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MetaOmniCity: Towards immersive urban metaverse cyberspaces using smart city digital twins

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ABSTRACT The movie — The Matrix (1999) — boosted our imagination about how further we can be immersed within the cyber world, i.e., how further the cyber world can be indistinguishable from the real world with the metaverse space travel. Nobody had expected involving the creators that the aspirational fictional virtual worlds such as "ActiveWorlds (1995)", and "Second Life (2003)" with many urban experiences embedded into a rich featured 3D environment would impact the way of experiencing our real urban environments. Are we going to feel/become ourselves — our cyber-physical presence (e.g., our augmented avatars) — in other mirror worlds doing many other things? Are the created imaginary worlds becoming a part of the real worlds or vice versa? The recent once-in-a-lifetime pandemic has confirmed the importance of location and time-independent Digital Twins (DTs) (i.e., virtual scale models) of cities and their automated services that can provide everybody with equity and accessibility by democratising all types of services leading to increased Quality of Life (QoL). This study analyses how the metaverse (3D elevation of linear Internet), that aims to build high-fidelity virtual worlds with which to interact with the real world, can be engaged within the Smart City (SC) ecosystem with high immersive Quality of Experiences (QoE) and an urban metaverse ecosystem framework — MetaOmniCity — that is designed to demonstrate a variety of insights and orchestrational directions for policymakers, city planners and all other stakeholders about how to transform data-driven SCs with DTs into virtually inhabitable cities with a network of shared urban experiences from a metaverse point of view. MetaOmniCity, allowing the metaversification of cities with granular virtual societies, i.e., MetaSocieties, and eliminating the boundaries (e.g., time, space and language) between the real world and their virtual counterparts, can be shaped to the particular requirements and features of cities. This can pave the way for immersive globalisation with the bigger and richer metaverse of Country (MoC) and metaverse of World (MoW) being an immersive DT of the broader universe with digitally connected cities by removing physical borders. MetaOmniCity is expected to accelerate the building, deployment, and adoption of immersive urban metaverse worlds/networks for citizens to interface with as an extension of real urban social and individual experiences.

INDEX TERMS Metaverse, smart city (SC), Digital Twins (DTs), avatars, blockchain, Augmented Reality (AR), Virtual Reality (VR), Web 3.0, web3.

I. INTRODUCTION

THE movie — The Matrix (1999) — boosted our imagination about how further we can be immersed within the cyber world, i.e, how further the cyber world can be indistinguishable from real worlds. Nobody had expected that the aspirational creations such as "ActiveWorlds (1995) [1]", "Second Life (2003) [2]" as online fictional virtual worlds with many urban experiences embedded into rich, 3D environments would impact the way of experiencing our real urban environments. The vast landscape of "Second Life" consists entirely of user-generated content, built by someone else — an avatar controlled by a live human user; these avatars build and buy homes, form friendships, get married, and make money; An avatar named Wendy, whose creator always makes her go to sleep before she logs out; "So the actual world is Wendy's dream until she wakes up again in

[1]https://www.activeworlds.com
[2]https://secondlife.com

Second Life" [1]. Will it be good for us to live in a remote world designed by us to feel as powerful as God? Are we going to watch ourselves (e.g., our 3D avatars) in other mirror worlds doing many other things? Will our avatars — digital human twins — present in remote urban real-world locations in real-time for solving particular real-world problems? Are the created imaginary worlds becoming a part of real worlds or vice versa?

The concept of Digital Twins (DTs) attributed to NASA (2012) was constructed to integrate ultra-high fidelity simulation with the vehicle's on-board integrated vehicle health management system, maintenance history and all available historical and fleet data to mirror the life of its flying twin and enable unprecedented levels of safety and reliability [2]. DTs, with the main components i) a physical entity, ii) a virtual representation entity of that entity, and iii) bidirectional near-real-time data streaming between these two entities, have changed the way of procedures in each discipline. The once-in-a-lifetime pandemic has forced many to rely on digital technology as the only way to communicate, collaborate, learn and sustain our lives [3]. In the same manner, with decreasing contact with the real physical world and people, the recent pandemic has confirmed the importance of location and time-independent DTs (i.e., digital replicas) of cities and their enabled remote services that can provide everybody with equity and accessibility, in particular, senior citizens and disabled residents by democratising all types of services leading to increased Quality of Life (QoL) with societal flourishing. Data-centric Smart City (SC) DTs are analysed in Section III-B4 in detail leading to the establishment of urban metaverse worlds, i.e., urban crypto worlds. The pressure is growing on city governments to leverage every opportunity to improve QoL for inhabitants [4] due to the ever-growing demands of citizens, economic concerns, and imminent environmental risks. In this manner, to alleviate the problems of rapid urbanisation and improve the liveability of citizens, there are many concerns to be taken into account in urban development and efficient urban management with effective public services. In a broader inclusive definition, SC can be defined as an opportunistic concept that enhances harmony between the lives and the environment around those lives perpetually in a city by harnessing smart technology enabling a comfortable and convenient living ecosystem paving the way towards smarter countries and a smarter planet [5]. SCs are being implemented to combine governors, organisations, institutions, citizens, environment, and emerging technologies in a highly synergistic synchronised ecosystem to increase QoL and enable a more sustainable future for urban life with increasing natural resource constraints [5].

"Avatar" comes from the Sanskrit word avatāra meaning "descent"; Within Hinduism, it means a manifestation of a deity in bodily form on earth, such as a divine teacher; It technically means "an incarnation, embodiment, or manifestation of a person or idea" [6]. In this paper "3D Avatars" — pseudo-physical presence (i.e., digital image) of users — are the residents of the worlds — so-called "Metaverse" first used by Neal Stephenson in 1992 in his novel "Snow Crash". In "Snow Crash", players can teleoperate among multiple parallel lives in an immersive virtual world enriched with Virtual Reality (VR) to challenge each other for social status using their avatars. Recent advances in metaverse technologies are providing many opportunities and urging city governments to change the way of managing cities more intelligently in location and time-independent high-fidelity virtual worlds. A metaverse can be defined as the expansion of DTs in the fields of people and society [7] and as the digital extension of our physical world equipped with Mixed Reality (MR). It provides us with an immersive environment to perform our daily routines in the physical world. The metaverse helps reduce the perceived differences between the real and virtual worlds. How the metaverse can contribute to the smartness of urban life is analysed within this paper. SCs, with DTs, are expected to significantly benefit from the promising potentials of the metaverse in the most optimum way. The combination of metaverse and SC will increase further in the forthcoming periods, and this will affect urban life by spreading to all SC applications [8]. The South Korean capital, Seoul, has already invested billions into the urban metaverse project to be the first metaverse SC and to make the city more functional and lively by overcoming temporal and spatial restrictions. The metaverse, by combining the real environments with DTs enriched with AR and by providing users with a highly realistic experience, help incorporate next-generation innovative technologies into the SC concept to create a location- and time-independent, smarter, lively, sensing, and embracing city ecosystem that can behave like the physical city and can be nurtured continuously with user partnerships (e.g., the creation of interoperable 3D avatars, digital services and virtual real-world equivalent experiences). It, with more realistic DTs, is expected to improve SC services further and unite cities to the residents and universe on a more realistic immersive nature that can be grasped by the human brain and easier to engage with. SCs using the metaverse are being implemented to combine governors, organisations, institutions, citizens, environment, and emerging technologies in a highly synergistic, immersive, synchronised ecosystem to embody.

It is worth noting that the metaverse indicates a broad description of the development of many types of real-world-like parallel virtual worlds using the 3D elevation of linear internet —so-called — "second-generation of the internet". In this paper, The metaverse is examined with a particular emphasis on the SC concept with a new terminology, MetaOmniCity representing the location- and time-independent real-world-like omnipresent in a multitude of urban virtual evolving worlds augmented with reality (i.e., hybrid urban spaces) with a high-level of user-centric immersive exploration. MetaOmniCity aims to enable citizens to interact with the city ecosystem using real city data in a more immersive way. To the best of the observed knowledge, this is the first comprehensive study that highlights a research gap in establishing urban metaverse worlds using SCs with DTs.

While aiming to fill this gap, particular contributions in this paper are outlined as follows.

1) How to make urban metaverse worlds a reality is analysed with key aspirations — real-world urban metaverse initiatives with successful use cases, future urban metaverse development plans, potentials of recent and future technological developments and the expectations and requirements of city residents.
2) A roadmap with a framework — MetaOmniCity — is designed to facilitate the building of community- and citizen-tailored high-fidelity virtual urban metaverse cyberspaces (Urban metaverse as a Service (UMaaS)) for future sustainable smart urbanism in which the city productivity and wealth, and QoL can be increased substantially benefiting every citizen with location- and time-independent omnipresent and enabling innovation and economic development within a city.
3) MetaOmniCity aims to show concrete technical-oriented directions infused by social dynamics about how cities can engage with the metaverse to make the residents feel the city in a collaborative and immersive 3D metaverse cyberspaces where the two worlds — physical and virtual — can be more tangibly connected with highly immersive Quality of Experience (QoE).

The remainder of this paper is organised as follows. The related works are presented in Section II. The proposed methodology — MetaOmniCity — is introduced in Section III. Section IV discloses the essential challenges in developing urban metaverse worlds. The lessons learned are unfolded in Section V. Discussion along with open issues in developing urban metaverse worlds is provided in Section VI. Finally, Section VII concludes the key findings and outlines potential future directions.

II. LITERATURE REVIEW

In a broader perspective, the metaverse taxonomy, definitions, architecture, applications, challenges, issues, solutions, and future trends are reviewed in [9], [10], [11]. Artificial Intelligence (AI) specific to the metaverse is surveyed in [12] and the fusion of blockchain and AI with the metaverse is surveyed in [13]. Blockchain-empowered service management for the decentralized metaverse of Things (MoTs) is analysed in [14] at aiming to resolve the problem of synchronized data transmission and service provision through multiple devices to ensure immersive engagement of end users through all available means of sensing and visualization. A basic metaverse framework is analysed from the aspects of graphics, user interactions and visual construction of metaverse worlds as well as the construction of visual DTs in [15]. Building metaverse cyberspaces using DTs at all scales, states, and relations is analysed in [16]. Some of the key issues required in order to realise metaverse services based on DTs are discussed in a short paper in [17].

From an SC perspective, the metaverse fundamental technologies for SC are surveyed in a highly restrictive concept as a short paper in [18]. The vision of using Non-Fungible Tokens (NFTs) — blockchain-based tokens — in SCs is analysed in [19]. More specifically, the main components of NFTs and how smart city applications, such as smart governance, smart services, smart economy, smart industry, smart environment, and smart mobility and transportation, can benefit from them are described in the study. In a narrower SC domain concept: a survey on current metaverse applications in healthcare regarding the SC health and welfare domain is performed in [20], [21], [22]; A theoretical framework by reviewing literature and synthesising best practices in designing metaverse learning environments regarding the SC education domain is proposed in [23]; Extensible metaverse Implication for an SC regarding the SC tourism is disclosed in [24]. The metaverse applications built for specific SC domains are elaborated in Section III-A3.

There is a research gap in establishing urban metaverse worlds using SCs with DTs. This study aims to fill this gap. This paper, within a holistic framework different from the studies in literature, aims to help the metaverse concept, i.e., the 3D version of the internet, to mature in urban environments in terms of the design and development of virtual and augmented urban spaces. The designed framework, the so-called MetaOmniCity, is designed to demonstrate a variety of insights and orchestrational directions for policymakers, city planners and all other stakeholders about how to transform data-driven SCs with DTs into virtually inhabitable cities from a metaverse point of view. MetaOmniCity, allowing the meta-versification of cities with MetaSocieties and eliminating the boundaries (e.g., time, space and language) between real worlds and their virtual counterparts, can be shaped to the particular requirements and features of cities and urban social dynamics.

III. METHODOLOGY: METAOMNICITY

Social media focuses on content creation rather than creating experiences. “Experiences” are the main focus of the metaverse. In this treatise, MetaOmniCity, as conceptualised in Fig. 1, is designed to guide the local governments in developing immersive urban metaverse worlds and to provide residents with highly realistic immersive experiences with rich urban activities using numerous metaverse tools and utilities. Background of this research involving urban use-cases of the metaverse and future urban plans with the metaverse is analysed in Section III-A before exploring MetaOmniCity in Section III-B in detail in order to conceptualise the MetaOmniCity framework in a better way.

A. BACKGROUND

1) Smart Cities (SC)

The concepts of Internet of Everything (IoE) and Automation of Everything (AoE) [42] brings the people, organisations, lives, processes, data, and things into a concrete coherent structure — Cyber-Physical Systems (CPSs) to develop a synergistic smarter connected globe [5]. SC is defined as a city connecting physical infrastructures, Information Communication Technology (ICT) infrastructures, social infras-

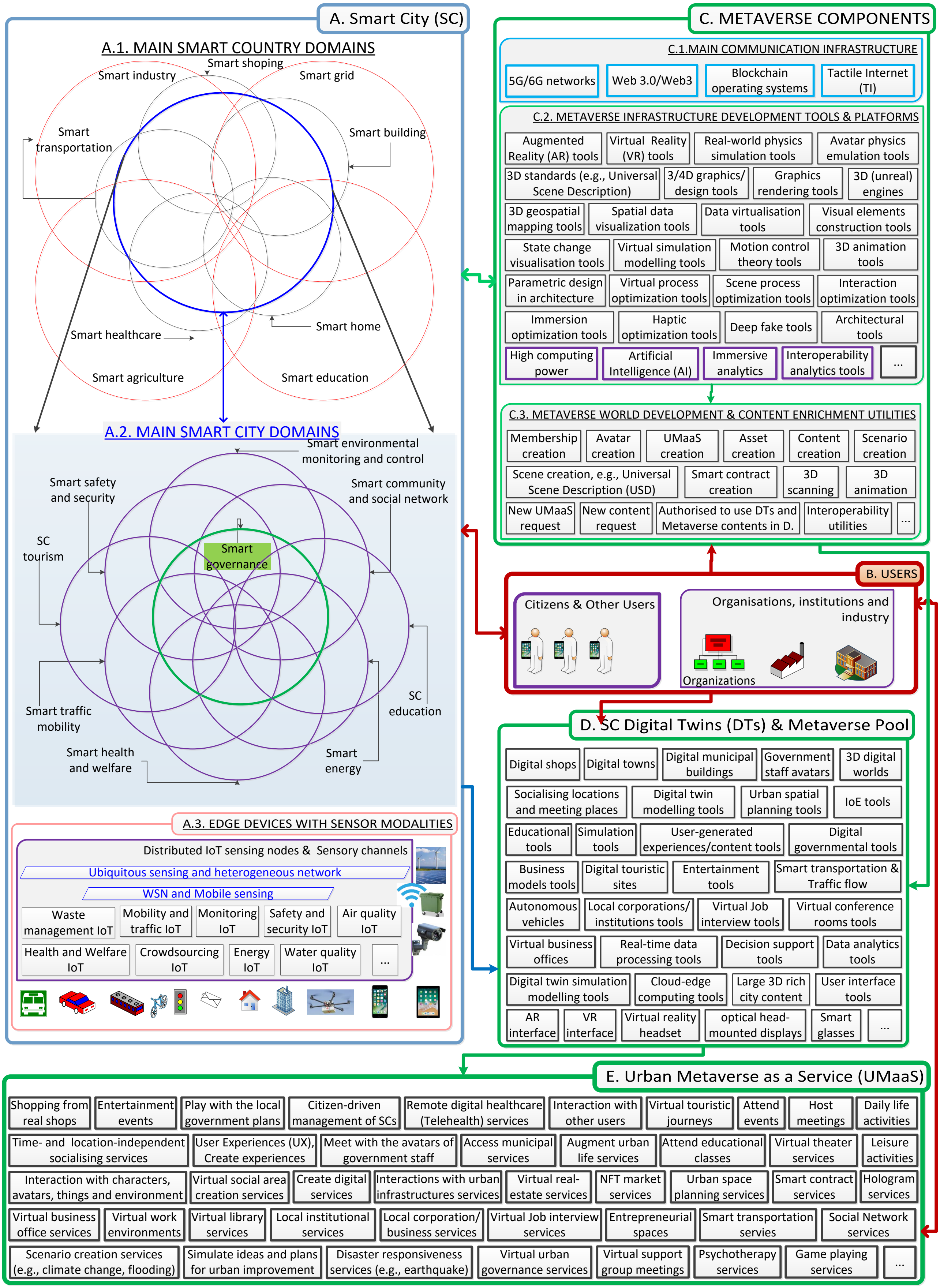

FIGURE 1: Architectural framework of MetaOmniCity: Main components of MetaOmniCity and their interaction with each other.

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TABLE 1: Public sector, local businesses and community engagement in the urban ecosystem using the metaverse.

Metaverse Platform	Subject	Particular implementation	City
Metaverse Seoul	Smart governance, smart tourism	urban metaverse platform combines DTs, virtual reality (VR) and collaboration to improve city services as well as planning, administration and support for virtual tourism. Users can create avatars and explore a virtual representation of the mayor's office [25], Seoul FinTech Lab, Invest Seoul and Seoul Campus Town [26].	Seoul
Metaverse Seoul	Smart governance, smart environmental monitoring	The S-Map service provides a DT for urban planning, real-time fire monitoring and wind path analysis [25].	Seoul
Metaverse Seoul	Smart safety and security	A safety service called the Ansimi App connects users with Seoul police services, who can tap into local location data and camera feeds to speed investigations [25].	Seoul
Metaverse Seoul	Smart community and social networks, smart industry	A business services portal is providing startups for new business ideas and services [25].	Seoul
Metaverse Seoul	Smart community and social networks	More than 16,000 people joined a year-end bell-ringing festival hosted by the Seoul city government in the metaverse [27].	Seoul
Metaverse Seoul	Smart community and social networks, smart education	An educational portal brings together 34 campus towns to provide coaching, collaboration and networking opportunities [25].	Seoul
Virtual London (ViLO)	Smart community and social networks	The ViLO platform integrates the real-time weather information, that affects the visual aspect of the digital model [28].	London
Virtual London (ViLO)	Smart transportation	A specific emphasis was put on the visualisation of mobility data sets. ViLO has the capability to retrieve and visualise the location and data of bike-sharing docks, bus networks and tube lines, including the location of bus stops and tube stations and the real-time position of buses and trains [28].	London
Play-to-Earn Metaverse	Smart industry	The city is using the metaverse to gamify its shopping district via user interaction by earning tokens to put in digital wallets and purchase physical items in the city shops [29]. This platform uses Pokemon Go like gamification of the city streets enriched with more socially immersive ideas similar to the TikTok applications.	Santa Monica
Real-Based Metaverse: 'AR Incheon'	Smart tourism	AR service in Incheon is more than other simple AR services such as the delivery of information through digital display, description, and guide content which most SCs and museums provide. It provides AR navigation service and AR map, but it is differentiated by providing historic maps and experiences from the past. It engages the users in the environment(real world), providing Extended Reality (XR) experience, such as environment-related historic figures guiding the tourists, a panoramic virtual mirror world through AR where tourists can share experiences on the social network, seamlessly connecting real-world based and virtual world based metaverse [30].	Incheon
Virtual-Based Metaverse: 'Incheon-craft'	Smart tourism	Incheon developed metaverse entertainment content which provides 'Incheon experience' through using Minecraft. Integrating Minecraft, a sandbox game in which players explore a virtual world freely as avatars. This enabled users to create and experience Incheon without limits in the metaverse world, allowing Incheon to deliver the smart metaverse experience to tourists without their physical visit [30].	Incheon
Metaverse Seoul	Smart tourism	Virtual tourism services will allow locals and international visitors to explore current attractions and historical recreations [25].	Seoul
Virtual London (ViLO)	Smart tourism, smart governance	The ViLO model is composed of above ground and underground infrastructure and it is an interactive and collaborative digital platform used to visualise and analyse spatio-temporal urban datasets [28].	London
Liberland Metaverse city	Smart tourism, smart industry	It is a digital replica (i.e., cyber-urban) of the physical micronation of the Republic of Liberland in the metaverse where people can buy plots of land with cryptocurrency and enter digital buildings as an avatar [31].	Liberland

tructures, and business infrastructures to leverage the collective intelligence of the city [43]. The main objectives of establishing SCs can be summarised as i) enabling the integration of the distributed services and resources in a combined synergistic fashion, ii) improving existing public services and providing new effective citizen-centric, user-driven, and demand-oriented services, iii) monitoring a city with easy-to-use visualisation tools, iv) enabling near-real-time services for end-users and/or further smart actuation, v) increasing the sustainability with optimised services, vi) improving the lives and livelihoods of citizen, and vii) drive economic development, innovation and global city investment competitiveness [5].

Readers are referred to [5] for the technological infrastructure of SCs involving communication networks and further information about real-world SC use cases. To summarise, its main layers enabling proper sensing and appropriate autonomous actuation are i) strictly engagement with all the stakeholders, ii) edge IoT devices and citizens to collect data and interact with the environment intelligently by harnessing large amounts of near-real-time data using sophisticated communication technologies, iii) edge/fog platforms, iv) the cloud platform involving cloudlets, and v) integration of smart domains not only within itself but also with the national and global smart domains. The main smart elements of SC are shown in Fig. 1 A.2. The other smart domains into which SC (Fig. 1 A.1) is incorporated to create a synergistic implementation enabling a gate to the development of a group

TABLE 2: Future urban plans with the metaverse.

Metaverse Platform	Subject	Particular Objective	City
Metaverse Seoul	Smart governance	An AI-based public servant will work in the metaverse office in close collaboration with others for public services [25].	Seoul
Metaverse Seoul	Smart Governance	The project aims to create a metaverse ecosystem for all areas of its municipal administration, such as economic, cultural, tourism, educational and civic service [26].	Seoul
Metaverse Seoul	Smart Governance	The government will open "Metaverse 120 Center", a virtual public service centre. The avatar public officials in the metaverse will provide convenient consultations and civil service, which was available only through the civil service centre at Seoul City Hall [26].	Seoul
Makassar Metaverse	Smart Governance	The concept of Makaverse Metaverse is a continuation of Sombere and SC, that uses technologies to support interaction and information solubility by the City Government in improving public services [32].	Makassar
Jakarta Metaverse	Smart Governance	The Provincial Government of Jakarta has established a strategic partnership to develop a metaverse platform with PT WIR Asia Tbk (WIR Group) – a leading AR-based technology company in Southeast Asia – to realise the vision of Jakarta as a developed city with excellent public services [33].	Jakarta
Five-year plan	Smart governance, smart industry	First mention of metaverse in China, it encourages the application of the metaverse in areas such as public services, business offices, social entertainment, industrial manufacturing, production safety and electronic games [34].	Shanghai
Two-year Metaverse innovation	Smart governance, smart industry, smart education, smart tourism	Beijing's innovation plan is aimed at promoting the development of metaverse-related industries and helping the capital of China build a benchmark city for its digital economy, which would require every district to adhere to the new Web3 innovation plan; It promotes digital education scenarios, supports in-depth cooperation between metaverse-related technology companies and educational institutions, expands intelligent and interactive online education models, and develop industry-wide digital teaching platforms. [35].	Beijing
Metaverse Seoul	Smart governance, smart industry, smart education	The long-term vision is to add support for business development services, education and support for city services for filing complaints, inquiring about real estate and filing taxes [25]. The platform will be expanded to all areas of its municipal administration in order to increase the working efficiency of government officials [26].	Seoul
10 measures	Smart governance, smart industry	Guangzhou's Huangpu district released a document with 10 measures for promoting innovation and development in the metaverse — the first official policy support for the metaverse in the Guangdong-Hong Kong-Macao Greater Bay Area [36].	Guangzhou
Metaverse Seoul	Smart industry	The project will provide virtual coworking spaces to allow citizens to work remotely as if working in a real office [25].	Seoul
2022 work plan	Smart industry	The local government has announced plans to embrace the metaverse to boost its pandemic-devastated economy by integrating the metaverse, blockchain, big data, cloud computing, geospatial information and quantum technology into its economy [37].	Wuhan
Metaverse Hub	Smart industry	The initiative outlined several major objectives in 2023, including establishing a full supply chain and industry ecosystem, enhancing innovation, and fostering the use of metaverse applications in sectors such as e-commerce and entertainment with competence in AR, VR, MR, blockchain, and AI industries [38].	Zhejiang
Technology Plan	Smart industry	The local government has declared to invest in the metaverse to boost its industry in the years to come [39].	Hefei
Dubai Metaverse	Smart industry	The Dubai Metaverse Strategy aims to turn Dubai into one of the world's top 10 metaverse economies as well as a global hub for the metaverse community. The strategy aims to build on Dubai's achievement of attracting more than 1,000 companies in the fields of blockchain and metaverse using Web3 technology. It also promotes Dubai's ambitions to support more than 40,000 virtual jobs by 2030 [40].	Dubai
Metaverse Barbados embassy	Smart industry, smart governance, smart tourism	Barbados is preparing to legally declare digital real estate sovereign land with the establishment of a metaverse embassy. The various projects will be assisting with identifying and purchasing land, architecting the virtual embassies and consulates, developing facilities to provide services such as "e-visas" and constructing a "teleporter" that will allow users to transport their avatars between the various worlds [41].	Barbados
Metaverse Seoul	Smart tourism	Seoul's major tourist attractions, such as Gwanghwamun Plaza, Deoksugung Palace and Namdaemun Market, will be introduced through the "Virtual Tourist Zone", and lost historical resources, such as Donuimun Gate, will be recreated in the virtual space [26].	Seoul
Metaverse Seoul	Smart safety and security	The government will develop services for the socially vulnerable including safety and convenience content for people with disabilities using extended reality (XR) [26].	Seoul

of SCs and consequently smart states and smart countries are explicated in [5] as well. The development of DTs is an indispensable part of establishing SCs and data-centric SC DTs are examined in Section III-B4.

2) Metaverse

A metaverse can be defined as "democratised, decentralised, user-driven virtual and augmented immersive 3D spaces where two worlds — virtual and physical existence — can

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be more tangibly connected and people who are not in the same physical space can come together with their avatars to feel many different types of experiences". The metaverse — a blended harmonised virtual and physical existence — aiming at developing high-fidelity virtual worlds as rich as the real world, is still in its infancy, requiring a great deal of evolution. First and foremost, open-source metaverse development platforms are in high demand and they are expected to expedite the development of many undiscovered metaverse experiences. Truly persistent and immersive computing, at scale and accessible by billions of humans in real time, will require a 1000 times increase in computational efficiency from today's state of the art [3] where a standard kind of Moore's law curve is only going to get us to about 10 times growth over the next five years based on hardware improvement and high computation requirement can be alleviated by energy-efficient computing, better algorithms, better architectures as stated by Intel to balance 1000 times improvement [44]; an example of which is Ethereum's "transition to a mechanism known as proof of stake" to reduce their energy use around 99% with energy-efficient computing and processing. Limited by resources, computing power with edge intelligence, and sensory devices, the metaverse is still far from realising its vision of immersion, materialisation, and interoperability [45].

Blockchain, a type of Distributed Ledger Technology (DLT), is implemented as a decentralised Peer-to-Peer network and stores a digital ledger in a distributed and secure manner; Smart contracts extend the capabilities of the blockchain technology; they are executable codes that can softwarise all the terms and conditions of an agreement between various entities and are deployed on the blockchain; Some of the advantages provided by smart contracts are automation, access control, trust-building, and elimination of third-party execution [46]. Blockchain can be actively utilised in urban metaverse worlds as digital proof of asset ownership. The key components of the metaverse (Fig. 1 C) in developing urban worlds are investigated in Section III-B while exploring the proposed framework — MetaOmniCity — in this research.

3) Urban use cases of Metaverse and future trends

We are employing technology to solve our urban problems and enhance the life quality of citizens. How can the metaverse be deployed to serve this purpose? How the metaverse is currently contributing to the urban ecosystem and will add value in the future regarding the future urban metaverse plans is investigated in this section. Smart virtualisation of urban living and working has already started in various cities in numerous forms. Seoul, the first metaverse SC, has pioneered numerous urban metaverse projects. Santa Monica becomes the first U.S. city to join the metaverse [29]. The engagement of the metaverse with SC applications is increasing exponentially as a part of smart urbanisation. The real-world urban metaverse use cases that are still in their early development stages are presented in Table 1 to reveal how cities are engaging with the metaverse. Moreover, the targeted future urban metaverse objectives, trends and demands in the public and private sectors are demonstrated in Table 2 to reflect how cities may engage with the metaverse in the years and decades to come. Many local governments in cities, particularly, in China, have recently announced their metaverse plans to transform their SC applications into metaverse environments. There is no representative initiative for a comprehensive urban metaverse space development and MetaOmniCity designed and proposed in this study aims to help city managers first envision and then generate this environment through identifiable agreed-upon guidelines.

B. INFRASTRUCTURE OF METAOMNICITY

Urban metaverse cyberspaces can mainly contribute to better democratisation of city services with increased User Experience (UX) and Quality of Services (QoS) leading to increased QoL. MetaOmniCity allows residents to experience urban elements simultaneously through urban DTs and user-friendly metaverse utilities and tools. The general infrastructure of the MetaOmniCity framework with the key enabling technologies is depicted in Fig. 1.

1) Urban Metaverse communication infrastructure on a decentralised network (Fig. 1 C.1)

The engines of the metaverse communication infrastructure on which metaverse applications can run seamlessly are placed in Fig. 1 C.1. The foundational pillars of this infrastructure are 5G/6G networks, Web 3.0/Web3, Blockchain operating systems and Tactile Internet (TI).

The communication infrastructure in cities to establish SC applications has already been analysed in my previous research [5], [47], [48]. Therefore, this subject is not elaborated in this paper and the readers are referred to these studies about the communication technologies employed in SCs. To summarise, city communication infrastructure provides large-scale machine-type communications with a multiplicity of communication modalities using an orchestration of backhaul and fronthaul (i.e., crosshaul) mechanisms. Delays in data processing and user feedback deteriorate users' immersive experience leading to serious cybersickness. Moreover, the disorientation of various feedback (e.g., audiovisual information and haptic data) is prime important not to cause cybersickness. With 1 ms Point-to-Point (P2P) data transfer capability in 4G, the End-to-End (E2E) round-trip latency is 20-25 ms for an ideal environment, which clearly indicates that 4G is not able to meet the stringent requirements of tactile response and immersive requirements [49], [50]. On the other hand, with 0.1 ms P2P data transfer capability, 5G communication technology within a decentralised architecture enabling Ultra-Reliable and Low-Latency Communication (URLLC) with i) enhanced mobile broadband (eMBB) focusing on high-resolution multimedia services, ii) massive Machine-Type Communications (mMTC) focusing on IoT services enabling communication for a million devices/km^2 [51], and iii) distributed computing abilities focusing on the accommodation of the ubiquitous implementation of applications within location-independent heterogeneous environments using Software-Defined Networking (SDN) and Virtual Network Function (VNF) (e.g., Network Function Virtualisation (NFV)) where they are complementary to one another and it takes its indispensable place in IoE mobile applications. The integration of generic services such as eMBB, mMTC, critical Machine-Type Communication (cMTC), and URLLC can improve the performance of 5G-based applications; this service heterogeneity can be achieved by network slicing for an optimised resource allocation and an emerging technology, TI, to achieve low latency, high bandwidth, service availability, and E2E security [52]. This communication infrastructure helps a bidirectional stream of near-real-time information, knowledge and wisdom [53] between the physical and virtual environments of SC blended DTs that is investigated in III-B4 with related metaverse content.

Instant feedback through the metaverse technologies (e.g., high-definition (HD) rendering, smart wearable devices, haptics (tactile and kinesthetic) (sense of touch), audiovisual modalities, olfactory (sense of smell), gustatory (sense of taste)) is going to play a pivotal role in establishing a strong immersive metaverse implementation that enables a tight interface between the physical and virtual worlds by coupling with artificial sensors and actuators. Haptics, as an extension of visual and auditory modalities, refer to both kinaesthetic and tactile information and include position, velocity, force, torque, vibration, etc [54]. With the advent of commercially available haptic/tactile sensory and display devices, conventional triple-play (i.e., audio, video, and data) communications now extend to encompass the real-time exchange of haptic information (i.e., touch and actuation) for the remote control of physical and/or virtual objects through the Internet [55]. Furthermore, a lot of more novel, intelligent, user-friendly haptic devices are emerging with the advent of new functional materials, smart actuators and sensors, embedded computers, and the latest advances in real-time intelligence, Machine Learning (ML), cognitive science, and AR/VR/MR [56] leading to a better bilateral exchange of energy between two remote nodes. These advancements are highly supported by the standardisations of haptics on an application basis, e.g., IEEE P1918.1 [57].

User-centric and decentralised Web 3.0, with rich media content, semantic immersive UX and AI capabilities, has changed our communication and interaction behaviours significantly compared to one-way text-based Web 1.0 and ubiquitous vision-based user-driven Web 2.0. Furthermore, the incorporation of blockchain technologies into Web 3.0 has created a more evolved decentralised web — Web3. Web3, using multiple operating systems, provides data sovereignty (e.g., creative asset sovereignty) for individuals allowing a more advanced user-centric decentralised network with further individual data management capabilities. While 5G technologies are taking their indispensable places in real-world implementations, it is worth mentioning that future 6G, at the expense of increased complexity, considers not only delivering another 1000x increase in data rates, but also diving into self-sustaining networks and dynamic resource utilisation; 6G will also put an end to smartphone-centric networks, introducing new system paradigms (e.g., human-centric services) [58]. 6G, not only promises to connect things with URLLC (1 microsecond latency) leading to no delay in real-time, but also promises to connect things intelligently with ultra-high density connections (i.e., over 100 devices per cubic metre). In this sense, the use of location awareness immersive technologies, AR/VR/XR/MR as well as holographic communication, will be eased with 6G since intelligence, as the key component of immersive technologies, is connected. The combination of blockchain and 6G allows the streamlining of a peak rate of 1 Tbit/s [46] using a Terahertz-sized frequency band to achieve a network delay with a transmission rate of less than 1 ms and the probability of communication interruption less than one in a million using spatial multiplexing technology [45] and many SC initiatives are very much familiar with Web3 by using blockchain technologies for their various applications. Blockchain technologies, enabling individual data ownership, are already being used by cities to store, share and process the information that is under the control of the users. Readers are referred to [59] for the SC blockchain application examples. The widespread use of current blockchain technologies as well as newly developing blockchain technologies specific to the urban ecosystem in establishing SC DTs (i.e., digital shadows of avatars of the urban ecosystem) will boost and ease the integration of these technologies into establishing UMaaS worlds. An example of applying blockchain technologies into metaverse virtual spaces for ensuring timely multi-scale spatial data processing using a data layer between physical worlds and their DTs is presented in [7].

2) Metaverse infrastructure development tools and platforms (Fig. 1 C.2)

The elements of the metaverse infrastructure building tools and platforms are placed in Fig. 1 C.2. Some of these tools and platforms are AR/VR, real-world physics simulation, avatar physics emulation, open source 3D standards (e.g., Universal Scene Description), 3D/4D graphics/design and rendering (e.g., Unreal Engine), 3D geospatial mapping and visualization, state change visualisation, virtual simulation, motion control theory, and optimisation. The targeted outcome of these tools can be shaped with AI, Immersive analytics, and most importantly interoperability analytics tools to yield platform-independent products using high computing power. These tools and platforms are still being developed. They need to be advanced further and need to be readily accessible to the engineers in the metaverse development community at affordable prices. These tools and platforms can only be developed by a group of engineers from different disciplines and they are required to enable trained engineers to deploy "Metaverse world development and content enrichment utilities" which are demonstrated in Fig. 1 C.3

and elaborated in Section III-B3. No single company has sufficient resources to create these tools alone on a wide scale since the rich diversity of these technologies require multiple technology companies to mould their expertise in an advanced metaverse infrastructure development platform. Companies from various disciplines with varying skills and a rich variety of enabling technologies need to collaborate to build advanced metaverse development platforms using a broad amalgamation of advanced technologies leading to an increase in impressiveness. Nowadays, 3D/4D design (e.g., CAD) platforms are the essential employed tools before the production of goods in almost every industry. The companies that are developing applications that can be used to design 3D virtual products are expected to be a part of developing the metaverse 3D/4D design tools. The companies that are producing multi-user competitive games are expected to develop advanced AR/VR enrichment tools that can be equipped with AI implementations. The communication network companies will be developing the ideal city communication network environments that satisfy the requirement of Web 3.0, Web3, and TI. Currently, it seems that the aforementioned widespread used technologies can help build advanced metaverse development tools when moulded in a synergistic system by which creativity will drive the metaverse. Technology companies and policymakers should combine their resources with advanced planning to foster international and interdisciplinary dialogue for establishing advanced SC immersive Metaverse parallel worlds.

3) Metaverse world development and content enrichment utilities (Fig. 1 C.3)

The elements of the metaverse world development and content enrichment utilities are placed in Fig. 1 C.3. Some of these utilities are avatar creation, UMaaS creation, asset creation, content creation, scenario creation, scene creation, smart contract creation, and 3D scanning and animation. The members of UMaaS worlds are authorised to use DTs and metaverse contents that are already created and shared as depicted in Fig. 1 D and elaborated in Section III-B4. Trained engineers, people and residents can create and enrich metaverse urban worlds with high-fidelity rich content and experiences representing real-world services using these easy-to-use utilities with functional interfaces requiring no high-level expertise. For instance, current AI technologies such as Ready Player Me/OZ, Unreal Engine, Nvidia, and Microsoft Mesh's Holoporation enable to generate hyper-realistic avatars. Rules, elements and properties of MetaHumans — avatars are elaborated in Section III-B7.

4) SC Digital Twins (DTs) & Metaverse Content

The success of urban metaverse applications depends on the quality of data-driven SC data, the seamless exchange of this data and the processing of the data effectively and efficiently. To this end, the construction of DTs, i.e., blueprints of SCs, that facilitate the means to monitor, understand and optimise the functions and Situational Awareness (SA) of all physical entities by i) pairing of the virtual and physical worlds [60], ii) enabling data to be seamlessly transmitted between the physical and virtual worlds with two-way communication [61] and iii) enabling the virtual entity to exist simultaneously with the physical entity [62] is an integral part of building healthy SCs and UMaaSs augmentation with real-time streaming data. SCs, filled with ubiquitous sensors (Fig. 1 A.3), ease the detection of real urban environments and they stream this information simultaneously to build urban DTs for accurate topography, visualisation, simulation, anticipation, precise interpretation and predictions, and solving urban problems with innovative eco-friendly ways of urban planning benefiting the well-being of citizens. DTs are tied to their physical counterparts in real time using MR to automate tasks and extract insights that can increase the quality of citizens' lives. DTs integrate AI, software analytics, and ML data to create virtual models that update and change as their physical equivalents change [63] with fast and accurate data processing using advanced hardware and communication networks. Through DTs, the real world can be accurately replicated in the virtual plane digitally across multiple levels of granularity and can interact dynamically and evolute synchronously with the virtual twin in the virtual plane [64]. Although the metaverse concept existed 10 years before the emergence of DTs, it is still in the concept stage, and DTs have been widely utilised in industries and other fields [7] given the broad scope of DTs. SCs have been building their DTs (i.e., virtual replicas) of the physical city implementation infrastructure using their technological infrastructure and real-world SC domains using CPSs. Singapore is developing a digital copy of the entire city to monitor and improve utilities [65] using a dynamic model with real-time sensory data. Powered by Unreal Engine, covering almost 4,000 square kilometres and built using information from satellites, drones and sensors in the real Shanghai, the digital replica could soon have the power to simulate events in the city's future with astonishing accuracy [66]. The readers are referred to [5] for many real-world SC implementations all around the world. DTs created within the DUET (Digital Urban European Twins) supported by the EU provide virtual city replicas which make it easy to understand the complex interrelation between traffic, air quality, noise and other urban factors [67]. DUET involves partners from across Europe with a variety of backgrounds from cities to academia, researchers, technologists, and small and Medium-Sized Enterprises (SMEs) and produced numerous SC DTs in multiple cities such as Ghent, Athens, and Pilsen. It is noteworthy to mention that establishment of a city-scale DT with multiple sub-SC domain twins requires the streaming and processing of real-time data from the physical city environment by mimicking the real environment in the same space-time where the two worlds coexist simultaneously. DTs of physical worlds would be the base for developing ultra-realistic metaverse worlds. The more advanced immersive technologies such as TI with quality haptic feedback, the better immersive urban metaverse worlds using urban DTs leading to better

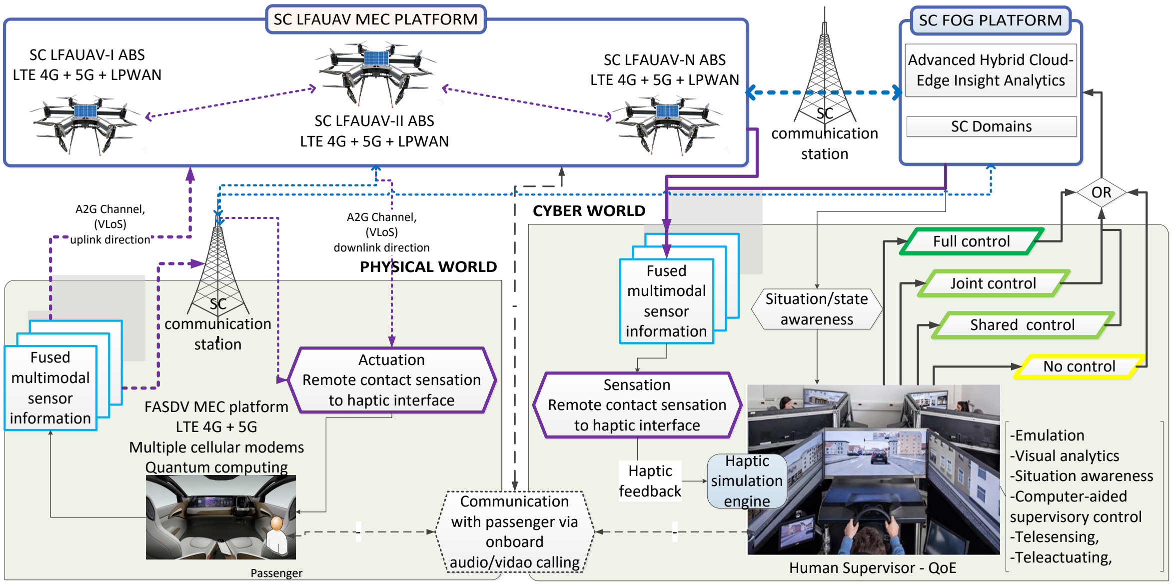

FIGURE 2: Bidirectionally connected DTs of driving an AV in real-world urban environment.Any change in the state of the physical twin is reflected in the virtual counterpart and vice versa any action in the virtual twin is actuated in the physical counterpart [51].

SC services. The concept of the metaverse with its advancing immersive tools would not only enable the development of the realistic modelling of urban processes as they behave in their physical worlds, but also, it would encourage and accelerate further community engagement by addressing user requirements better leading to more advanced models.

It is also worth emphasising that the metaverse is not the equivalent of DTs, it is a concept with a more comprehensive structure, allowing the removal of boundaries between these two worlds as elaborated throughout this paper. A metaverse, which is parallel to the physical world, needs mature and secure DTs technology in addition to parallel intelligence to enable it to evolve autonomously [7]. DT network (DTN) realises co-evolution between physical and virtual spaces through DT modelling, communication, computing, data processing technologies [68] and DTs technology can map the composition, characteristics, functions, and performance of physical entities into the metaverse in real-time [68]. The realisation of the metaverse is highly correlated with the advancements in DTs [17], [68] that reflect the lively atmosphere of a real-time physical entity in which urban physical objects (e.g., roads, buildings) along with real-world real-time data (e.g., traffic flow) are digitised in a moulded environment.

Most of the cities have their multiple 3D models involving underground infrastructure used for planning and construction and these models are categorised as "(high-fidelity virtual) SC physical worlds (twins)" and this should not be confused with "SC DTs". Highly realistic "SC DTs" (i.e., models) are composed of synchronised "(high-fidelity virtual) SC physical worlds (twins)" and related delay-sensitive "SC digital data twins" (Fig. 5) allowing residents and other users to interact with the SC ecosystem that is created similarly to SC ecosystem. In other words, 3D models of SC objects or SC environments (buildings, streets, roads, walkways, etc.) that represent the body of a system (i.e., virtual clone) are combined with their related streamed data that represent the instant dynamics/activities in the body not only to build more realistic systems, but also to make user interactions more realistic. Real SC data is continuously streamed into the data-driven SC DTs simultaneously as in the real SC environment, which makes the interaction feels the same as interacting with the real SC environment.

DTs help map the real-time dynamic features of physical entities to the virtual world in multidimensional space as exemplified in Figs. 2, 3, and 4. One example of the SC DTs is investigated in my previous study in [51] for the urban use of Autonomous Vehicles (AVs). In that research, Human-on-the-loop (HOTL) real-time haptic delay-sensitive teleoperation with AVs is analysed in the aspects of human-vehicle teamwork by establishing two similar remote parallel worlds — real-world vehicle time-varying environment and cyber-world emulation of this environment, i.e., DTs (Fig 2) — in which a Human TeleSupervisor (HTS), as a biological agent, immersed with the absence of cybersickness enables omnipresence through a timely bidirectional flow of energy and information. Again, in my another previous study in [47], the roads of Preston city where our campus is located were designed in 3D forms and a DT was created by streaming the traffic flow data into this high-fidelity virtual DT. Drivers in the city can observe the live traffic at any point by interacting with these points in more realistic 3D environments (Fig. 3) and can choose their most convenient route to their destination based on the visual traffic volumes and congestion patterns. During an SC project, in which I took part, it was possible to stream the traffic data into the

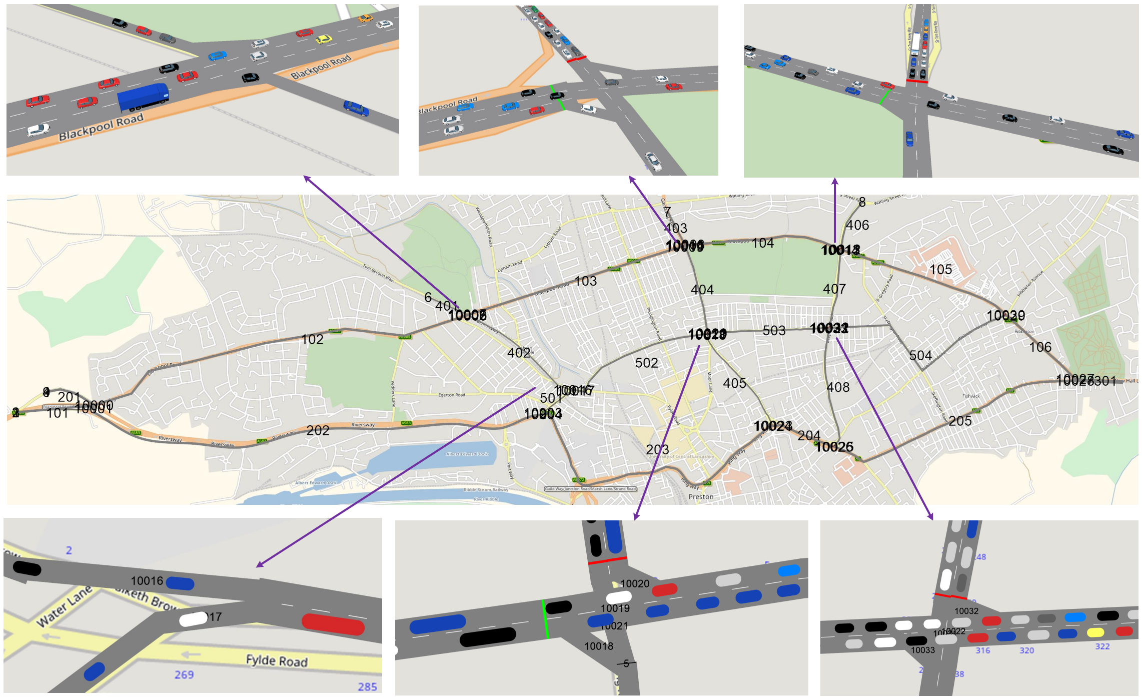

FIGURE 3: DT of the traffic flow in Preston with the streaming of traffic data [47]. 3D urban road modelling and virtual vehicle objects reflecting the streamlining of the real-data traffic flow are blended.

city roads using the smartphone locations and their speeds acquired from a live smartphone-location pool established by the communication companies without using any particular onboard sensors. Another project — Virtual London (ViLO) platform — (Fig. 4) [28] integrates the real-time weather information, that affects the visual aspect of the digital model. Regarding "Smart transportation", a specific emphasis was put on the visualisation of mobility data sets. ViLO can retrieve and visualise the location and data of bike-sharing docks, bus networks and tube lines, including the location of bus stops and tube stations and the real-time position of buses and trains. Regarding "Smart tourism, smart governance", it is composed of above-ground and underground infrastructure and it is an interactive and collaborative digital platform used to visualise and analyse spatio-temporal urban datasets. ViLO has been used to explore the uses of innovative digital technologies, such as VR/AR devices and Game Engine technologies, to enrich the toolbox of architects and urban planners to better communicate current and future urban environments. Residents can visit the SC DTs to observe how the broader picture they are interested in is developing for better decision-making. These similar DTs — digitised copies/mirrors of SC domains — in highly synchronised environments are not only utilised to manage SC assets efficiently and effectively, but also, help SC services to be integrated into the metaverse platforms easier to facilitate a more immersive experience leading to significantly increased quality of urban living. .

SC DTs are the building blocks of urban metaverse worlds. The recent advances in the cyber–physical domains, cloud and edge platforms along with advanced communication technologies play a crucial role in connecting the globe more than ever, which is creating large volumes of data at astonishing rates and a tsunami of computation within hyper-connectivity [53]. Large volumes of BD being generated exponentially in different formats are in the geo-distributed cloud platforms and likely input for all other smart systems and enterprises as insights, which will contribute to the smooth working of these systems and enterprises substantially [53]. New approaches (Ex: Deep Insight-as-a-Service (DINSaaS) [53]) using Federated Learning (FL) need to be developed to process BD in a timely manner by reducing BD transfer and they would be the key pillar in developing intelligent and functional twins. In FL, training data-driven ML models is an act of collaboration between multiple clients without requiring the data to be brought to a central point, hence alleviating communication and storage costs and providing a great degree of user-level privacy [69]. The integration of 6G-enabled AI with FL as next-generation wireless E2E intelligence communication would integrate us with more realistic real-time intelligence by unlocking the potential of BD with high QoE.

Many of the potential urban metaverse worlds are yet to be discovered and developed and the ready-to-use off-the-shelf SC twins and newly built twins are expected to expedite the development of more resilient metaverse implementations in the SC ecosystem. The number of companies that are experienced in the development of particular SC sub-DTs with future smart urbanisation concepts from transportation to green infrastructure is rapidly increasing,

FIGURE 4: Simulation of reality through DTs: ViLO model showing live sensor data on infrastructure equipped with VR and AR [28]. 3D urban modelling and virtual urban static and mobile objects reflecting the streamlining of the real data of CPSs are blended and this scene is augmented with information/knowledge/wisdom from real world activities for effective decision-making.

which will accelerate this evolution further with explosive growth. In the meantime, AR within SC services can be used as a complementary technology to understand the behaviours of urban environments and their physical objects in a much better-visualised way considering the real-physics rules and real data. For instance, the display of instant streamed information (e.g., velocity) over vehicles in urban traffics is complementary information/knowledge/wisdom created by AR as an extension or continuity of life. People, off-site all around the world, can meet with on-site residents in urban environments using their immersive holographic telepresence and communication through immersive interaction. In other words, physical worlds are augmented digitally. On the other hand, VR is the creation of real objects in their DTs or unreal objects that help observe the environment and develop situations better aiming to increase the immersiveness. For instance, the vehicles in Fig. 3 created using VR are the representatives of their counterparts in the real environment or a gigantic police created by VR, not a part of the real environment, can appear suddenly for some time if a vehicle exceeds the speed limit to warn the driver/AV. Residents can create further spaces — user-generated content— parallel to the real world using VR tools. The metaverse tools would turn the DT concept in SCs into another dimension with increasing benefits — immersive coupling with the urban ecosystem. MetaOmniCity is a parallel world of a real city in which the boundaries between the physical entities and their DTs are reduced using the metaverse immersive technologies (Fig. 6). The cities that have already established their DTs within the SC ecosystem would adopt the metaverse technologies more efficiently and effectively than the other cities.

5) Rules, elements and properties of MetaOmniCity

The rules, elements and properties of MetaOmniCity are presented in Table 3. MetaOmniCity is a parallel plane of urban virtual existence, i.e., 3D-rendered virtually shared urban experiences augmented with simultaneous streaming reality using DTs. It is designed to provide residents and other users with immersive and realistic collaboration environments — the so-called Urban metaverse as a Service (UMaaS) (Fig. 5) — to realise urban activities with an increased sense of presence leading to high urban awareness, just as in the real world. The concept of UMaaS is explained in III-B6 in detail. DTs of urban static and mobile objects with their realistic characteristics and behaviours are integrated into MetaOmniCity to realise the visual realism of urban environments.

In addition to SC domains, SC DTs, metaverse development tools and utilities, MetaOmniCity is composed of a collection of metaverse urban rooms/worlds — UMaaSs as exemplified in Fig. 1E. The structural design of MetaOmniCity regarding UMaaSs is presented in Fig. 6. Virtual worlds augmented physically and physical worlds augmented digitally are blurred with decreasing borders in MR. To mitigate the resource and computing constraints regarding the resource-hungry 3D metaverse worlds (elaborated in III-A2), MetaOmniCity consists of multiple, granular, configured, and dedicated UMaaS models that aim to provide users with customised, reduced, and resource-hungry solutions with high QoE while experiencing city-wide events. These virtual spaces, where residents can socialise, interact, work, shop, attend events, etc., can be designed by individuals or authorities or together. An UMaaS, with user-centred multi-player interaction, customises particular urban

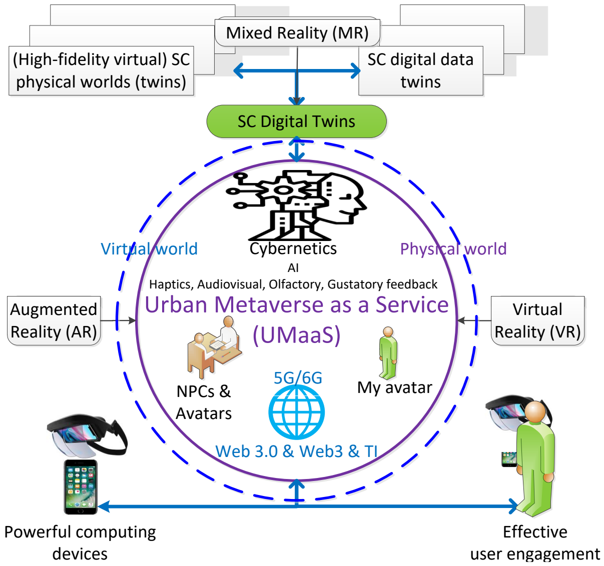

FIGURE 5: Pivotal components of UMaaSs. Blurring borders between virtual and physical worlds.

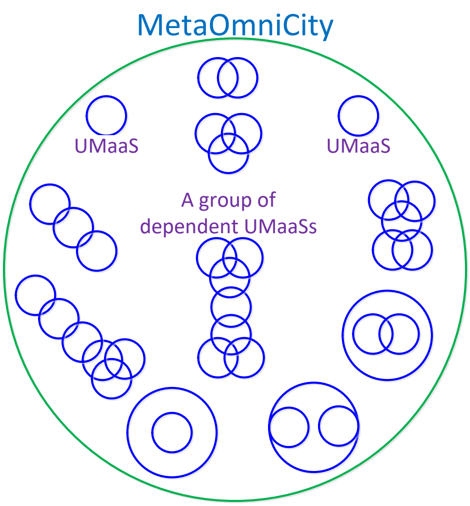

FIGURE 6: Structural MetaOmniCity: Various structural design models of UMaaSs within MetaOmniCity: Jointed (dependent) and unconnected (independent) spaces (Fig. 1E).

metaverse services with a more flexible and scalable design structure permanently (e.g., Intelligent Transportation Systems (ITS)) or on a temporary basis (e.g., concerts). UMaaSs can be tailored and orchestrated in various structural design forms with unconnected virtual spaces (i.e., isolated and jointed/integrated/composite) as exemplified in Fig. 6 to manage services intelligently on an on-demand basis. Isolated UMaaSs correspond to independent operations whereas jointed/integrated/composite UMaaSs indicate interrelated/dependent services. The integration between UMaaSs as jointed UMaaSs is conducted to combine interrelated worlds in an efficient management travel structure. Within a group of jointed UMaaSs, every virtual space has assets, rule sets, members, and relationships to other virtual spaces — 1-to-1, 1-to-many, sharing similar spaces, and a part of a larger space (inclusive), independent spaces within a larger space.

TABLE 3: Rules, elements and properties of MetaOmniCity.

#	MetaOmniCity
1	MetaOmniCity has its user instructions and guidance as well as rules and regulatory procedures.
2	MetaOmniCity is formed by many dependent and independent individuals.
3	MetaOmniCity has its particular data and communication infrastructure (e.g., blockchain operating systems).
4	MetaOmniCity is composed of dependent and independent virtual spaces — UMaaSs.
5	MetaOmniCity has smart contracts to guarantee transactions based on the rules and regulatory procedures.
6	MetaOmniCity targets crime- and criminals-free environments.
7	MetaOmniCity has its own digital assets — physical, content, economic, UMaaSs — created by its users.
8	There are activities (i.e., UMaaSs) designed for resident avatars — e.g., municipal services.
9	There are activities (i.e., UMaaSs) designed for guest avatars — e.g., tourism, shopping, and activities (e.g., concerts).
10	There are collaborative activities (i.e., UMaaSs) (e.g., concerts) designed for any avatars (resident or guest).
11	NPCs, e.g., pedestrians, behave under a set of rules defined for them.
12	MetaOmniCity may have limitless number of avatars.
13	MetaOmniCity may have limitless number of NPCs.
14	MetaOmniCity has its own digital currency — e.g., OmniCur — which can be combined with real money.
15	Residents, with metaverse-enabled AR glasses, can communicate through SC services, SC infrastructure, and SC real-world spaces by augmenting 3D objects in the real world.
16	Virtual shops can be opened using authentication tokens given by the government to avoid scams.
17	Interactions and boundaries between avatars, assets, and other objects e.g., the distance between them, are regulated continuously by CMC specific to UMaaSs.
18	Interoperable MetaOmniCities created for different cities based on the metaverse development standards can be seamlessly connected.

6) Urban Metaverse as a Service (UMaaS)

UMaaSs are the fragment worlds of MetaOmniCity. The rules, elements and properties of UMaaSs are presented in Table 4. The driving components of UMaaS are depicted in Fig. 5. UMaaS is parallel urban rooms within MetaOmniCity, allowing the efficient customisation of particular urban metaverse services. The main building blocks in establishing UMaaSs — moulding the physical world and virtual world within an intertwined environment— are cybernetics, avatars, assets, non-player characters (NPCs) and SC DTs. The aspects of SC DTs are explored in Section III-B4. Granular UMaaSs provide residents with specific immersive shared observations, interactions, collaboration and social experiences via well-designed user interfaces leading to high QoE. The generation of granular UMaaSs would reduce required computing resources at a time significantly. UMaaSs, with rich activities, are the multiple urban metaverse worlds, i.e., co-existence and co-dependence between the physical world and virtual world. UMaaSs, tailored and enriched with individuals' experiences using AR and VR tools, aim to eliminate

TABLE 4: Rules, elements and properties of Urban Metaverse as a Service (UMaaS).

#	Urban metaverse as a Service (UMaaS)
1	UMaaSs can be created permanently (e.g., Intelligent transportation Systems (ITS)) or on a temporary basis (e.g., concerts).
2	UMaaSs are established and enriched by many dependent and independent individuals who are the members of these granular worlds.
3	Each UMaaS (virtual space) has its specific user instructions and guidance as well as rules and regulatory procedures.
4	Each UMaaS has its specific static and dynamic 3D objects and scenes.
5	Behaviours of dynamic 3D objects are defined, e.g., the maximum speed of a vehicle.
6	All UMaaSs have the same data and communication infrastructure (e.g., same blockchain operating systems) as the main MetaOmniCity has.
7	Each UMaaS has its own assets — physical, content, and economic.
8	Each UMaaS may have a limitless number of avatars.
9	Each UMaaS may have a limitless number of NPCs.
10	NPCs, e.g., pedestrians, behave under a set of rules defined for them specific to their UMaaSs.
11	Each UMaaS requires authentication tokens to access.
12	Each UMaaS has smart contracts to guarantee the transactions based on the rules and regulatory procedures specific to its metaverse world.
13	Each UMaaS has its own digital assets created by its users.
14	UMaaSs can be visited by guest interoperable avatars belonging to other cities as resident if verified by the city they belong, enabling metaverse travels between MetaOmniCities.
15	Each UMaaS accommodates real-time real-world information/knowledge/wisdom generated using AR.
16	Each UMaaS is enriched using VR with real/unreal objects/materials that help observe the environment and the developing situations better.
17	Members of each UMaaS are informed with Situation Awareness (SA) mechanisms when its state is changed to provide users with high QoE with a high level of timely immersion using near-world rich visualisation and interaction mechanisms (e.g., haptics).
18	Interoperable UMaaSs in one MetaOmniCity can be transported into another MetaOnmiCity with their assets and/or avatars. Moreover, interoperable businesses already established in the metaverse, such as Nike's metaverse shop, can be incorporated into MetaOmniCity.

the boundaries such as time, space and language between real worlds and their immersive counterparts. UMaaSs represent isolated and jointed/integrated/composite immersive worlds (Fig. 6) designed for particular and restrictive objectives and can provide an effective and flexible membership solution for avatars. Teleoperation between UMaaSs is possible to complete various specific tasks since a resident has only a single avatar within MetaOmniCity. The value of UMaaS can be measured based on how successful SC DTs are established and how easily the users are engaging with them with no cybersickness. Physically accurate immersive worlds can be connected or combined to generate larger virtual metaverse spaces — a group of dependent UMaaSs — or each can individually serve as a UMaaS (Fig. 6) to help meet the particular requirements of the city, city managers, residents and non-residents who are interrelated with the city.

TABLE 5: Rules and properties of avatars — twinning humans.

#	Avatars
1	Avatars are the extension of users' unique hyper-realistic presence in VR with a sense of uniqueness. They identify users regarding their appearance, gender, age, ethnicity, manners, emotions etc. Users may prefer to stay anonymous with their authenticated avatars if desired against other Avatars.
2	Avatars can create their clothes and feelings or they can purchase already created assets such as virtual clothes and virtual feelings.
3	Avatars can create their assets and interact with other assets already created.
4	Avatars with digital properties can have virtual or real assets using NFTs.
5	Avatars interact within UMaaS virtual worlds and their assets.
6	Avatars behave independently, free of pre-written scripts or scenarios, performing human-based activities.
7	Avatars interact with each other independently from time, space, and language.
8	Avatars can interact with NPCs.
9	Avatars have their digital wallets and use the digital currency — e.g., OmniCur — of MetaOmniCity to trade.
10	Avatars have responsibilities and liabilities for their actions.
11	Avatars have legal rights and are protected by laws.
12	Every resident may have an avatar — resident avatar.
13	Every guest may have an avatar — guest avatar.
14	Avatars, with freedom of movement, can teleport between virtual spaces (UMaaSs) and MetaOmniCities belonging to different cities considering interoperability.
15	Avatars may have clones to remove time-space restrictions further for completing different tasks in different virtual spaces at the same time.
16	Avatars can act in multiple urban metaverse worlds, UMaaSs, at once using their authenticated clones.
17	Avatars are rewarded with electronic cash — cryptocoins/tokens — for their desired actions, e.g., taking part in a physical exercise event or being educated in the field of healthcare and they are incentivised by the immersive worlds to be good citizens in this way at first for themselves and the healthier societies.
18	Avatars, with data sovereignty, can monetise their own data as well as their assets for many different types of reasons.
19	Children (<18 years old), who are a huge potential for the enhancement of urban metaverse worlds, can generate their avatars to take part in allowable UMaaS worlds after their parents' or guardians' consent.
20	Avatars, multilingual metahumans, can communicate using numerous languages even if their human counterparts do not know these languages. The language used by the human counterparts can be translated into other languages chosen as a communication channel by other users, simultaneously, eliminating the language boundary with a highly interactive experience.
21	Avatars can use natural language processing such as text-to-speech and speech-to-text.
22	Avatars can interact with holographic communications.

7) Rules, elements and properties of Avatars (MetaHumans)

The main actor in the metaverse, Avatar, was first used in a game — Avatar running on PLATO — in the 1970s [70]. Avatars, DTs of residents, are the assets of MetaOmniCity and they present physically in UMaaSs rooms/worlds to interact with the urban environments and other avatars representing other residents allowing the feeling of being in the same room. The appearance of our avatars in expressing our reaction against events, and interaction with people and all other objects is essential in UMaaSs. In other words, our digital self and physical self are coupled to increase the immersiveness within MetaOmniCity in a bidirectional physical and emotional flow of feeling (e.g., facial expression, smell, touch). For instance, the Cambria VR headset developed by Meta enables users readily reflect their facial expressions to their avatars via immersive eye contact, aiming to achieve visual fidelity. In the other direction, what avatars interact in UMaaS worlds are reflected back to the physical self within a bidirectional flow of interactions (e.g., smell, touch). The rules, elements and properties of avatars — digital humans — are presented in Table 5. The applications that allow 3D scanning using smartphones help create more realistic avatars. Residents can scan themselves with varying emotions and expressions from different angles and their realistic avatars can be created in several minutes. The current advancing technologies e.g., Unreal Engine, and DeepFake allow the creation of hyper-realistic MetaHumans that look like the characters of their counterparts [3] concerning the appearance, gender, age, ethnicity, manners, mimics, emotions etc. More advanced engines will enable us to create MetaHumans that look exactly like us in the years to come. Augmented avatars are controlled by their human counterparts and they, enabling co-presence, interact with other avatars, all other urban metaverse elements, (e.g., objects, assets, and NPCs) within UMaaSs to convey their messages and feel the messages and interactions coming from the environment. Avatars can use their clones to eliminate time-space restrictions further for completing different tasks in different virtual spaces at the same time. For instance, an avatar can attend a concert within a UMaaS using his/her clone while interacting with government staff within another UMaaS space. Physics-based character skills of individuals can be gained through reinforcement learning, which can improve the realism of individuals in reflection into avatars [71]. How effective an avatar can control its environment as desired considering the physical rules and individual physics-based character skills and can feel the quality of immersiveness will be a research-intensive topic as the metaverse ecosystem evolves.

It is worth mentioning that NPCs, such as other people or animals, in UMaaSs are neither avatars nor controlled by people. They are utilised to make the worlds look exactly like the real world for modelling and visualising a realistic virtual environment. For instance, all pedestrians are presented as NPCs to show real-time human mobility in the urban environment while an avatar is driving a vehicle on urban roads. NPCs, enabling visual realism, behave under a set of rules defined for them representing their real-world characteristics by fulfilling the scene anticipation of UMaaSs. Avatars can interact with NPCs concerning the rules defined for NPCs. Furthermore, AI-powered digital humans will be taking their places in metaverse worlds soon to serve many different purposes. "Digital Einstein" powered by the digital human company, UNEEQ, embodying Albert Einstein's personality traits and mannerisms as a good example of experiential AI, is the next evolution of human-to-machine interaction, leveraging digital humans to drive personality-led engagements that move customers, patients, students, and end users beyond transactions and into meaningful, emotional interactions [72]. Regarding the development of realistic avatars, the interoperable avatars that can teleport into any cyberspace and the transfer of realistic body language to avatars will be the key concept in the years to come.

[3] Ex: https://www.youtube.com/watch?v=6mAF5dWZXcI

TABLE 6: Rules and properties of the assets.

#	Assets
1	MetaOmniCity has its own assets — physical, content, economic, and UMaaSs.
2	Each UMaaS has its own assets.
4	Assets belonging to UMaaSs can be carried by avatars themselves when they travel between jointed virtual spaces (e.g., UMaaS) with no cost (Fig. 6).
5	Assets can be created by users.
6	The assets (virtual offices, houses, entertainment, clothes) already created can be traded using NFTs with an exchange value, MetaOmniCity cryptocurrency, and smart contracts.
7	Assets (e.g., buildings, public transportation vehicles) belonging to UMaaSs cannot be carried by avatars when they travel between disjointed virtual spaces (e.g., UMaaS) (Fig. 6).
8	Assets (e.g., vehicles) belonging to avatars can be carried by users themselves when they travel between jointed and disjointed virtual spaces (e.g., UMaaS) with no cost (Fig. 6).
9	Assets (e.g., crypto coins) belonging to MetaOmniCity can be carried by avatars when they travel between jointed and disjointed virtual spaces (e.g., UMaaS) with no cost (Fig. 6).
10	Interoperable assets are not incompatible from one UMaaS to another; no need to convert them regarding compatibility and no cost for moving digital assets between different UMaaSs.
11	Avatars can travel with their virtual assets — data belongs to the avatars.

8) Rules, elements and properties of assets

MetaOmniCity, in particular, UMaaSs have their own assets. The assets can be created while UMaaSs are being generated and they can be created by users during the lifetime of UMaaSs. The rules, elements and properties of assets are presented in Table 6.

9) Governance of MetaOmniCity

Effective governance of metaverse worlds requires a high level of philosophical thinking. The City Metaverse Committee (CMC) consisting of numerous disciplines is the ultimate authority in developing and managing urban metaverse parallel worlds.

10) Citizen engagement with MetaOmniCity and its elements: UMaaSs and Metaverse content

No two urban environments are the same, as they come with various demographic, social, cultural, and geographical contexts, resulting in a great diversity in SC challenges [73]. Citizen engagement is generally not seen as a critical part of the improvement process and SC initiatives make little or no attempt to gain insight or collect subjective information from humans [74]. Effective and efficient human-based data collection, intervention and decision-making should be the main driving force of metaverse worlds, essentially to quickly identify the requirements of residents and cities, to meet urgent input requirements of a low-latency real-time application via crowdsourcing and consequently to support proper urban development in various aspects benefiting citizens and the sustainability of cities. While citizens tend to be the implied beneficiaries of SC projects, they are rarely consulted about what they want, and their ability to contribute to making a city work better is often ignored; Citizens must, however, be at the centre of the decision-making process in any SC project if they are to benefit from the intended outcomes [74]. Citizens should not be treated as just some kind of manageable element and active citizen engagement in SC development and enhancement is the major success criterion. To make cities truly smart for the future we need to make sure that the technology is used to deliver things that people want and need, and that add real value to how life is lived in these cities [75] by engaging with citizens and focusing on the social aspect of urban life within people-friendly environments. In this context, there is no strict “best formula” to follow in building and enhancing SCs depending on the size (e.g., megacity) and diverse requirements [5]. Residents are the main stakeholders in a city; Universities, other schools, industry, local businesses, non-governmental organisations (NGOs), and all other institutions and organisations are the other very important stakeholders of a city to be taken into consideration; They have demands to be met to perform their tasks effectively and efficiently and they can be the voice of many residents who may not have the chance to point out their needs and thoughts. SC development is not only transforming the cities but also all other elements including those stakeholders are transformed within an orchestrated smart environment [5]. Most importantly, those stakeholders with their immense and immersive backgrounds would be a great help in identifying proper requirements and specifications; Their ideas and directions accommodating their workforce with massive experience would be prime important and must be incorporated into every phase of SC development [5].

Most of UMaaSs are required to be generated under the authority of CMC for users to both interact with using their avatars and generate their content. Citizens and other users can also develop new urban parallel worlds from scratch and they can enrich the parallel worlds (UMaaSs) already established using the tools defined in Fig. 1 C.3 as "Metaverse world development & enrichment components" such as “membership creation”, “avatar creation”, “asset creation”, “scenario creation”, “scene creation”, and “smart contract creation”. They can demand specific UMaaSs and further content from CMC using the tools, “New UMaaS request”, and “new content request”. More explicitly, users can engage in UMaaSs already generated as exemplified in Fig. 1 E by creating their digital citizenship, avatars, assets, user-specific content and most importantly interacting with lively parallel worlds involving other avatars, assets, environment and the procedures and rules. Contents of UMaaSs are created by formal (recruited) and many informal (ordinary citizens) labours. AI such as generative adversarial network (GAN) can help generate high-quality dynamic scenarios and context images [51] and users can run their scenarios to generate and enrich UMaaSs based on their needs using the tools, assets and DTs already configured in Fig. 1 D as "D. SC DTs & Metaverse Pool". Quickly created UMaaSs can be later configured by the owners to realise their ideal parallel worlds. The assets created within UMaaSs can be placed in "D. SC DTs & Metaverse Pool" for expediting the generation of UMaaSs when similar assets are needed. As elaborated in Section III-B4, dynamic changes of objects in real-world environments are reflected in the immersive world via physical twins based on real-world physics. Environmental changes such as rain, snow, wind, storm, lighting, daylight and so on, are animated using simulation tools by mimicking their physical characteristics. How metaverse worlds can be exploited in urban environments and how cities are engaging with the metaverse can be visualised with the the real-world urban metaverse use cases presented in Tables 1 and 2. The examples below in the following paragraphs are presented to envision how MetaOmniCity can be exploited via user engagement with concrete metaverse experiences concerning the SC objectives, main smart data domains and their subdomains (Fig. 1 A.1, A.2, A.3).

Regarding “smart industry and smart shopping” (Fig. 1 A.1), residents can visit many shops in a short time and test products (e.g., clothes, shoes, perfumes) on them. Similar to shopping in a real-world mall, virtual assets (e.g., virtual offices) and real goods can be traded within urban metaverse worlds. Real estate agencies within MetaOmniCity can generate their UMaaSs in which they and buyers can meet and walk through real estate with near-realistic metaverse property tours as they do in their real-time worlds, which helps save time for both agencies and buyers with reduced costs through efficient house-viewing meetings.

“Smart health and welfare” (Fig. 1 A.2) domain can benefit substantially within MetaOmniCity. Hospitals, health surgeries, and even physicians can generate their medical UMaaSs equipped with tactile feedback technologies in which physicians can examine patients similar to real-life examinations and physicians from different disciplines in different locations can collaborate to examine patients with complex diseases empowering clinical decision-making. The monitoring of patients with chronic diseases such as Alzheimer’s, Parkinson’s, and Asthma will be eased using these UMaaSs. Moreover, these platforms can be utilised for consultations and healthcare education platforms for residents targeting healthier societies who can take care of their health with practical directions. Holographic construction and emulation of patient’s organs through holographic anatomy modelling by combining the data from different modalities (CT/MR) enriched with AR and VR can help diagnosis, consultation, medical decision-making and remote assistive surgery leading to collaborative medical and clinical research [76] with highly immersive healthcare metaverse worlds. Holography-guided heart surgery for more precise, speedier incisions using the 4D MR and CT rendering was already performed at National University Hospital [4]. Visual data using AR are directly projected to the operator's retina and overlaid onto the surgical field as a GPS navigator in front of your eyes, thereby removing the requirement to shift attention to a remote display and screws can be placed with an accuracy of 96.7% during spinal operation at the Johns Hopkins University School of Medicine [77]. Moreover, psychotherapy support and virtual support group meetings can be carried out within healthcare metaverse worlds effectively.

Proposing that a city's citizens contribute through crowdsourcing activities is a way to benefit from their knowledge of the field [4]. Crowdsourcing is revolutionising SCs, particularly the real-time smartness of SCs by interacting with entities, citizens or objects. It is an effective technique that incorporates human intelligence and smart machines to collect disparate sensing data in pervasive environments [78] to support sophisticated applications. SCs should have the tools to enable citizens to know what is happening, when it is happening and how it affects citizens, tourists, companies and city administrators [75] about social activities, parking spaces, crime, traffic congestion, traffic accidents, better driving directions, pollution levels, emergency concerns (e.g., flood, earthquake, strong wind), directions for the closest gathering spots under any emergencies based on the individual smartphone locations, areas to be avoided and so on. Regarding "Smart safety and security, Smart environmental monitoring and control" (Fig. 1 A.2), what happens if a natural disaster (e.g., earthquake, floods, tsunamis, fires") or an abnormal event (e.g., terrorism) emerges is simulated by VR and AR tools in UMaaS titled "Disaster responsiveness services" to forecast/anticipate event-related pending conditions of the physical counterpart and how to behave in case of abnormal situations is visualised with a real-time augmented 3D representation of effected urban areas enabling efficient management of these events. To exemplify, residents are alerted about imminent floods due to any heavy rains; How their houses, their current locations and urban areas are affected based on the speed of rainfall and the course of rivers and their avatars are directed to the less affected urban spaces for evacuation based on their current locations.

SCs should have the tools to enable users to always interact with the events taking place in their environments within brainstorming chambers. Citizens can be encouraged to participate in the decision-making process with the crowdsourcing approaches effectively using the wisdom of the crowd. Regarding "Smart environmental monitoring and control", "Smart community and social network" and "SC tourism" (Fig. 1 A.2), users, exploiting the wearable tools (Fig. 1 D), in particular, virtual reality headset, optical head-mounted displays, and smart glasses, can communicate to urban infrastructure and enrich this environment with most recent up-to-date developments, e.g., "what roads need repair?", and can be incorporated into the decision-making processes.

[4]https://www.youtube.com/watch?v=hHpfsQNlzRw

TABLE 7: Computation of SSQ scores [83].

	SSQ Symptoms	Weight		
		Nausea (N)	Oculomotor (O)	Disorientation (D)
1	General discomfort	✓& coeff=1	✓& coeff=1	
2	Fatigue		✓& coeff=1	
3	Headache		✓& coeff=1	
4	Eye strain		✓& coeff=1	
5	Difficulty focusing		✓& coeff=1	✓& coeff=1
6	Increased salivation	✓& coeff=1		
7	Sweating	✓& coeff=1		
8	Nausea	✓& coeff=1		✓& coeff=1
9	Difficulty concentrating	✓& coeff=1	✓& coeff=1	
10	Fullness of head			✓& coeff=1
11	Blurred vision		✓& coeff=1	✓& coeff=1
12	Dizzy (eyes open)			✓& coeff=1
13	Dizzy (eyes closed)			✓& coeff=1
14	Vertigo			✓& coeff=1
15	Stomach awareness	✓& coeff=1		
16	Burping	✓& coeff=1		
	TOTAL SCORE (TS)	[1]	[2]	[3]
N = [1] * 9.54				
O = [2] × 7.58				
D = [3] × 13.92				
TS = ([1] + [2] + [3]) × 3.74				

Regarding "SC tourism" (Fig. 1 A.2), virtual exhibition knowledge about human density and mobility patterns is the key element toward efficient urban development [79]. In this sense, a new concept — cyber-physical social systems (CPSSs) [80], [81], [82] has been proposed along with CPSs in which citizens are being maintained in the loop of smart system development and enhancement as sensors and/or actuators, particularly to develop human-centric systems serving real-time autonomous decision-forming purposes and anticipating future trends in real time by engagement with other users as well. Such systems consist of not only cyberspace and physical space but also human knowledge, mental capabilities, and sociocultural elements [80]. Regarding "Smart traffic mobility" (Fig. 1 A.2), Statistical data shows that one of the biggest inefficiencies in our urban transportation system is related to parking. "Smart traffic mobility" aims to integrate user-centric efficient mobility services and products for making urban areas more livable places.

11) Quality of Urban Metaverse World experiences

The fuse of Quantum computing with an exponentially increasing computation power and 6G technologies is expected to provide the residents with highly powerful computing and comminations environments, which would boost the QoE significantly with urban metaverse worlds, in particular, with worlds requiring high-quality edge computing and edge intelligence such as holographic construction, emulation and communication.

Immersive metaverse environments, enabling the feeling of the environment rather than seeing, are expected to reduce screen fatigue. Nevertheless, cybersickness will still be an issue in those environments. It is aimed to be measured where the unpleasant symptoms are raised because of the discrepancies between the digital twins — real-environment and cyber environment — i.e., differences between the ex-

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pectations and contents perceived that may be caused by the communication delay in transmitting the sensory information between the two environments [51] (i.e., sensory conflicts or sensory discordance or perceptual conflict). The measurement of cybersickness should be carried out to i) develop an understanding of the magnitude of the cybersickness problem and its implications to task performance, ii) determine the various drivers of cybersickness and create a predictive model, iii) establish means of determining user susceptibility to cybersickness and aftereffects, iv) establish countermeasures to aftereffects, v) develop an automated solution to track cybersickness symptom magnitude during exposure, vi) establish product acceptance criteria and standardisation to ensure that cybersickness and aftereffects will be minimized [84]. UMaaS can be evaluated using psychometrically tested questionnaires specific to metaverse parallel worlds for cybersickness assessment. Currently, there is no such evaluation tests specific to metaverse parallel worlds and these tests need to be developed by involving expertise from numerous disciplines. To assess the severity of the simulator sickness symptoms, the most widely applied measure, the so-called, simulation sickness questionnaire (SSQ) developed by Kennedy et al. [83] has been employed for many types of applications so far. SSQ containing 16 symptoms' as shown in Table 7 is investigated for measuring undesirable symptoms mainly due to the autonomic nervous system activation along with physiological discomfort. The severity of each symptom in the SSQ is rated on a four-point scale (0-3), i.e., "none","slight", "moderate" or "severe' and on three subscales: nausea (N), oculomotor disturbances (O) and disorientation (D) disturbances as well as the total SSQ score (T). These subclasses are grouped with 7 symptoms as displayed in Table 7. It is worth noting that some of these items are used to assess the multiple subclasses as can be noticed in the table. For instance, "Difficulty focusing" is used to assess both "oculomotor" and "disorientation". The rated scores multiplied by their coefficients (i.e., 1) in these subclasses are added within their groups and the obtained sums are multiplied by their particular weights — 9.54 for nausea ranging from 0 to 200.34; 13.92 for disorientation ranging from 0 to 292.32; 7.58 for oculomotor disturbance ranging from 0 to 159.18. All the scores rated for each symptom are added and their sum is multiplied by 3.74 to result in the total severity which can range from 0 to 179.52.

12) CyberSecurity of MetaOmniCity

Cybersecurity threats against the metaverse are analysed in [85], [86], [87], [88]. The techniques and approaches for cybersecurity to address security and privacy concerns are being developed as cyberattacks are taking place every day for citizens in the cyber-physical world. Different from the cybersecurity risks faced by standard internet users, the metaverse has created new security challenges due to its different structure; for example, virtual identities, digital currencies, and NFTs (i.e., unique identities representing all types of assets) are interesting economic targets for hackers [86]. NFTs can be used to represent digital assets in a smart city that are required to be immutable, secure, and traceable and they are not a standalone technology, as they require a well-configured blockchain and an efficient off-chain data storage solution in order for them to function properly [19]. There is a risk of blockchain-related fraud in financial institutions [86]. The design of a secure mutual authentication scheme for metaverse environments using a blockchain scheme is proposed in [89]. The concept of smart contracts aims to ensure that transactions are completed safely.

Wearable hardware, which is one of the most important components of the metaverse, can also create new threats. With the increase in the use of virtual reality glasses and headsets—which may serve as suitable access points for hackers—or augmented reality devices in which the biometric data of users are stored, they may become ideal targets for attacks. Implementing advanced multiverse realms with smart wearables is analysed in [90]. Due to the expected massive number of connected devices and network tenants, the 6G ecosystem would tend to be highly prone to Distributed Denial of Service (DDoS) attacks [46]. Denial-of-service attacks and theft of avatars, in particular, for wearable metaverse devices, are two main cybersecurity concerns in metaverse environments. Prevention of privacy intrusions without reducing overall QoE along with real socialising need to be ensured. Blockchain technology has been recently introduced to mitigate these concerns in urban use cases. A framework that uses blockchain technologies was proposed in [91] for DTs to ensure the security of transactions during the data streaming between virtual entities and physical entities. Similar security frameworks are expected to be developed in parallel with the increasing number of metaverse use cases in the years to come.

UMaaSs facilitate the exchange of information in a trusted way through the metaverse ecosystem built on decentralised blockchain technologies. 6G networks are expected to emerge as Distributed Trust-Based Secure Networks (TBSN) where security, privacy and trust are the key pillars to meet these requirements [46]. Regarding the metaverse environment, quantum information technology is capable of enhancing the system's security and privacy, improving the computational scales, optimizing the output, improving the communication, securing the network channels, providing absolute randomness for metaverse-based applications, and supporting ML implementations in the metaverse by integrating quantum ML [92]. On one hand, promising quantum computing enables advanced immersive environments, on the other hand, the encryption codes of blockchains, which can not be hacked for 10s/100s of years using the current computing power, can be broken in hours/days/weeks using the high power of quantum computing. Therefore, cybersecurity in blockchain technologies should be improved in parallel with quantum computing. Blockchain technologies may be replaced by other newly promising technologies to mitigate this concern.

IV. CHALLENGES

The essential challenges are summarised as follows:

1) Regulatory framework: Metaverse worlds require the implementation of different laws and the current laws and regulations need to make implementation adjustments in the metaverse worlds [93]. There is no agreed-upon regulatory framework for the urban metaverse ecosystem. The lack of regulatory framework is the main concern of the users, e.g., what might be the consequences if an avatar is attacked by other avatars or harassed sexually as witnessed recently in Horizon Worlds [94]?

2) Lack of agreed standards: Industry standards are yet to be established in building metaverse worlds even though the giant leading technology companies (Meta, Microsoft, Google, NVIDIA, Intel, Apple, Roblox) are massively investing in metaverse technologies4. Interoperability among different metaverse applications is accepted as the crucial building block. Therefore, tightly connected multiple metaverse worlds are highly difficult to share spaces due to the lack of interoperability caused by harsh competition.

3) High-power computers and high bandwidth: The creation and engagement with high-fidelity virtual urban worlds require high-powered computers. Most of the residents do not have these types of devices, which is currently the biggest problem in encouraging more people to participate in these environments. I envision that this problem will be handled with more powerful computing devices taking their place in residential houses in 5-10 years while the technology is renovating itself in 18 months (Moore's Law) [95]. Residents will be able to have high-powered computing devices at the same price as the technology renovates itself. Currently, the inequalities in access to high-powered devices with high bandwidth capabilities can be mitigated by dispersed meta-city connection hubs that may be placed all around the city.

4) Inefficiency of blockchain technologies: With the increasing number of users, blockchain technologies can be inefficient to complete transactions rapidly. Quantum computing is a good candidate to mitigate this concern within urban metaverse worlds as elaborated in Section III-B12.

5) No centralised authority: The owner of the data will be the users who have the data with data sovereignty, and no central authority is required for transactions. The users should be cautious against spoofing in the blockchain environment and should not share their private keys with anyone. They will lose access to their wallet forever if they forget their private key. Moreover, the data of a user will be lost forever if a user dies or a service provider fails.

6) Digital skills: The lack of digital skills of residents poses a significant challenge in engaging with high-fidelity virtual worlds thoroughly, particularly, for elderly residents. Therefore, first and foremost, UMaaSs for training the residents need to be developed to immerse every citizen in urban metaverse parallel worlds to provide equity — a target of urban metaverse worlds — in the society.

7) Digital SC domain twins: Many cities are far from establishing their SCs and SCs have yet to build their DTs of SC domains (Fig. 1 A.2). These SC DTs need to be established to build high-fidelity virtual urban worlds that can rise upon DTs as elaborated in Section III-B4.

8) Antisocial behaviours and misuse of the platform: Urban metaverse ecosystem, with immersive abilities, would be an ideal space for antisocial behaviours such as cyberbullying, sexual assault, and fraud. In a virtual reality game, VRChat, a violating incident occurs about once every seven minutes [96]. Criminal actions are expected to increase as the metaverse expands with multiple application areas. These crimes will impact the victim's emotional and mental health, much like the way these crimes affect victims in the physical world [85]. These crimes, impacting emotional and mental health, can be committed by avatars with fake identities and may not be traceable regarding data sovereignty. Avatars should be registered to UMaaSs to mitigate these concerns, enabling the tracing of bad behaviour within the metaverse ecosystem, and leading to holding users accountable for their inappropriate actions. Furthermore, physical rules of Avatars can be enforced using the metaverse software. For instance, Meta recently launched "Personal Boundary" for Horizon Worlds that will give people more control over their VR experience; the roughly 4-foot distance between an avatar and others will remain on by default for non-friends, and now an avatar will be able to adjust his/her personal boundary from the settings menu in Horizon Worlds [97].

9) Potential damages to children: The interaction of children with strangers in metaverse worlds needs to be analysed before allowing children to immerse within these virtual worlds concerning the misuse of these networks.

9) Long time: Being a long time in immersive metaverse worlds may create significant tiredness, headache, and most importantly a break-away from real life leading to adaptation problems with the disturbance of perception of reality, e.g., how would it be for driving a real car after spending driving in a virtual immersive world, e.g., up to 6 hours. There are still many unanswered questions to be analysed further by numerous experts.

10) Identity falsification (i.e., identity forgery, dual identity) and falsification of digital assets: Replicas of other famous people's avatars with identity theft can be created to deceive residents. Moreover, businesses and users will create digital replicas of their real physical assets (e.g., real-world stores) in urban metaverse worlds. These digital assets can be copied by criminals to scam businesses. For instance, criminals can create a fake store that looks identical to the real one to sell counterfeit products and the users may believe that they are buying real goods. Registration of avatars and businesses to MetaOmniCity and UMaaSs using authentication tokens given by the government (Table 3) can mitigate these concerns.

11) Phubbing and societal concerns: There is a high probability with the urban metaverse ecosystem that the level of phubbing increases within our real social environments. From a cyber-dystopia point of view, the reduction of urban real physical social interactions — intimate, real close re-

lationships — replaced by virtual interactions using avatars within urban metaverse worlds may cause unforeseen negative effects and new types of psychological problems (e.g., feeling of loneliness, social segregation, social exclusion) for humans since metaverse worlds can not be sufficient to meet the real closeness despite their immersive services, which should be analysed by related disciplines and the ways for addressing these societal concerns need to be revealed. Moreover, it is well known that physical inactivity increases the risk of serious health conditions coronary heart disease, stroke, hypertension, and osteoporosis [98]. The massive use of metaverse environments may cause physical inactivity and physical activities should be incentivised within urban metaverse worlds to avoid aforementioned health problems.

12) Non-accessible experiences and non-ergonomic VR headsets: VR headsets as well as some virtual experiences can not be affordable by a majority of society and many people who can afford them do not show much interest to acquire them. Furthermore, VR headsets are not ergonomic to wear due to their large size and not being sophisticated to be immersive with the environment seamlessly, i.e., lack of sense of both presence and living via effective engagement with urban elements.

12) High energy usage: As of August 2022, published estimates of the total global electricity usage for crypto-assets are between 120 and 240 billion kilowatt-hours per year, a range that exceeds the total annual electricity usage of many individual countries, such as Argentina or Australia [99] even though current crypto-assets, running on blockchain technologies, are based on text-based processing. Regarding the 3D visual immersive metaverse environments, according to the evaluation of Intel, metaverse, with hundreds of millions of real-time immersive interactions, requires a 1000 times increase in today's energy consumption [44]. It is highly critical to use renewable energy sources in developing urban metaverse worlds where energy consumption would increase significantly with the use of these virtual parallel worlds. Meta and Microsoft, as good examples and main candidate developers of metaverse worlds, have committed to achieving net zero greenhouse gas emissions by 2030 using renewable energy sources [100], [101].

V. LESSONS LEARNED

The lessons learned in this research are summarised below.

1) Urban metaverse virtual worlds can overcome the constraints of space, time, and language with location-, time- and language-independent UMaaSs that contribute to digital inequalities significantly.

2) Many of the potential urban metaverse experiences are yet to be discovered and developed. The metaverse will open up new frontiers and opportunities for a multitude of urban businesses and services in our immersive urban environments. It is time for SCs to take the necessary measures to realign their ecosystems with the potential avenues of the metaverse and meet the changing demands and requirements thoroughly based on the changing technological ecosystem.

3) Incentives to participate in UMaaSs such as "play-to-earn" would contribute to the exploration and development of urban metaverse worlds significantly with increased immersive collaborative experiences.

4) Urban metaverse worlds would impact how citizens communicate with one another. They would result in behavioural changes in residents in cities. SCs enriched with metaverse implementations not only will increase the interaction of citizens with the services of the city they live in, but also encourage people all around the world to engage with the city using their own avatars, which makes the cities worldwide cities leading to new economies in cities.

5) Privacy protection in urban metaverse worlds will be an active research field (Ex: [102]) even though the data is owned individually.

6) 6G, expected by 2030 [46], as a key pillar in developing metaverse technologies, would significantly enhance QoE for immersive implementations [64] along with quantum computing.

7) A new profession, metaverse legal expertise (e.g., lawyers), will emerge soon along with their particular legal courts.

8) The universities should shape their training regarding the future metaverse requirements by accommodating related educational needs to support certain jobs and the skills such as content creators and metaverse platform and tool developers.

9) SC metaverse worlds are currently being created using virtual SC DTs established from their real-world counterparts. With the developing metaverse concept, this trend is expected to be reversed where cities need to be extended with new structures, infrastructure and further services. In other words, firstly, virtual SC DTs will be designed creatively without any restrictions and then their real-world counterparts will be built. For some types of UMaaSs, the design of virtual spaces and building their physical counterparts need to go hand in hand in a hybrid way equipped with AR to establish an immersive interaction with each other leading to embodying highly improved parallel metaverse worlds by experiencing precision science. The creation of SCs in the metaverse with the help of all residents will be the dominant concept in the years to come where many unexplored ideas, skills and talents can be put into practice in the playground metaverse environment, which paves the way for eco-friendly physical environments with many practical functionalities and further democratisation of societies.

VI. DISCUSSION

The leading gigantic companies such as Meta, Microsoft, NVIDIA, Intel, Apple and Samsung as well as many others are investing heavily in developing advanced metaverse technologies. Other major companies such as Nike and Coca-Cola are also transporting their business into the metaverse environment to create immersive experiences for their customers to interact with their products with high QoE. This immense involvement with the metaverse will carry this 3D elevation of linear Internet (i.e., second-generation of internet) to the next level in which more people would be immersed in virtual worlds augmented with reality, which would create new businesses and many conventional businesses would benefit from this increasing immersive engagement significantly. Digital ownership of high-fidelity virtual assets on Web 3.0 is increasing exponentially, which is an indication that the economical value of the digital virtual worlds using blockchain technologies will increase significantly in the years to come, promising much further economic growth. The near future will embrace more metaverse applications fuelled by more advanced metaverse technologies leading to a change in the way of doing business in the urban ecosystem. A more recent 3D Ethereum-based virtual world platform owned by its users, Decentraland (2020) and Horizon Worlds (2021) are good examples of connecting people in the world and allowing users to feel a shared digital experience using their virtual currency to trade virtual assets (e.g., lands). Readers are referred to the OpenSea web site [5] for many different kinds of decentralised virtual worlds with different immersive experiences using the free-flowing futuristic style architectural design and limitations in different categories created all around the world to explore. These worlds, not representing any physical reality, are not the clones of real worlds, with no data streaming between the physical city ecosystem and these worlds. In other words, these virtual worlds are not augmented physically. The evolution of similar conceptual virtual lives augmented physically can be realised using SC DTs and real citizens doing real things with real experiences by avoiding cartoonish designs (e.g., cartoonish avatars) within quality rendered UMaaS worlds (Fig. 1 E) using the advanced Metaverse tools, platforms, and utilities (Fig. 1 C).

The registered metaverse trademarks are hyper exponentially increasing. the metaverse, aiming to accommodate hundreds of millions of real-time immersive interactions, opens a new era of urban development, urban living and urban business (Ex: Gucci [6], concert of Ariana Grande [7], Manchester city stadium [103]), enabling a more sustainable future for urban life. The SC ecosystem, in which many SC DTs have been already developed along with many development initiatives, would accommodate a better environment for the incorporation of the metaverse technologies. SC DTs can transform into UMaaSs with the concept of community as a major player in mind. The multi-awarded movie, "Ready Player One (2018)" based on Ernest Cline's novel of the same name, has already impacted our thinking with metaverse environments by envisioning that a user may have the ability to physically feel things inside the metaverse using full-body actuator suits as s/he feel in the real world. More realistic environments can be created with further advances in cybernetics (e.g., haptics) technologies (smart wearable metaverse devices (e.g., haptics gloves developed by Meta for feeling the sensation such as handshake and holding an object)) that would provide users with better impressiveness with tactile feedback. SC traffic flow can be mapped into the metaverse environment and we can visualise ourselves in this environment while driving a car simultaneously using real-time physics simulation. This environment can shape our decisions in traffic such as changing lanes or taking another path with less traffic or with no accidents, and so on. Moreover, we can teleoperate an AV using the metaverse environment more realistically in real time.

DTs — precise, virtual copies of machines or systems — are revolutionizing industry [65]. This research analyses the creation of SCs in the metaverse. To this end, the framework — MetaOmniCity — virtualises and digitises SC with intertwined immersive physical and virtual worlds. The realisation of the urban metaverse worlds as proposed in this research will greatly reduce the need for physical travel while many activities (e.g., social events, exercise, meetings, work) would take place in virtual worlds as they are happening in real worlds based on logics and rules in the real life leading to an immersive urban evolution. This will reduce the carbon emission significantly with less air pollution in urban living in addition to reducing the need for extensive transport infrastructure and other physical infrastructure, e.g., workplace facilities. In this way, the high usage of energy in the urban metaverse worlds can be balanced and cities can meet more green spaces. In the meantime, blockchain technologies should be improved concerning the high energy use to meet the requirement of the objectives of the sustainable urban ecosystem. For instance, Ethereum's recent cut in its energy use by around 99% promises that new structural changes (e.g., transition to a new consensus mechanism known as proof of stake) in blockchain technologies may curb the climate footprint significantly in the web3 network [104]. Municipalities are building their future with the concept of the metaverse. New economies will be created with MetaOmniCity by moving local industries with their real assets into the metaverse and playing with the real world remotely, having virtual assets and trading them. The city resources will be reallocated with the urban metaverse virtual worlds. Do-from-home models with urban metaverse worlds will encourage residents to live in rural areas away from urban locations, which help reduce the urbanisation problems such as pollution, traffic, and the high cost of urban living. Critical skills and services will be democratised through citizen-shared experiences within UMaaSs. MetaOmniCity encourages city residents to participate in contributing to building high-fidelity virtual worlds to be used as UMaaSs. Future metaverse worlds are expected to be evolved to be more immersive with advanced real-time data-driven virtual/augmented platforms and hyper-realistic MetaHumans. Younger individuals in the new generation, very much familiar with multiplayer competitive games by which the borders between the virtual and real are diminishing, are expected to readily adopt socially immersive urban metaverse

[5]https://opensea.io/explore-collections?tab=virtual-worlds
[6]https://blog.roblox.com/2021/05/gucci-garden-experience/
[7]https://www.youtube.com/watch?v=gGYElBtjytU

environments.

The concept of MetaOmniCity based on the metaverse industry standards to be established would pave the way for immersive globalisation with the larger and richer metaverse of Country (MoC) and metaverse of World (MoW) as an immersive DT of the broader universe by removing physical borders. Nvidia has been building Earth-2 — a DT of weather, climate, and energy across the real earth — to understand climate change and its impacts at local scales, and to explore the consequences of human actions and climate change mitigation strategies in real time [105]. Interoperable MetaOmniCities created for different cities can be seamlessly connected to realise this objective using real local immersive high-fidelity DTs, i.e., urban metaverse worlds, UMaaSs designed for weather, climate, and energy.

"Is virtual experience a real experience" is discussed by Narula in his book [106] titled “virtual society”. According to Narula, a virtual experience is not necessarily supposed to be a real experience, rather, it is an experience that makes you a part of social life that touches you and others through back-and-forth interactions. Even, some of the virtual experiences may not be materialised in the real life, but can be generated as a part of virtual experience, e.g., entertainment Metaverse events (flying avatars are doing strange things for full of entertainment). I believe that Metaverse worlds will be shared by more people as they embrace more realistic visualisation scenes and objects (avatars, buildings, NPCs, etc.) equipped with aesthetics and logical visual orientation, physical rules, and near-real-time bidirectional data streaming between virtual and its counterpart real environment. Agreed-upon ideal futuristic SCs can be designed using SC DTs and the Metaverse tools and utilities. To this end, the framework of MetaOmniCity aims at designing an ecosystem to ease the implementation of UMaaSs in SC environments. It incorporates residents into this ecosystem with more degrees of freedom, which can create ample opportunities and a brighter future for cities and citizens in a more democratised society through the Metaverse globalisation with no borders and synergistic collaboration. It seems that urban Metaverse worlds will interface with our daily environments in many aspects by using numerous interoperable metaverse windows.

There will be numerous ways to interface with virtual worlds in the years to come. From a neuroscience standpoint, motor neuron prosthetics, Deep Brain Stimulation (DBS), Brain Implant Technologies (BIT), and Brain Computer Interface (BCI) with two-way communication are expected to help immerse with metaverse worlds as assistive devices in controlling digital smart environments using the brain‘s electrical activity, making science fiction science fact via mind reading with brain decoding, in particular, for those who are handicapped (e.g., Parkinson’s). These technologies may help regain independence leading to equality between people despite many controversial ethical issues and scepticism.

“Consider what is required to put two individuals in a social setting in an entirely virtual environment: convincing and detailed avatars with realistic clothing, hair and skin tones — all rendered in real time and based on sensor data capturing real-world 3D objects, gestures, audio and much more; data transfer at super high bandwidths and extremely low latencies; and a persistent model of the environment, which may contain both real and simulated elements; Now, imagine solving this problem at scale — for hundreds of millions of users simultaneously — and you will quickly realise that our computing, storage and networking infrastructure today is simply not enough to enable this vision” as stated by Intel [3]. This high resource-hungry requirement can be alleviated by energy-efficient computing, better algorithms, and better architectures as stated again by Intel [44]. To this end, MetaOmniCity is designed with multiple and dedicated UMaaS models with model-related users/avatars and objects (Fig. 6) to mitigate this resource-hungry requirement.

VII. CONCLUSIONS AND FUTURE RESEARCH IDEAS

Urban metaverse, not an alternative to urban reality, but an immersive parallel of it, in which physical and their equivalent virtual clones co-exist with massive immersive human-machine interactions, will be providing cities with new ways for the digital transition. It will respond to urbanisation with more intelligent services through the exploration and exploitation of the metaverse concept. Many practical metaverse implementations in the urban environment are on the way where architecture, technology and social dynamics are intertwined within extended reality, which boasts business, social and resident growth with increased QoL through increasing social adoption. The demands for city services equipped with better infrastructure and smart technologies are increasing at an alarming rate as the urban population continues to rise with many challenges to cope with. In this paper, potential urban application areas of the metaverse, as well as the future urban metaverse research opportunities to ease the burden of these challenges on urban societies with QoSs are investigated (Tables 1 and 2) and SC and metaverse concepts are moulded to create high-fidelity urban metaverse digital worlds by which we have a direct impact in the cities we live in. The proposed innovative framework — MetaOmniCity (Fig. 1) — derives a conceptual framework for the development of urban metaverse parallel worlds upon SC DTs by encouraging citizen cooperation with experiences. MetaOmniCity, as the logical extension of SC DTs, is proposed in this research to demonstrate the ways of practical implementations of metaverse technologies in the urban ecosystem and to make the residents feel the city nerves in collaborative and immersive 3D spaces where two worlds can be more tangibly connected and interact in real-time. MetaOmniCity aims to provide useful insights into transforming the general human-centric metaverse concept into a resident-centric urban metaverse creation concept to readily direct urban stakeholders about how to create realistic urban metaverse worlds. It will enable cities to provide their municipal services on a global scale via SC DTs integrated with the metaverse. MetaOmniCity, with its more charming immersive environments, is expected to attract more people to join the city ecosystem. The key points can be summarised as follows: i) SC services with a multitude of UMaaS applications would be more accessible within the location-, time- and language-independent immersive environments by mitigating the limitations and constraints such as time, space and language with the metaverse space travel, ii) Urban metaverse, enabling to perform businesses in a decentralised way, promotes a new immersive metaverse commerce in which numerous entrepreneurs and businesses in cities can thrive rapidly on a global scale and the wealth and the value of cities can increase significantly, benefiting every resident, iii) There is a lack of metaverse vision in cities when we analysed the future urban metaverse plans (Table 2) even though many cities are targeting to develop metaverse-oriented cities, iv) Enriching the urban metaverse worlds would touch and enrich residents' way of living by extending our urban lives to the next level with a rich set of useful experiences leading to creating a value beneficial to every citizen in the urban environments.

Broadly speaking, urban metaverse shared worlds, an extension of residents and urban life, where virtual and reality blend and more organically integrated would impact urban ways of living significantly with many practical implementations, would open doors for potential businesses with tremendous global economic value by democratizing skills within an urban environment with citizen-centric ultra immersive innovation. These urban worlds will be game changers within cities. What benefits avatars can bring to our twin worlds would be countless — e.g., there may be many assets in the future beyond our imagination for the time being. Will our avatars present in remote real-world locations in real time for solving particular real-world problems? Will our avatars actually enable us to physically sense with feel, touch, smell, and taste experiences using tactile, olfactory, and gustatory feedback? metaverse discipline and metaverse ethics will be the other developing fields in parallel with the development of metaverse worlds. Protection of users in the metaverse parallel world will be another fruitful research direction towards this discipline. MetaOmniCity, as it materialises, is expected to accelerate the building, deployment, and adoption of many immersive urban metaverse worlds with high-quality immersive experiences allowing the feel of existence in a parallel plane.

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