmm.2024.100865

[8] Yoo, K., Welden, R., Hewett, K., & Haenlein, M. (2023). The merchants of meta: A research agenda to understand the future of retailing in the metaverse. *Journal of Retailing, 99*(2), 173–192. https://doi.org/10.1016/j.jretai.2023.02.002

[9] Pillai, R., Sivathanu, B., Rana, N. P., Preet, R., & Mishra, A. (2023). Factors influencing customers' apparel shopping intention in metaverse.

Journal of Computer Information Systems, 1–16. https://doi.org/10.1080/08874417.2023.2280842

[10] GlobalData. (2023). Metaverse in Retail and Apparel – Thematic Intelligence.

[11] Statista. (2023). Metaverse eCommerce - Worldwide. https://www.statista.com/outlook/amo/metaverse/metaverse-ecommerce/worldwide

[12] Jin, D. (2024). Humanizing Metaverse: Psychological involvement and masstige value in retail versus tourism platforms. *International Journal of Consumer Studies, 48*(2), 1-20. https://doi.org/10.1111/ijcs.13025

[13] Mancuso, I., Messeni Petruzzelli, A., & Panniello, U. (2023). Digital business model innovation in metaverse: How to approach virtual economy opportunities. *Information Processing and Management*, *60*(5), 1-28. https://doi.org/10.1016/j.ipm.2023.103457

[14] SanMiguel, P., Sádaba, T., & Sayeed, N. (2024). Fashion brands in the metaverse: Achievements from a marketing perspective. *Journal of Global Fashion Marketing, 15*(3), 320–340. https://doi.org/10.1080/20932685.2024.2331518

[15] Wongkitrungrueng, A., & Suprawan, L. (2023). Metaverse Meets Branding: Examining consumer responses to immersive brand experiences. *International Journal of Human-Computer Interaction, 40*(11), 2905–2924. https://doi.org/10.1080/10447318.2023.2175162

[16] Adhini, N. V., & Prasad, C. V. V. S. N. V. (2024). Perceptions and drivers of the metaverse adoption: A mixed-methods study. *International Journal of Consumer Studies, 48*(4), 1-34. https://doi.org/10.1111/ijcs.13069

[17] Arya, V., Sambyal, R., Sharma, A., & Dwivedi, Y. K. (2023). Brands are calling your AVATAR in Metaverse‐A study to explore XR ‐ based gamification marketing activities & consumer ‐ based brand equity in virtual world. *Journal of Consumer Behaviour, 23*(2), 556 ‐ 585. https://doi.org/10.1002/cb.2214

[18] Mansoor, S., Rahman, S. M., & Bowden, J. L. (2024). Purchase spillovers from the metaverse to the real world: The roles of social presence, trialability, and customer experience. *Journal of Consumer Behaviour, 23*(5), 2501–2552. https://doi.org/10.1002/cb.2353

[19] Roblox (2025). Roblox Web Site. https://www.roblox.com

[20] Zepeto (2025). Zepeto Web Site. https://web.zepeto.me/en

[21] Lin, R. J. (2013). Using fuzzy DEMATEL to evaluate the green supply chain management practices. *Journal of Cleaner Production, 40*, 32–39. https://doi.org/10.1016/j.jclepro.2011.06.010

[22] Lu, Y. H., Yeh, C. C., & Liau, T. W. (2023). Exploring the key factors affecting the usage intention for cross-border e-commerce platforms based on DEMATEL and EDAS method. *Electronic Commerce Research, 23*(4), 2517–2539. https://doi.org/10.1007/s10660-022-09548-6

[23] Mishra, R. (2021). An analysis of factors influencing omnichannel retailing adoption using ISM-DEMATEL approach: an Indian perspective. *International Journal of Retail and Distribution Management, 49*(4), 550–576. https://doi.org/10.1108/IJRDM-03-2020-0108

[24] Parmar, P. S., & Desai, T. N. (2020). Evaluating Sustainable Lean Six Sigma enablers using fuzzy DEMATEL: A case of an Indian manufacturing organization. *Journal of Cleaner Production, 265*. https://doi.org/10.1016/j.jclepro.2020.121802

[25] Singh, C., Dash, M. K., Sahu, R., & Singh, G. (2023). Evaluating critical success factors for acceptance of digital assistants for online shopping using Grey–DEMATEL. *International Journal of Human-Computer Interaction,* 1–15. https://doi.org/10.1080/10447318.2023.2286124

[26] Noor, M. F., Kumar, A., Tripathi, S., & Gupta, V. (2024). Challenges in Adopting Industry 4.0 for Indian Automobile Industries: A Key Experts' Perspective. *Journal Europeen Des Systemes Automatises, 57*(1), 239–253. https://doi.org/10.18280/jesa.570123

[27] Kannan, J., Jayakumar, V., Pethaperumal, M., & Kather Mohideen, A. B. (2024). An intensified linear diophantine fuzzy combined DEMATEL framework for the assessment of climate crisis. *Stochastic Environmental Research and Risk Assessment*. https://doi.org/10.1007/s00477-023-02618-7

[28] Emovon, I., Norman, R. A., & Murphy, A. J. (2016). An integration of multi-criteria decision making techniques with a delay time model for determination of inspection intervals for marine machinery systems. *Applied Ocean Research*, *59*, 65–82. https://doi.org/10.1016/j.apor.2016.05.008

[29] Gupta, R., Rathore, B., Biswas, B., Jaiswal, M., & Singh, R. K. (2024). Are we ready for metaverse adoption in the service industry? Theoretically exploring the barriers to successful adoption. *Journal of Retailing and Consumer Services, 79*. https://doi.org/10.1016/j.jretconser.2024.103882

[30] Kou, G., Yüksel, S., & Dinçer, H. (2023). A facial expression and expert recommendation fuzzy decision-making approach for sustainable business investments within the metaverse world. *Applied Soft Computing, 148*, 110849. https://doi.org/10.1016/j.asoc.2023.110849

[31] Ahn, S., Jin, B. E., & Seo, H. (2024). Why do people interact and buy in the Metaverse? Self-Expansion perspectives and the impact of hedonic adaptation. *Journal of Business Research, 175*, 114557. https://doi.org/10.1016/j.jbusres.2024.114557

[32] Hadi, R., Melumad, S., & Park, E. S. (2024). The Metaverse: A new digital frontier for consumer behavior. *Journal of Consumer Psychology, 34*(1), 142–166. https://doi.org/10.1002/jcpy.1356

[33] Dwivedi, Y. K., Hughes, L., Wang, Y., Alalwan, A. A., Ahn, S. J., Balakrishnan, J., Barta, S., Belk, R., Buhalis, D., Dutot, V., Felix, R., Filieri, R., Flavián, C., Gustafsson, A., Hinsch, C., Hollensen, S., Jain, V., Kim, J., Krishen, A. S., … Wirtz, J. (2023). Metaverse marketing: How the metaverse will shape the future of consumer research and practice. *Psychology and Marketing, 40*(4), 750–776. https://doi.org/10.1002/mar.21767

[34] Buhalis, D., Leung, D., & Lin, M. (2023). Metaverse as a disruptive technology revolutionising tourism management and marketing. *Tourism Management, 97*, 104724. https://doi.org/10.1016/j.tourman.2023.104724

[35] Hollensen, S., Kotler, P., & Opresnik, M. O. (2023). Metaverse – the new marketing universe. *Journal of Business Strategy*, *44*(3), 119–125. https://doi.org/10.1108/JBS-01-2022-0014

[36] Bushell, C. (2022). The impact of Metaverse on branding and marketing - A study of how individuals and celebrities use metaverse as a brand extension, and the implications for marketing. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4144688

[37] Davis, F. D. (1989). Technology Acceptance Model: TAM. In M. N. Al-Suqri, & A. S. Al-Aufi (Eds.), *Information Seeking Behavior and Technology Adoption* (pp. 205-219). IGI Global.

[38] Classe, T. M. de, Castro, R. M. de, & Sousa, H. P. D. S. (2023). Evaluating Students' Technology Acceptance of Use of Metaverse as an Educational Information System for Hybrid Education. In *Proceedings of the XIX Brazilian Symposium on Information Systems* (pp. 197-205). https://doi.org/10.1145/3592813.3592906

[39] Teng, Z., Cai, Y., Gao, Y., Zhang, X., & Li, X. (2022). Factors affecting learners' adoption of an educational metaverse platform: an empirical study based on an extended UTAUT model. *Mobile Information Systems, 2022*, 1–15. https://doi.org/10.1155/2022/5479215

[40] Almarzouqi, A., Aburayya, A., & Salloum, S. A. (2022). Prediction of User's Intention to Use Metaverse System in Medical Education: A Hybrid SEM-ML Learning Approach. *IEEE Access, 10*, 43421–43434. https://doi.org/10.1109/ACCESS.2022.3169285

[41] Van, H.-T., Si, T. N., Quynh, A. V. T., Kieu, T. N. T., & Vo, T.-T.-T. (2022). A Conceptual Framework for Determining Metaverse Adoption in Vietnam IT Enterprises. *Proceedings - 2022 IEEE/ACIS 7th International Conference on Big Data, Cloud Computing, and Data Science*, BCD 2022, 14–17. https://doi.org/10.1109/BCD54882.2022.9900871

[42] Alshurafat, H., Arabiat, O., & Shehadeh, M. (2024). The intention to adopt metaverse in Islamic banks: an integrated theoretical framework of TAM and religiosity intention model. *Journal of Islamic Marketing*. https://doi.org/10.1108/JIMA-10-2023-0310

[43] Xi, N., Chen, J., Gama, F., Korkeila, H., & Hamari, J. (2024). Acceptance of the metaverse: a laboratory experiment on augmented and virtual reality shopping. *Internet Research, 34*(7), 82–117. https://doi.org/10.1108/INTR-05-2022-0334

[44] Davis, F. D., Bagozzi, R. P., & Warshaw, P. R. (1992). Extrinsic and Intrinsic Motivation to Use Computers in the Workplace. *Journal of Applied Social Psychology, 22*(14), 1111–1132. https://doi.org/10.1111/j.1559-1816.1992.tb00945.x

[45] Hassouneh, D., & Brengman, M. (2015). Metaverse retailing: Are SVW users ready to buy real products from virtual world stores? *Proceedings of the International Conferences on E-Health 2015, EH 2015, e-Commerce and Digital Marketing 2015, EC 2015 and Information Systems Post-Implementation and Change Management 2015, ISPCM 2015 - Part of the Multi Conference on Computer Science An*, 104–110.

[46] Patil, K., Bharathi S, V., & Pramod, D. (2022). Can Metaverse Retail lead to purchase intentions among the youth? A Stimulus-Organism-Response theory perspective. *2022 ASU International Conference in Emerging Technologies for Sustainability and Intelligent Systems, ICETSIS 2022*, 314–320. https://doi.org/10.1109/ICETSIS55481.2022.9888929

[47] Li, C.-Y. (2013). Persuasive messages on information system acceptance: A theoretical extension of elaboration likelihood model and social influence theory. *Computers in Human Behavior, 29*(1), 264–275. https://doi.org/10.1016/j.chb.2012.09.003

[48] Shukla, A., Mishra, A., Rana, N. P., & Banerjee, S. (2024). The future of metaverse adoption: A behavioral reasoning perspective with a text-mining approach. *Journal of Consumer Behaviour, 23*(5), 2217–2233. https://doi.org/10.1002/cb.2336

[49] Aburbeian, A. M., Owda, A. Y., & Owda, M. (2022). A Technology Acceptance Model Survey of the Metaverse Prospects. *AI, 3*(2), 285–302. https://doi.org/10.3390/ai3020018

[50] Lee, U. K., & Kim, H. (2022). UTAUT in Metaverse: An "Ifland" Case. *Journal of Theoretical and Applied Electronic Commerce Research, 17*(2), 613–635. https://doi.org/10.3390/jtaer17020032

[51] Riar, M., Xi, N., Korbel, J. J., Zarnekow, R., & Hamari, J. (2023). Using augmented reality for shopping: a framework for AR induced consumer behavior, literature review and future agenda. *Internet Research, 33*(1), 242–279. https://doi.org/10.1108/INTR-08-2021-0611

[52] Habil, S. G. M., El-Deeb, S., & El-Bassiouny, N. (2024). The metaverse era: leveraging augmented reality in the creation of novel customer experience. *Management and Sustainability:, 3*(1), 1–15. https://doi.org/10.1108/MSAR-10-2022-0051

[53] Hwang, I., Shim, H., & Lee, W. J. (2022). Do an Organization's Digital Transformation and Employees' Digital Competence Catalyze the Use of Telepresence? *Sustainability (Switzerland), 14*(14). https://doi.org/10.3390/su14148604

[54] Patil, K. P., & Pramod, D. (2023). 'Real Worlds Illusion!' Consumer Response to Metaverse Technology Applying Flow Theory. *2023 7th International Conference On Computing, Communication, Control And Automation, ICCUBEA 2023*. https://doi.org/10.1109/ICCUBEA58933.2023.10392210

[55] Daft, R. L., & Lengel, R. H. (1986). Organizational information requirements, media richness and structural design. *Management science, 32*(5), 554-571. https://www.jstor.org/stable/2631846?seq=1&cid=pdf-

[56] Sun, H., & Guo, R. (2024). The Effect of Metaverse Concert Characteristics on User Re-Participation Intention: A Combination of the ETAM and the SPICE Model. *International Journal of Human-Computer Interaction*, 1–14. https://doi.org/10.1080/10447318.2024.2331859

[57] Lee, U.-K. (2022). Tourism Using Virtual Reality: Media Richness and Information System Successes. *Sustainability (Switzerland), 14*(7). https://doi.org/10.3390/su14073975

[58] Zhang, L., Anjum, M. A., & Wang, Y. (2023). The Impact of Trust-Building Mechanisms on Purchase Intention towards Metaverse Shopping: The Moderating Role of Age. *International Journal of Human-Computer Interaction, 40*(12), 3185–3203. https://doi.org/10.1080/10447318.2023.2184594

[59] Efendioğlu, İ. H. (2023). The Effect Of Information About Metaverse On The Consumer's Purchase Intention. *Journal of Global Business and Technology, 19*(1), 63–77.

[60] Barta, S., Gurrea, R., & Flavián, C. (2023). How Augmented Reality Increases Engagement Through Its Impact on Risk and the Decision Process. *Cyberpsychology, Behavior, and Social Networking, 26*(3), 177–187. https://doi.org/10.1089/cyber.2022.0087

[61] Murtas, G., Pedeliento, G., & Mangiò, F. (2024). Luxury fashion brands at the gates of the Web 3.0: An analysis of early experimentations with NFTs and the metaverse. *Journal of Global Fashion Marketing, 15*(1), 90–114. https://doi.org/10.1080/20932685.2023.2249476

[62] Soni, S., & Sharma, B. K. (2023). Mitigating the risk induced by Online shopping by using Metaverse. *2023 International Seminar on Application for Technology of Information and Communication: Smart Technology Based on Industry 4.0: A New Way of Recovery from Global Pandemic and Global Economic Crisis, ISemantic 2023*, 129–134. https://doi.org/10.1109/iSemantic59612.2023.10295282

[63] Kumar, A., & Shankar, A. (2024a). The bold decision to go "all in": Understanding the reasons behind consumers' willingness to migrate to the metaverse. *Psychology and Marketing, 41*(8), 1769–1791. https://doi.org/10.1002/mar.22009

[64] Aliman, D. N., Hennig-Thurau, T., & Henke, A. (2024). Navigating the enterprise metaverse: How virtual reality affects business agility and meeting outcomes. *Business Horizons*. https://doi.org/10.1016/J.BUSHOR.2024.05.007

[65] Kumar, A., & Shankar, A. (2024b). Will metaverse revolutionize retail banking? Understanding user acceptance towards metaverse banking. *International Journal of Retail and Distribution Management, 52*(6), 629–646. https://doi.org/10.1108/IJRDM-06-2023-0396

[66] Caboni, F., & Pizzichini, L. (2023). Smart Extended Reality in the Metaverse-Tailing: The Rise of New Retail Landscape. In *Springer Series on Cultural Computing* (pp. 307–321). https://doi.org/10.1007/978-3-031-27166-3_17

[67] Chen, J., Xi, N., Pohjonen, V., & Hamari, J. (2023). Paying attention in metaverse: an experiment on spatial attention allocation in extended reality shopping. *Information Technology and People, 36*(8), 255–283. https://doi.org/10.1108/ITP-09-2021-0674

[68] Csikszentmihalyi, M. (2014). Flow and the foundations of positive psychology: The collected works of Mihaly Csikszentmihalyi. *In Flow and the Foundations of Positive Psychology: The Collected Works of Mihaly Csikszentmihalyi*. https://doi.org/10.1007/978-94-017-9088-8

[69] Park, Y., Ko, E., & Do, B. (2023). The perceived value of digital fashion product and purchase intention: the mediating role of the flow experience in metaverse platforms. *Asia Pacific Journal of Marketing and Logistics, 35*(11), 2645–2665. https://doi.org/10.1108/APJML-11-2022-0945

[70] Lee, S.-E., Domina, T., & MacGillivray, M. (2011). Exploring consumers' flow experiences in virtual shopping: An exploratory study. *International Journal of Electronic Marketing and Retailing, 4*(2–3), 165–182. https://doi.org/10.1504/IJEMR.2011.043046

[71] Sirgy, M. J. (1985). Using self-congruity and ideal congruity to predict purchase motivation. *Journal of Business Research, 13*(3), 195–206. https://doi.org/10.1016/0148-2963(85)90026-8

[72] Balakrishnan, J., Das, R., Alalwan, A. A., Raman, R., & Dwivedi, Y. K. (2024). Informative and peripheral metaverse: Which leads to experience? An investigation from the viewpoint of self-concept. *Computers in Human Behavior, 156*, 108223. https://doi.org/10.1016/J.CHB.2024.108223

[73] Kim, J., & Bae, J. (2023). Influences of persona self on luxury brand attachment in the Metaverse context. *Asia Pacific Journal of Marketing and Logistics, 36*(9), 2068–2081. https://doi.org/10.1108/APJML-05-2022-0390

[74] Dennis, A. R., Fuller, R. M., & Valacich, J. S. (2008). Media, tasks, and communication processes: A theory of media synchronicity. *MIS Quarterly: Management Information Systems, 32*(3), 575–600. https://doi.org/10.2307/25148857

[75] Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS Quarterly: Management Information Systems, 13*(3), 319–339. https://doi.org/10.2307/249008

[76] Wang, G., & Shin, C. (2022). Influencing Factors of Usage Intention of Metaverse Education Application Platform: Empirical Evidence Based on PPM and TAM Models. *Sustainability (Switzerland), 14*(24). https://doi.org/10.3390/su142417037

[77] Al-kfairy, M., Alomari, A., Al-Bashayreh, M., Alfandi, O., & Tubishat, M. (2024). Unveiling the Metaverse: A survey of user perceptions and the impact of usability, social influence and interoperability. *Heliyon, 10*(10). https://doi.org/10.1016/j.heliyon.2024.e31413

[78] Harrisson-Boudreau, J.-P., Bellemare, J., Bacher, N., & Bartosiak, M. (2023). Adoption Potentials of Metaverse Omnichannel Retailing and Its Impact on Mass Customization Approaches. *In Lecture Notes in Mechanical Engineering*(pp. 110–119). https://doi.org/10.1007/978-3-031-34821-1_13

[79] Chen, C., & Yao, M. Z. (2022). Strategic use of immersive media and narrative message in virtual marketing: Understanding the roles of telepresence and transportation. *Psychology and Marketing, 39*(3), 524–542. https://doi.org/10.1002/mar.21630

[80] Liu, Z., Gong, S., Tan, Z., & Demian, P. (2023). Immersive Technologies-Driven Building Information Modeling (BIM) in the Context of Metaverse. *Buildings, 13*(6), 1559. https://doi.org/10.3390/buildings13061559

[81] Cha, S. S., Kim, C. Y., & Tang, Y. (2024). Gamification in the Metaverse: Affordance, perceived value, flow state, and engagement. International *Journal of Tourism Research, 26*(2). https://doi.org/10.1002/jtr.2635

[82] Huang, L., Solangi, Y. A., Magazzino, C., & Solangi, S. A. (2024). Evaluating the efficiency of green innovation and marketing strategies for long-term sustainability in the context of Environmental labeling. *Journal of Cleaner Production, 450*, 141870. https://doi.org/10.1016/j.jclepro.2024.141870

[83] Rad, M. a. V., Fard, H. F., Khazanedari, K., Toopshekan, A., Ourang, S., Khanali, M., Gorjian, S., Fereidooni, L., & Kasaeian, A. (2024). A global framework for maximizing sustainable development indexes in agri-photovoltaic-based renewable systems: Integrating DEMATEL, ANP, and MCDM methods. *Applied Energy, 360*, 122715. https://doi.org/10.1016/j.apenergy.2024.122715

[84] Scott, S. A., Himang, C., Ancheta, R., Maturan, F., Aro, J. L., Evangelista, S. S., Atibing, N. M., & Ocampo, L. (2024). Three-way decision TOPSIS for food business location under a benefit-opportunity-cost-risk platform. *Journal of Management Analytics, 11*(3), 518–553. https://doi.org/10.1080/23270012.2024.2348480

[85] Mkedder, N., & Das, M. (2023). Metaverse integration challenges: An in-depth ISM and MICMAC analysis. *Journal of Retailing and Consumer Services, 77*, 103684. https://doi.org/10.1016/j.jretconser.2023.103684

[86] Sim, J., Saunders, B., Waterfield, J., & Kingstone, T. (2018). Can sample size in qualitative research be determined a priori? *International Journal of Social Research Methodology, 21*(5), 619–634. https://doi.org/10.1080/13645579.2018.1454643

[87] Esfandiar, K., Seryasat, M. R., & Kozak, M. (2023). To shop or not to shop while traveling? Exploring the influence of shopping mall attributes on overall tourist shopping satisfaction. *Tourism Recreation Research, 49*(6), 1411–1426. https://doi.org/10.1080/02508281.2023.2186088

[88] Koca, G., Egilmez, O., & Akcakaya, O. (2021). Evaluation of the smart city: Applying the dematel technique. *Telematics and Informatics, 62*, 101625. https://doi.org/10.1016/j.tele.2021.101625

[89] Cheung, M. L., Leung, W. K. S., Chang, L. M. K., Aw, E. C. X., & Wong, R. Y. M. (2024). Immersive time in the metaverse and visits to the physical world: why not both? A holistic customer engagement framework. *International Journal of Contemporary Hospitality Management, 36*(11), 3674–3703. https://doi.org/10.1108/IJCHM-07-2023-0999

[90] Shin, H., & Kang, J. (2024). How does the metaverse travel experience influence virtual and actual travel behaviors? Focusing on the role of telepresence and avatar identification. *Journal of Hospitality and Tourism Management, 58*, 174–183. https://doi.org/10.1016/J.JHTM.2023.12.009

[91] Lowry, P. B., Gaskin, J. E., Twyman, N. W., Hammer, B., & Roberts, T. L. (2013). Taking 'fun and games' seriously: Proposing the hedonic-motivation system adoption model (HMSAM). *Journal of the Association for Information Systems, 14*(11), 617–671. https://doi.org/10.17705/1jais.00347

[92] Hackbarth, G., Grover, V., & Yi, M. Y. (2003). Computer playfulness and anxiety: Positive and negative mediators of the system experience effect on perceived ease of use. *Information and Management, 40*(3), 221–232. https://doi.org/10.1016/S0378-7206(02)00006-X

Journal of Metaverse
Research Article
Received: 2024-12-05 | **Reviewing:** 2024-12-09 & 2025-03-19 | **Accepted:** 2025-03-19 | **Online:** 2025-03-21 | **Issue Date:** 2025-06-30
Year:2025, **Volume:**5, **Issue:**1, **Pages:**64-72, **Doi:** 10.57019/jmv.1596909

Human-Centric IoT-Driven Digital Twins in Predictive Maintenance for Optimizing Industry 5.0

Özlem SABUNCU
Electrical and Electronic Engineering &
Research Center for Science, Technology and Engineering (BILTEM)
Near East University
Mersin, Türkiye
ozlem.sabuncu@neu.edu.tr
0000-0002-9159-7791
(Corresponding Author)

Bülent BİLGEHAN
Electrical and Electronic Engineering &
Research Center for Science, Technology and Engineering (BILTEM)
Near East University
Mersin, Türkiye
bulent.bilgehan@neu.edu.tr
0000-0003-1615-6766

***Abstract*— Predictive maintenance now heavily relies on digital twins and the Internet of Things (IoT), allowing industrial assets to be monitored and make real-time decisions. However, adding human components to conventional optimization processes creates new difficulties as Industry 5.0 moves toward human-centric systems. Existing frameworks frequently disregard human preferences, intuition, and safety considerations, which makes human operators distrustful and unwilling to accept them. This paper presents a novel multi-objective optimization framework to enable predictive maintenance that incorporates human feedback into IoT-driven digital twins. The framework uses an enhanced particle swarm optimization (PSO) algorithm to reconcile competing goals, including maintaining operator safety, optimizing asset reliability, and minimizing maintenance costs. Furthermore, maintenance tasks are adaptively scheduled using built-in reinforcement learning (RL), and optimized model parameters are fine-tuned to improve predictive accuracy using Bayesian optimization. The latter is based on real-time operational data. In addition to promoting a safer working environment, the suggested approach significantly reduces unplanned downtime and maintenance costs. This research contributes to developing more resilient, adaptive, and collaborative industrial systems by aligning with the human-centric principles of Industry 5.0. The proposed model was tested using the maintenance duration and improved 10 to 100 hours. The model was compared with the PSO algorithm, demonstrating its superiority with a 7.5% reduction in total maintenance cost and a 6.3% decrease in total downtime. These improvements enhance operational efficiency and better human-machine collaboration by minimizing unnecessary interventions and optimizing resource allocation.**

Keywords*— *Industry 5.0, Digital twin, IoT, Predictive maintenance, Enhanced PSO

I. INTRODUCTION

The integration of digital twin and Internet of Things (IoT) technologies into the industry makes a significant contribution to its innovation potential [1-4]. Digital twin technology is a real-time virtual representation of physical environments, which simulates industries' operations and optimizes companies' processes [5-8].

The continuous data flow from the sensors updates the historical data in operation. Compared to traditional methods, proactive and predictive maintenance approaches minimize operational interruptions in industries and extend equipment lifespan [9-12].

The advent of Industry 5.0 has shifted the focus towards a deeper collaboration between human intelligence and machine capabilities, moving beyond the automation-driven approach of Industry 4.0. This transition introduces new technological requirements, including the need for systems that prioritize human factors such as safety, satisfaction, and collaborative decision-making alongside technical efficiency [13, 14]. As such, Industry 5.0 calls for more advanced optimization frameworks that integrate human-machine synergy, allowing for more adaptable, context-aware systems in rapidly evolving environments. Compared to the old version, Industry 5.0 requires an advanced optimization approach that considers human and technical aspects to ensure performance and user-centricity. Despite the increasing importance of human-machine collaboration in existing predictive maintenance frameworks, human preferences, intuition, and real-time feedback are not sufficiently considered. This deficiency leads to wrong decisions, reduced trust in automated systems, and reduced adaptability in rapidly changing industrial environments [15-20].

This study proposes a framework to improve and optimize maintenance processes by considering the human factor using IoT-based digital twins. This method is established to solve the weaknesses in the current system to increase system and employee safety, reduce maintenance costs, and balance conflicting objectives. The algorithm provides a flexible optimization system that complies with Industry 5.0 standards and strengthens human-machine collaboration, enabling effective decision-making [21-26].

The proposed optimization offers three main contributions. The first is to interface humans with the machine, allowing humans to be integrated into the process. The second is to weight the parameters to minimize cost and time using the digital twin process. The third is introducing a framework to reduce maintenance costs, increase accuracy, and promote calibration between humans and the automated system.

This paper is organized as follows: Section 2 presents the related work. Section 3 provides the proposed system architecture and optimization methodology. Section 4 introduces the mathematical model and problem formulation. Section 5 gives the simulation setup and results. Section 6 concludes the research work.

Cite (APA): Sabuncu, O., Bilgehan, B. (2025). Human-Centric IoT-Driven Digital Twins in Predictive Maintenance for Optimizing Industry 5.0. *Journal of Metaverse*. *5*(1), 64-72. **Doi:** 10.57019/jmv.1596909

II. RELATED WORK

The predictive maintenance process became significant after IoT and digital twin technology were introduced. The main task in such an operation is to improve equipment reliability, allow data-driven decision-making, and enable real-time monitoring. The work in this paper investigates a research method for Industry 5.0 using optimization method, IoT, and digital twin for a successful predictive maintenance method. There are several research papers [27, 28] investigating the use of IoT to enable real-time data collection for industrial equipment. The latest research papers [29, 30] are considering machine learning methods to predict the failures of industrial systems. The paper in [31] presented a framework that combines machine learning with IoT-related data to forecast the lifespan of critical components. The studies indicate precise predictions by using IoT technology. The work in Industry 4.0 did not include the human factor in the operation. However, the upcoming Industry 5.0 requires the human factor to be essential to the operation to increase trust and cooperation. The operational accuracy of Industry 5.0 has further increased by applying digital twins.

The paper [32] introduces a digital twin operation that duplicates physical assets for major predictive maintenance. The advantage of this operation is that it allows real-time simulation and analysis for predictive maintenance. The paper also demonstrates the precision of decision-making stages. The paper [33] indicated that digital twins can lower the risk of failures for unplanned operations.

The studies are important to highlight the application of the digital twins, but human-centric factors and multi-objective optimizations are not considered in the process. The multi-objective optimization method is one of the suitable algorithms for predictive maintenance strategy. The paper [34] optimizes the maintenance schedule, considering reliability and cost factors. Furthermore, the paper [35] utilizes machine learning methods to modify maintenance in real-time based on the conditions of the equipment. Most research papers concentrate on technical performance majors without cooperating user references as needed in Industry 5.0.

The literature provides optimization methods for predictive maintenance. These methods include IoT and digital twins. The methods used today concentrate on cost and reliability factors, but little is known about dynamic, real-time optimization methods.

The proposed model presents an optimization framework using a multi-objective algorithm that considers the IoT-driven digital twins and humans in the mechanisms. The proposed model prioritizes safety and human concerns for predictive maintenance systems. This research aims to increase the flexibility and understandability of predictive maintenance approaches.

III. SYSTEM ARCHITECTURE

This section describes the methodology for combining advanced optimization methods and IoT digital twins into a maintenance framework for Industry 5.0. As shown in Figure I, the main difference between Industry 4.0 and Industry 5.0 is the human interaction, including resilience and sustainability.

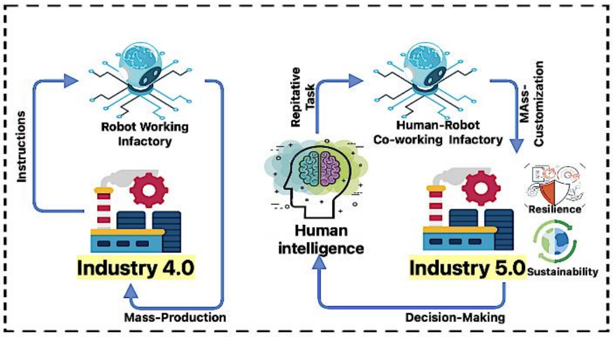


FIGURE I. ARCHITECTURE OF INDUSTRY 4.0 AND INDUSTRY 5.0

Figure I illustrate the transition from Industry 4.0, which focuses on automation and robotics, to Industry 5.0, which integrates human intelligence into production.

On the left side of the figure, Industry 4.0 is depicted with a robot-driven factory where robots receive instructions and perform mass production. The primary characteristic here is automation, with minimal human involvement.

In the center, human intelligence plays a crucial role in shifting from repetitive tasks to more complex decision-making.

On the right side of the figure, Industry 5.0 introduces human-robot collaboration, emphasizing mass customization rather than generic mass production. This approach enhances resilience and sustainability, as seen in the accompanying icons representing these principles.

The flow between the two paradigms highlights how industries are evolving to balance automation with human creativity and flexibility.

The work adopts a digital twin model that enables the analysis of the equipment's life cycle using real-time data sent from the sensors. Digital twin processing offers the advantage of simulating the behaviour and monitoring the maintenance procedure of the equipment and machinery in the production line. The main block of the digital twin architecture is shown in Figure II.

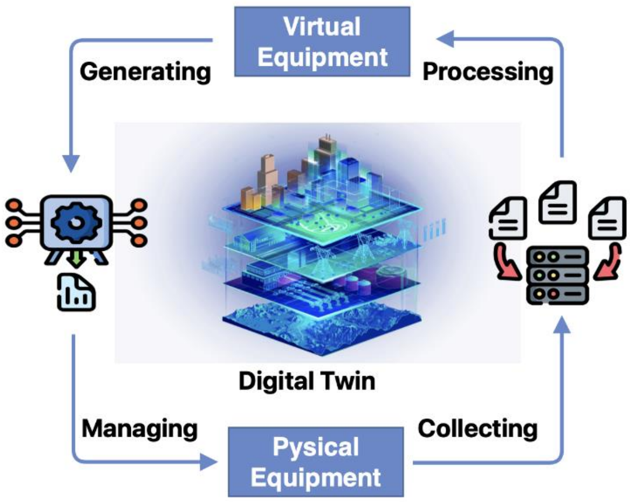


FIGURE II. DIGITAL TWIN STRUCTURE

The main parts of the framework consist of the IoT sensing layer, the digital twin layer, and the human interaction optimization layer to operate a maintenance prediction mechanism. The designed architecture provides real-time monitoring, a data-driven decision model, and human-machine interaction. Figure II illustrates physical and virtual equipment interaction through a digital twin.

At the bottom, physical equipment collects data through embedded sensors. The collected data moves to the processing stage, where a system interprets and stores it.

The processed data is used in the top section to generate a virtual representation of the equipment. The cycle is completed as the generated insights are used for managing physical equipment, enabling real-time monitoring, fault detection, and predictive maintenance.

The digital twin system creates a feedback loop, ensuring continuous optimization and improved efficiency.

The complete framework architecture was generated using ChatGPT and demonstrated in Figure III.

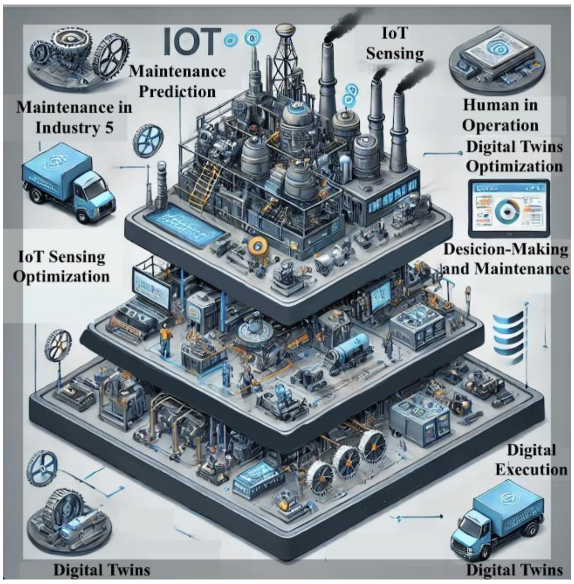


FIGURE III. FRAMEWORK ARCHITECTURE LAYERS

The main units consisting of the framework layers are described in the following subsections.

Figure III provides a multi-layered visualization of an advanced smart factory that integrates IoT sensors, Digital Twins, and AI-driven decision-making for optimized industrial operations.

The bottom layer represents Digital Twins, creating a virtual simulation of machinery and processes. The middle layer focuses on IoT sensing optimization, where interconnected devices collect real-time data. The top layer emphasizes decision-making and maintenance, where AI-driven analytics predict potential failures, ensuring proactive maintenance.

The human operator's role is also evident, as decision-making is enhanced through human expertise rather than being fully automated. The factory benefits from predictive maintenance, resource efficiency, and enhanced operational reliability.

A. IoT Sensing Layer

The IoT sensing layer is responsible for real-time data collection from the equipment's sensor units. The sensors transmit data to the digital twin using an IoT gateway. The data includes important parameters such as vibrations, temperature, pressure, and operational status.

B. Digital Twin Layer

The digital twin receives data continuously from the IoT sensors within the units and machinery. The data received from IoT sensors update the historical data in the storage. The updated data remains a database that can be used for failure prediction purposes. The prediction is an analysis to identify the variation between the historical data and updated data. The digital twin model tests various scenarios with different maintenance approaches using different decision variables before they are implemented in the real system. Implementing the digital twin model improves the model's predictive accuracy and reduces the risk included in maintenance decisions.

C. Human Interaction Optimization Layer

Human interaction optimization contributes by integrating real-time user preferences, domain expertise, and adaptive decision-making feedback into the optimization process. By using the enhanced PSO algorithm with human-in-the-loop adaptation, the aim is to reduce cost, increase reliability, and enhance safety.

The human interface actively gathers inputs, including operator adjustments, expert-driven parameter tuning, heuristic insights, and contextual awareness, ensuring the optimization process remains dynamic and responsive to real-world conditions. Unlike traditional autonomous optimization approaches, this framework allows human operators to inject qualitative judgment, adjust constraints, and fine-tune algorithmic parameters in response to environmental changes, operational demands, or unexpected anomalies.

To facilitate seamless human-machine collaboration, the system employs interactive dashboards, real-time monitoring tools, and feedback loops that provide users with actionable insights and performance metrics. These interfaces enable operators to analyze optimization trends, compare different parameter configurations, and introduce modifications that align with specific operational goals such as energy efficiency, resource allocation, or fault tolerance.

Furthermore, integrating AI-driven decision support systems enhances the interaction layer by offering suggestive feedback mechanisms, predictive analytics, and scenario-based recommendations. This ensures that human inputs are reactive and proactive in anticipating challenges, mitigating risks, and optimizing outcomes.

By embedding human expertise within the optimization cycle, the system achieves a hybrid intelligence approach, where algorithmic efficiency is complemented by human intuition, strategic reasoning, and contextual adaptability. This ultimately leads to a more robust, adaptive, and user-centric optimization framework.

IV. METHODOLOGY

The maintenance prediction operation has multiple inputs and a single output. The inputs are considered to be multi-objective functions that produce an efficient system output. The multi-objective functions are represented with different parameters as input to the system. The introduced optimization method fine-tunes the parameter values to yield the most efficient system output. The typical multi-objective parameters are sensor data, historical repair, operational feedback, and asset condition data.

The introduced optimization method uses the best of three different algorithms to produce an accurate solution. The algorithms are known as PSO, RL, and Bayesian optimization algorithms. The PSO optimization can consider multiple input parameters to form a correlation between variables and increase the system's efficiency. The RL optimization uses feedback from the system to update the learning procedure. The updated learning procedure enables accurate decisions to be taken with real data. The system operating under such conditions is classified as a dynamic operation. The Bayesian optimization algorithm can fine-tune the parameters for such an operation.

The combinational use of three methods increases the system's reliability and accuracy. Initially, the PSO considers a large number of solution functions but reduces to the most accurate solution to yield the most accurate output. The RL algorithm continuously monitors the system's behaviour and feeds back to update the historical data. The Bayesian algorithm provides more accurate results for the maintenance prediction operation. The combinational use of three algorithms provides accuracy for maintenance prediction at minimum periods and minimizes the overall cost of the operation.

The enhanced combination of the introduced optimization is described in Algorithm I.

ALGORITHM I. ENHANCED OPTIMIZATION

Parameter Definitions:

- **swarm_size (N)**: Number of particles
- **dimensions (D)**: Size of the problem (number of parameters to be optimized)
- **max_iter**: Maximum number of iterations
- **w**: Inertia weight (coefficient of preservation of the previous speed of the particles)
- **c1**: Cognitive coefficient (coefficient of attraction of a particle to its best solution)
- **c2**: Social coefficient (coefficient of regression to the best solution in the swarm)
- **v_min, v_max**: Speed limits
- **x_min, x_max**: Position limits

Step 1: Initialization Process for the particles

1. For each and individual particle:
    - [x_min, x_max] ⟵ random selection
    - [v_min, v_max] ⟵ random selection
    - Set the best local position of the particle as the starting position.
2. Set the particle's best local fitness value to infinity.
    - Set the best global position in the swarm equal to the position of a random particle.
    - Set the global best fitness value to infinity.

Step 2: Use RL and PSO for maintenance planning

1. Start a loop and process the following

    Adaptively schedule maintenance tasks using the RL model:

    - The RL model determines which maintenance tasks to perform and when based on real-time data from IoT sensors.
    - The model plans maintenance with a dynamic decision process based on safety, cost and failure risks.
2. PSO Main Loop (Iterations): iter = 1 to max_iter:

    For each particle:

    - Calculate the fitness function of the particle.
    - If the current fitness is smaller than the best local fitness of the particle:
        - Update the particle's best local position.
        - Update the particle's best local fitness value.
    - If current fitness is less than the global best overall fitness:
        - Update best global position.
        - Update global fitness best.

    For each particle:

    - Update the particle's speed:

    $$v[i] = w \cdot v[i] + c1 \cdot \text{random}() \cdot (p\_best[i] - x[i]) + c2 \cdot \text{random}() \cdot (g\_best - x[i])$$

    - limit speed

    $$v[i] = max(min(v[i], v\_max), v\_min)$$

    - update the particle’s location

    $$x[i] = x[i] + v[i]$$

    - limit position

    $$x[i] = max(min(x[i], x\_\text{max}), x\_min)$$
3. Complete the Iteration

Step 3: Fine-Tuning Model Parameters with Bayesian Optimization

- Optimize model parameters with Bayesian optimization using parameters obtained from PSO:

- Bayesian Optimization improves the accuracy of the predictive maintenance model by fine-tuning model parameters.
- This process is used to improve the performance and accuracy of the model, based on operational data.

- According to the Bayesian model results, the model parameters used in the maintenance process are dynamically updated and optimized.

Step 4: Combining Results with PSO, RL and Bayesian

- At the end of each iteration:
  - PSO updates the position of particles and searches for the best solution.
  - RL model performs adaptive maintenance planning and determines the most appropriate maintenance processes.
  - Bayesian Optimization makes model parameters more precise.
  - As a result, maintenance costs are minimized, and fault prediction accuracy is increased.

End Last Repeat

Step 5: Finalizing the Solution

- The best global position g_best is considered as the optimal solution.
- The best global fitness value fitness_g_best refers to the best fitness result of the solution.
- Optimized parameters as a result of Bayesian Optimization increase the model's prediction accuracy.

Output:

- g_best: Optimal solution (best global position)
- fitness_g_best: Optimal fitness value
- RL Plan: Adaptive maintenance plan determined by RL
- Bayesian Optimized Parameters: Fine-tuned model parameters

V. Simulations and Results

A. Simulation Setup

The details of the equipment used in the simulation are described below.

- Operating System: Windows 11 Pro, 64-bit.
- Processor: Intel Core i9-12900K, 16 cores with a base clock speed of 3.2 GHz and turbo boost up to 5.2 GHz.
- RAM: 64 GB DDR4, operating at 3600 MHz
- Storage: 2 TB NVMe SSD for primary storage and 4 TB SATA SSD for data storage and backup.
- Graphics Processing Unit (GPU): NVIDIA RTX 3080 Ti, 12 GB GDDR6X memory.
- MATLAB Version: MATLAB R2024a with Signal Processing, Communication System, and Neural Network Toolboxes.
- Programming Language: MATLAB with integrated C/C++ MEX files for optimized computational performance.
- Compiler: Microsoft Visual Studio 2022 C++ Compiler (for MEX file compilation).
- Additional Toolboxes: Optimization Toolbox and Statistics and Machine Learning Toolbox for model analysis and verification.
- Parallel Computing Setup: Utilized MATLAB's Parallel Computing Toolbox with up to 12 workers (parallel threads) for simulation acceleration.

The predictive maintenance model in this work is trained and validated using a publicly available Kaggle dataset, which consists of sensor readings and operational data collected from industrial equipment.

The dataset comprises 23,000 samples with multiple sensor readings collected over time, covering different operational states of industrial machines. Each sample represents a time-series instance with various sensor parameters.

The dataset includes multiple sensor modalities, such as temperature, vibration, pressure, rotation speed, and power consumption, allowing for comprehensive failure pattern recognition.

The dataset provides labelled failure instances, distinguishing between normal operation, early warning signs, and critical failures. These labels are essential for supervised learning and model evaluation.

The dataset includes data from various machine types and operating conditions, enabling robust model generalization.

The dataset follows a time-series structure, allowing for trend analysis and early fault detection using sequential modelling techniques.

By leveraging this dataset, the proposed model ensures that the proposed predictive maintenance model is trained on diverse, real-world industrial scenarios, improving its fault detection accuracy and adaptability to varying operational conditions.

The maintenance intervals are realistic to show the true performance of the proposed model. Initially, the proposed algorithm iteratively generated possible solutions for the maintenance schedules using the defined objective functions. The enhanced PSO algorithm helps to escape local minima and improves the quality of the solution. The improved algorithm has introduced its significant values using the methods listed below.

- Adjust Weighting Factors: Modify the outputs more significantly.
- Enhance Local Search: The number of iterations in the local search was increased, and a more sophisticated local search strategy, such as gradient descent, was implemented.

- Dynamic Parameters: Adaptive parameters are adopted in the operation to change the iteration or performance metrics, leading to better solution space exploration.
- Added Constraints: Added constraints guide the search towards feasible results and potentially produce more optimal solutions based on the specific context of the optimization problem.

The algorithm aims to use performance matrices such as maintenance interval, cost, downtime, and reliability score. The performance achievement of the matrices can be described below.

Maintenance Interval (Hours):

The selection of the maintenance interval is a critical performance metric. The purpose of these metrics is to balance system downtime and preventive maintenance. The time taken for a repair may be shorter, but it may increase the maintenance cost. Therefore, the balance between the two parameters must be selected carefully. The other effective point is that longer maintenance periods may increase the failure rates. The optimization algorithm adjusts the interval to minimize unexpected breakdowns and helps to increase the equipment's lifespan.

Cost:

The cost of the operation is a key factor in identifying the financial maintenance strategy. Comparing the unplanned downtime and the optimized preventive maintenance yields the system's efficiency. The resulting output produces a cost-benefit analysis to justify the investment in IoT-based predictive maintenance technologies.

Downtime:

The downtime parameter indicates the efficiency of equipment and machinery. It directly increases productivity efficiency in the case of predictive planning against downtime. In a predictive maintenance algorithm, downtime reduces the time devices remain out of operation.

Reliability:

The reliability factor is directly related to the system's performance over time. It prevents devices from being out of service in critical situations, ensures smooth operation, and prevents unexpected breakdowns. A high-reliability value indicates the system's robustness and ability to promptly meet expected demand.

VI. RESULTS

The proposed algorithm considerably reduces the maintenance intervals for all equipment in operation. The maintenance intervals and scheduling were analyzed to reveal the algorithm's applicability. Results are plotted in Figure IV for visual examination.

Figure IV demonstrates the difference between normal and optimized maintenance intervals. The plots show the reduction of optimized maintenance gain in hours. The data in the simulation improved between 10 to 100 hours of maintenance duration. The overall cost reduces as the maintenance interval reduces. The PSO algorithm sets the maintenance intervals to 150 hours for all equipment indices. This occurs due to the PSO-based approach optimizing maintenance scheduling using real-time equipment data from Kaggle while maintaining a fixed threshold. The proposed method, however, refines the decision criteria, enabling dynamic adjustments to maintenance intervals and resulting in a more flexible and efficient scheduling strategy.

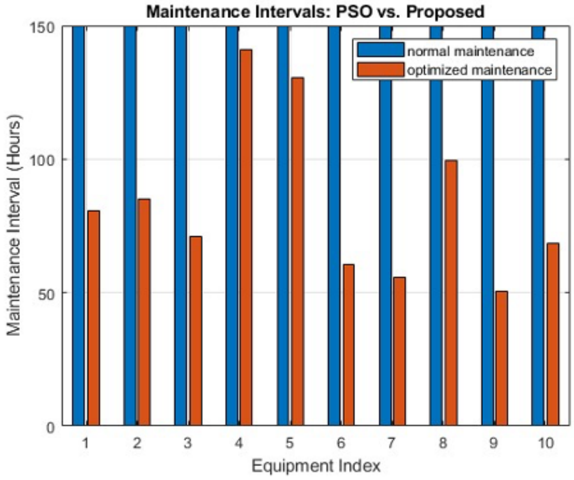


FIGURE IV. COMPARISON OF THE MAINTENANCE INTERVALS

The other parameter to consider is the maintenance cost. Figure V compares and plots the proposed and the most suitable PSO algorithms.

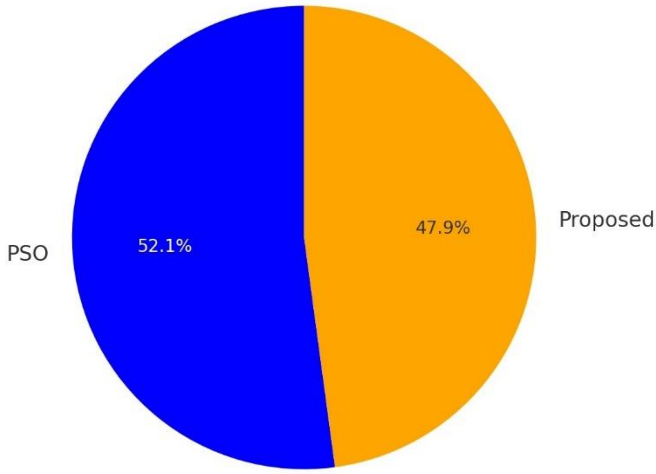


FIGURE V. COST COMPARISON OF THE MAINTENANCE

The cost reduction plots in Figure V. show the efficiency of the proposed method. The results prove that the proper allocation of resources minimizes unnecessary interactions and concentrates on predictive maintenance that avoids costly repairs. The execution of the proposed method yields results as:

Total Cost with Optimized Maintenance Intervals: $44600.00

Cost Reduction: 15.72%

Cost reduction is significant for large manufacturing industries.

The other effective parameter is to analyze the system's total downtime. The downtime analysis is compared with the PSO algorithm, and the results are plotted in Figure VI.

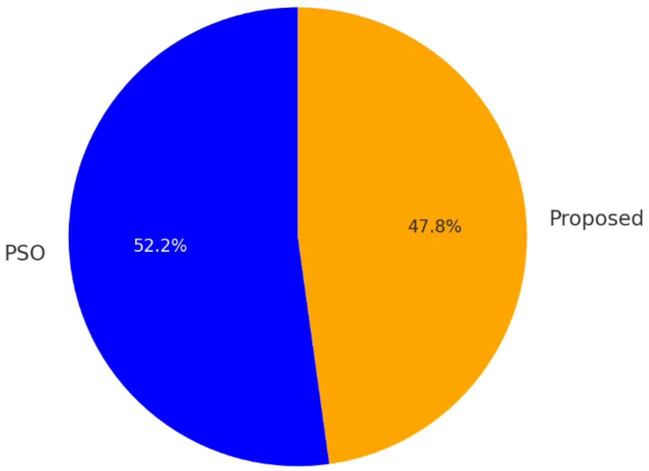


FIGURE VI. COMPARISON OF THE TOTAL DOWNTIME

The total downtime under the proposed method is lower than that of the PSO-based method. The reduction in this dataset is approximately 13 hours, which means the equipment remains operational for longer periods, improving overall system availability and productivity.

The proposed algorithm was further examined using performance metrics such as the reliability score. The results are compared and plotted in Figure VII.

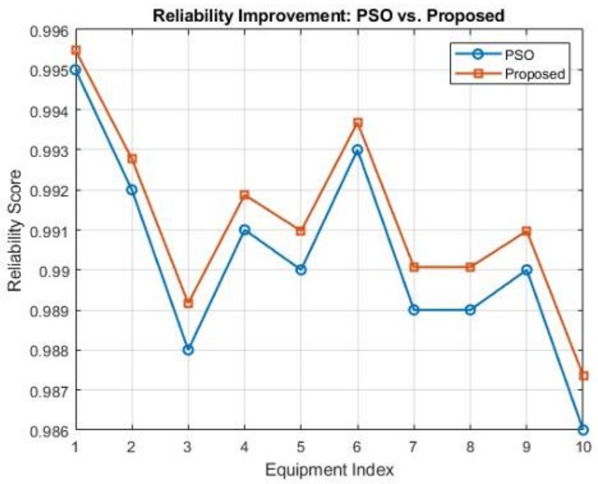


FIGURE VII. RELIABILITY ACHIEVEMENT

The reliability score identifies the success of the system operation. The proposed method scored a higher reliability value for all equipment indices. The higher reliability score is considered a performance measure to suggest that the proposed method is more robust and resilient, especially for critical assets. The resulting reliability score guarantees the equipment to meet the demands, increase the system's robustness, and reduce unexpected failures.

VII. CONCLUSION

The proposed IoT-based predictive maintenance model considered well-known performance measure matrices to evaluate its success. The model uses real data to show its applicability in real-time operations and is compared with a well-known PSO algorithm. The proposed model reduces the maintenance cost by 15.72%. The tested performance metrics such as the maintenance interval, system reliability, and downtime demonstrated high improvements.

The results indicate that the proposed model is superior in terms of offering successful maintenance scheduling, reducing maintenance intervals, and increasing the lifespan of the equipment. The model prevents unexpected failures from occurring that are costly in manufacturing.

The comparison algorithms demonstrate the superiority of the proposed model by minimizing equipment downtime, enhancing operational availability, and increasing productivity. The system's robustness, demonstrated by the reliability score, proves the efficacy of the proposed framework.

The results validate the proposed model to provide a superior solution for predictive maintenance that offers a less costly and better maintenance strategy. The study also reveals another important factor that demonstrates that the proposed model has the potential to be integrated with IoT-based systems for maintenance management in Industry 5.0.

However, several limitations of the proposed method must be considered. One of the primary concerns is the subjectivity and accuracy of human inputs. In industrial settings, the quality of data gathered from human-operated sensors or devices may vary, leading to inconsistencies that can affect the model's predictions. Such inaccuracies could influence the system's overall performance, particularly in environments with more prevalent human error. Future work can address this by improving data collection processes, integrating advanced automation, and using more reliable sensor technologies to reduce human dependency.

Additionally, the proposed model's scalability for large-scale industrial systems remains a challenge. As the system's complexity increases, so does the computational demand, which may affect the model's applicability in larger operations. Exploring ways to optimize computational efficiency, such as through cloud computing or parallel processing, could make the model more feasible for use in larger industrial settings.

For future work, more specific research directions can be pursued. Applying the model across different industrial sectors, such as energy, transportation, or manufacturing, would provide valuable insights into its adaptability and performance in varying contexts. Testing the model with diverse datasets from multiple industries would help identify potential challenges and allow for further system refinement. Additionally, further integration of the model with IoT-based systems, particularly in Industry 5.0, could provide new opportunities for automating maintenance decisions and incorporating advanced machine learning techniques for continuous optimization.

ACKNOWLEDGEMENT

Not applicable

FUNDING

This research did not receive any outside funding or support. The authors report no involvement in the research by the sponsor that could have influenced the outcome of this work.

AUTHORS` CONTRIBUTIONS

All authors have participated in drafting the manuscript. All authors read and approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

DATA AVAILABILITY

The data supporting the findings of this study are available upon request from the authors.

ETHICAL STATEMENT

This article followed the principles of scientific research and publication ethics. This study did not involve human or animal subjects and did not require additional ethics committee approval.

DECLARATION OF AI USAGE

The complete framework architecture was generated using ChatGPT.

REFERENCES

[1] Deepu, T. S., & Ravi, V. (2021). Exploring critical success factors influencing adoption of digital twin and physical internet in electronics industry using the grey-DEMATEL approach. *Digital Business*, *1*(2), 100009. https://doi.org/10.1016/j.digbus.2021.100009

[2] del Campo, G., Saavedra, E., Piovano, L., Luque, F., & Santamaria, A. (2024). Virtual Reality and Internet of Things Based Digital Twin for Smart City Cross-Domain Interoperability. *Applied Sciences*, *14*(7), 2747. https://doi.org/10.3390/app14072747

[3] Bisanti, G. M., Mainetti, L., Montanaro, T., Patrono, L., & Sergi, I. (2023). Digital twins for aircraft maintenance and operation: A systematic literature review and an IoT-enabled modular architecture. *Internet of Things*, 100991. https://doi.org/10.1016/j.iot.2023.100991

[4] Trendowicz, A., Groen, E. C., Henningsen, J., Siebert, J., Bartels, N., Storck, S., & Kuhn, T. (2023). User experience key performance indicators for industrial IoT systems: A multivocal literature review. *Digital Business*, *3*(1), 100057. https://doi.org/10.1016/j.digbus.2023.100057

[5] Zhong, D., Xia, Z., Zhu, Y., & Duan, J. (2023). Overview of predictive maintenance based on digital twin technology. *Heliyon*, *9*(4). https://doi.org/10.1016/j.heliyon.2023.e14534

[6] Yao, J. F., Yang, Y., Wang, X. C., & Zhang, X. P. (2023). Systematic review of digital twin technology and applications. *Visual Computing for Industry, Biomedicine, And Art*, *6*(1), 10. https://doi.org/10.1186/s42492-023-00137-4

[7] Moshood, T. D., Rotimi, J. O., Shahzad, W., & Bamgbade, J. A. (2024). Infrastructure digital twin technology: A new paradigm for future construction industry. *Technology in Society*, *77*, 102519. https://doi.org/10.1016/j.techsoc.2024.102519

[8] Arowoiya, V. A., Moehler, R. C., & Fang, Y. (2024). Digital twin technology for thermal comfort and energy efficiency in buildings: A state-of-the-art and future directions. *Energy and Built Environment*, *5*(5), 641-656. https://doi.org/10.1016/j.enbenv.2023.05.004

[9] Van Oudenhoven, B., Van de Calseyde, P., Basten, R., & Demerouti, E. (2023). Predictive maintenance for industry 5.0: Behavioural inquiries from a work system perspective. *International Journal of Production Research*, *61*(22), 7846-7865. https://doi.org/10.1080/00207543.2022.2154403

[10] Murtaza, A. A., Saher, A., Zafar, M. H., Moosavi, S. K. R., Aftab, M. F., & Sanfilippo, F. (2024). Paradigm Shift for Predictive Maintenance and Condition Monitoring from Industry 4.0 to Industry 5.0: A Systematic Review, Challenges and Case Study. *Results in Engineering*, 102935. https://doi.org/10.1016/j.rineng.2024.102935

[11] Ejjami, R., & Boussalham, K. (2024). Resilient Supply Chains in Industry 5.0: Leveraging AI for Predictive Maintenance and Risk Mitigation. *International Journal for Multidisciplinary Research*, *6*(4), 1-32. https://doi.org/10.36948/ijfmr.2024.v06i04.25116

[12] Frick, J. (2023). Future of industrial asset management: A synergy of digitalization, digital twins, maintenance 5.0/quality 5.0, industry 5.0 and iso55000. *International Journal of Business Marketing and Management*, *8*(4), 93-99.

[13] Adel, A. (2023). Unlocking the future: fostering human–machine collaboration and driving intelligent automation through industry 5.0 in smart cities. *Smart Cities*, *6*(5), 2742-2782. https://doi.org/10.3390/smartcities6050124

[14] Pizoń, J., & Gola, A. (2023). Human–machine relationship—perspective and future roadmap for industry 5.0 solutions. *Machines*, *11*(2), 203; 1-22. https://doi.org/10.3390/machines11020203

[15] Alves, J., Lima, T. M., & Gaspar, P. D. (2023). Is industry 5.0 a human-centred approach? a systematic review. *Processes*, *11*(1), 193;1-15. https://doi.org/10.3390/pr11010193

[16] Marinelli, M. (2023). From Industry 4.0 to Construction 5.0: Exploring the Path towards Human–Robot Collaboration in Construction. *Systems*, *11*(3), 152; 1-23. https://doi.org/10.3390/systems11030152

[17] Peruzzini, M., Prati, E., & Pellicciari, M. (2024). A framework to design smart manufacturing systems for Industry 5.0 based on the human-automation symbiosis. *International journal of computer integrated manufacturing*, *37*(10-11), 1426-1443. https://doi.org/10.1080/0951192X.2023.2257634

[18] Zafar, M. H., Langås, E. F., & Sanfilippo, F. (2024). Exploring the synergies between collaborative robotics, digital twins, augmentation, and industry 5.0 for smart manufacturing: A state-of-the-art review. *Robotics and Computer-Integrated Manufacturing*, *89*, 102769. https://doi.org/10.1016/j.rcim.2024.102769

[19] Zhang, C., Wang, Z., Zhou, G., Chang, F., Ma, D., Jing, Y., ... & Zhao, D. (2023). Towards new-generation human-centric smart manufacturing in Industry 5.0: A systematic review. *Advanced Engineering Informatics*, *57*, 102121. https://doi.org/10.1016/j.aei.2023.102121

[20] Calzavara, M., Faccio, M., & Granata, I. (2023). Multi-objective task allocation for collaborative robot systems with an Industry 5.0 human-centered perspective. *The International Journal of Advanced Manufacturing Technology*, *128*(1-2), 297-314. https://doi.org/10.1007/s00170-023-11673-x

[21] Huang, W., Liu, Y., & Zhang, X. (2023). Hybrid particle swarm optimization algorithm based on the theory of reinforcement learning in psychology. *Systems*, *11*(2), 83. https://doi.org/10.3390/systems11020083

[22] Hu, S., & Li, K. (2023). Bayesian network demand-forecasting model based on modified particle swarm optimization. *Applied Sciences*, *13*(18), 10088. https://doi.org/10.3390/app131810088

[23] Abdul Karim, S. A., & Tamin, O. (2024). Intelligent System Modeling in Industrial 4.0. In *Intelligent Systems Modeling and Simulation III: Artificial Intelligent, Machine Learning, Intelligent Functions and Cyber Security* (pp. 1-13). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-67317-7_1

[24] Soesanto, J. (2024). *Digital Twin and Smart Automation for Bitumen Extraction Process*. [Master thesis, University of Alberta]. University of Alberta Education and Research Archive. https://doi.org/10.7939/r3-wgex-2h6

[25] Marugán, A. P. (2023). Applications of Reinforcement Learning for maintenance of engineering systems: A review. *Advances in*

Engineering Software, *183*, 103487. https://doi.org/10.1016/j.advengsoft.2023.103487

[26] Molęda, M., Małysiak-Mrozek, B., Ding, W., Sunderam, V., & Mrozek, D. (2023). From corrective to predictive maintenance—A review of maintenance approaches for the power industry. *Sensors*, *23*(13), 5970. https://doi.org/10.3390/s23135970

[27] Zhong, D., Xia, Z., Zhu, Y., & Duan, J. (2023). Overview of predictive maintenance based on digital twin technology. *Heliyon*, *9*(4). https://doi.org/10.1016/j.heliyon.2023.e14534

[28] Abouelyazid, M. (2023). Advanced Artificial Intelligence Techniques for Real-Time Predictive Maintenance in Industrial IoT Systems: A Comprehensive Analysis and Framework. *Journal of AI-Assisted Scientific Discovery*, *3*(1), 271-313.

[29] Qiu, S., Cui, X., Ping, Z., Shan, N., Li, Z., Bao, X., & Xu, X. (2023). Deep learning techniques in intelligent fault diagnosis and prognosis for industrial systems: a review. *Sensors*, *23*(3), 1305. https://doi.org/10.3390/s23031305

[30] Meriem, H., Nora, H., & Samir, O. (2023). Predictive maintenance for smart industrial systems: a roadmap. *Procedia Computer Science*, *220*, 645-650. https://doi.org/10.1016/j.procs.2023.03.082

[31] Rahman, M. S., Ghosh, T., Aurna, N. F., Kaiser, M. S., Anannya, M., & Hosen, A. S. (2023). Machine learning and internet of things in industry 4.0: A review. *Measurement: Sensors*, *28*, 100822. https://doi.org/10.1016/j.measen.2023.100822

[32] van Dinter, R., Tekinerdogan, B., & Catal, C. (2023). Reference architecture for digital twin-based predictive maintenance systems. *Computers & Industrial Engineering*, *177*, 109099. https://doi.org/10.1016/j.cie.2023.109099

[33] Weerapura, V., Sugathadasa, R., De Silva, M. M., Nielsen, I., & Thibbotuwawa, A. (2023). Feasibility of digital twins to manage the operational risks in the production of a ready-mix concrete plant. *Buildings*, *13*(2), 447. https://doi.org/10.3390/buildings13020447

[34] Boumallessa, Z., Chouikhi, H., Elleuch, M., & Bentaher, H. (2023). Modeling and optimizing the maintenance schedule using dynamic quality and machine condition monitors in an unreliable single production system. *Reliability Engineering & System Safety*, *235*, 109216. https://doi.org/10.1016/j.ress.2023.109216

[35] Khan, M. F. I., & Masum, A. K. M. (2024). Predictive Analytics And Machine Learning For Real-Time Detection Of Software Defects And Agile Test Management. *Educational Administration: Theory and Practice*, *30*(4), 1051-1057.