Internet of Things and Cyber-Physical Systems 4 (2024) 203–216

Contents lists available at ScienceDirect

Internet of Things and Cyber-Physical Systems

journal homepage: www.keaipublishing.com/en/journals/internet-of-things-and-cyber-physical-systems

Metaverse for smart cities: A survey

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ARTICLE INFO

Keywords:
Metaverse
Smart cities
Technologies
Applications
Opportunities

ABSTRACT

The concept of a smart city is geared towards enhancing convenience and the efficient management of city areas through innovation. As Metaverse rises in the 2020s, providing the possible direction for a new generation of the Internet, it has a huge number of opportunities to promote smart cities. The Metaverse can empower smart cities in various aspects. In this article, we provide a detailed review of smart cities based on Metaverse technologies. Firstly, we introduce the Metaverse and smart cities and describe the future vision and applications of smart cities, which are based on the Metaverse. In addition, we discuss the essential technologies for smart cities in the Metaverse and the currently available solutions. Additionally, we have some concerns regarding the potential of Metaverse and there are still unresolved issues that should be addressed. The purpose of this article is to provide researchers and developers with essential guidance and opportunities to propel the development of the Metaverse and smart cities.

1. Introduction

The Internet of Things (IoT) [84] and cyber-physical systems (CPS) [10,109] are crucial concepts in the modern technology landscape, filling gaps in many traditional systems and offering a wide range of new applications and opportunities, especially in Metaverse and smart cities. The Metaverse is a virtual digital world that interacts with and replicates various aspects of the real world. IoT and CPS can provide data and interactivity to the Metaverse [23,104]. For instance, through IoT sensors and devices, real-world data can be brought into the Metaverse, enriching and making it more realistic. Additionally, CPS can be used to simulate and test physical processes within the Metaverse to ensure their behavior aligns with the real world. From another aspect, smart cities use intelligent technology to enhance city operations, improve the quality of life for residents, and make city life more efficient. IoT and CPS play crucial roles in building smart cities [70]. IoT can be used to monitor various city data, such as air quality, traffic flow, and waste bin status, helping city managers make better decisions. CPS, from another aspect, can control and optimize city infrastructure like smart traffic lights, energy management systems, and water resource management systems. The combination of these technologies enables smarter, more sustainable city operations, ultimately enhancing residents' quality of life.

The Metaverse is essentially a process of virtualization and digitization of the real world. The "Metaverse" is a portmanteau of "Meta" and "Verse", which originated in the 1990s [62]. In the future scenario, the Metaverse depicts an immersive shared space where people walk and make contact between the real world and the Metaverse. Users can enter the Metaverse by having a computer and wearing a special pair of glasses. Although it is a virtual world, it makes people feel like they're in a real-world [27]. Moreover, any activity in the real world can be realized in the Metaverse [49]. With the rapid advancement of modern technologies, we are on the brink of a revolutionary new era of Internet-based Metaverse [49]. Metaverse is a concept that highlights the integration of the virtual and the real. It is not a simple technology, but instead a novel product that incorporates many new technologies [23], such as big data [94], interactive technologies [32], cloud computing [17], fog computing [29], artificial intelligence (AI) [50], 5G [77], digital twins [37], blockchain [39]. With the advent of the Metaverse, many changes will take place. These changes can be broadly categorized into five aspects: economy, innovation, culture, life, and cities, which are illustrated in Table 1.

Among the above changes, the city is one of the most significant, for cities have long been considered symbols of human civilization development, representing our ability to utilize resources and create advanced societies [30]. Each technological leap made by mankind will bring about a huge change in city form. As technology advances, it will have a

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https://doi.org/10.1016/j.iotcps.2023.12.002
Received 9 August 2023; Received in revised form 21 December 2023; Accepted 21 December 2023
Available online 10 January 2024

Table 1
The descriptions of common hybridization strategies.

Aspects	Description
Economy [47]	The emergence of the Metaverse will affect consumption patterns, and virtual consumption is no longer limited to games.
Innovation [116]	Metaverse will provide an innovation scene that allows people to experiment, manufacture, design, and collaborate in a virtual environment.
Culture [41]	Metaverse provides more opportunities to learn about the culture. For example, people can learn about historical sites even though they don't arrive at the scene.
Life [4]	The Metaverse aims to change our way of life by shifting more activities into the virtual world. By shifting more activities into this virtual realm, the Metaverse has the potential to redefine how we live, communicate, and interact, opening up new possibilities.
City [12]	The coming Metaverse can promote the construction of smart cities, which can not only innovate social governance but also provide the government with the convenience of governance and improve the quality of life of citizens.

significant impact on people's way of life and also reshape the form of cities [88]. With the new generation of information technology in the 2020s, the concept of smart cities has become popular. In general, the smart city is a framework consisting mainly of information and communication technologies (ICT) [70]. Smart cities are necessary for today's society and are designed to effectively utilize the latest information technology to address the challenges brought about by increasing globalization and urbanization in city industries [118]. The background of a city based on the next generation of innovation in the knowledge society enables large cities to achieve a deep integration of information technology, industrialization, and urbanization. The initiative is favorable to ease the pressure of city construction, improve the quality of urbanization, achieve refined and dynamic management, enhance the effectiveness of city management, and improve the quality of life of citizens.

There are many policies to encourage the formation of smart cities, and there are some prototypes of smart cities. For example, the ASEAN[1] smart cities network (ASCN) aims to promote the cooperation of smart cities and make efforts to build these smart cities into a complete network [16]. The European Union has been working on a strategy for the growth of intelligent cities in metropolitan areas [56]. The Ministry of City Development, Government of India, spearheaded "The Smart Cities Mission". The government of India has the ambitious vision of developing 100 cities by modernizing existing mid-sized cities[2]. Some larger IT, telecommunications, and energy management companies launched market initiatives for intelligent cities. For instance, *Alibaba* has created the City Brain[3]. *Microsoft* has a solution for smart cities named *Citynext*[4]. In addition, *Cisco*, launched the global "Intelligent Urbanization" initiative to advocate for cities to use the Internet as a fourth tool for integrated city management, improvement of citizens' quality of life, and economic development.

Moreover, the Metaverse initiative holds significant potential to alleviate the pressures of city construction and enhance the quality of urbanization. By leveraging Metaverse technologies, cities can achieve refined and dynamic management, leading to more effective city governance and improved quality of life for citizens. In this context, the integration of the Metaverse becomes crucial for the development of smart cities. The Metaverse is essentially a digital and gridded virtual world, which is just like the game *Minecraft*[5]. It is important to note that the concept of smart cities can also be interpreted in different ways. We can also have a different understanding of smart cities. In this sense, smart cities are part of a complete Metaverse. Thus, there are a lot of opportunities in smart cities, especially in the period that the Metaverse is developing. The technologies of Metaverse can provide valuable blueprints for smart cities.

For the above issues, this paper proposes the definition and characteristics of the Metaverse and smart cities, summarizes the current application scenarios and challenges of smart cities in the Metaverse, and puts forward future directions. The contributions of this article are as follows:

- Firstly, we provide an introduction to the Metaverse, covering its fundamental concept, distinguishing features, crucial technologies, and practical uses.
- Next, we discuss the concept of smart cities and explore potential solutions for the future. In addition, we examine how Metaverse technology can be integrated with smart cities and its potential applications.
- Moreover, the key technologies of the Metaverse for smart cities, including interactive technologies, cloud/fog computing, artificial intelligence (AI), 5G, digital twins, and blockchain, are introduced. The purpose is to explain why the Metaverse can empower smart cities better.
- Although the vision of a smart city empowered by the Metaverse is promising, it is important to acknowledge that there will be numerous open problems and challenges that need to be addressed. Thus, we further highlight and discuss some of these potential issues and opportunities.

Organization. The organization of this review is shown in Fig. 1. The rest of this paper is organized as follows. In Section 2, we introduce the Metaverse, including its basic concept, characteristics, key technologies, and applications. In Section 3, we discuss the future expectations and solutions for smart cities, as well as the integration of the Metaverse and smart cities. In Section 4, we present the applications of the Metaverse in smart cities, highlighting its potential contributions. In Section 5, we list the key technologies of the Metaverse for smart cities, showcasing how the Metaverse can empower smart cities. Based on the above sections, we explore some open problems and opportunities in Section 6. Finally, we conclude the paper in Section 7.

2. Metaverse

"Metaverse" is a term that has been in use for decades. It was first coined in the science fiction book *Snow Crash* in 1992 [124]. In this book, the Metaverse is described as an Internet-based virtual world that exists parallel to the natural world, where users can share experiences through avatars. The term "Metaverse" is composed of "Meta" [61], which means transcendence in Latin, and "Verse" taken from the word "universe", referring to a world beyond the present. With the development of emerging technologies such as blockchain [114] and cloud computing [83], the classic concept of the Metaverse has been reinterpreted. Currently, the Metaverse is understood as and referred to as a virtual world that integrates multiple technologies and can be mapped and interacted with in the real world [73,90]. It is an Internet application that combines virtuality and reality, representing the next stage of Internet development. In other words, the Metaverse is not separate from reality but emphasizes the primacy of the physical world, with the virtual world as a complementary element.

2.1. Characteristics of Metaverse

The development of the Metaverse represents a complex and multifaceted challenge that requires a wide range of technological, social, and economic solutions. It involves the integration of a vast array of

[1] ASEAN, short for the Association of Southeast Asian Nations, constitutes a political and economic alliance comprising ten member states situated in Southeast Asia.
[2] https://smartcities.gov.in.
[3] https://www.alibabacloud.com/solutions/intelligence-brain/city.
[4] https://www.microsoft.com/en-us/industry/government.
[5] https://en.wikipedia.org/wiki/Minecraft.

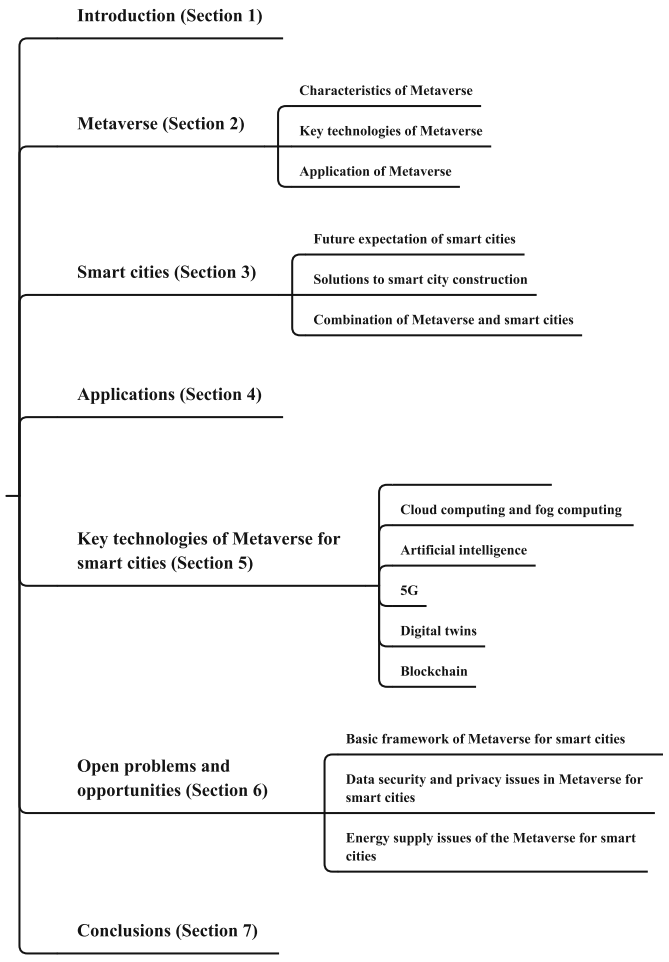

Fig. 1. The outline of our overview.

technologies and platforms, as well as the creation of new business models and economic systems that can support the growth and sustainability of the virtual world. At the same time, the Metaverse also presents a range of exciting opportunities for innovation and creativity, offering a platform for individuals and organizations to explore new ideas, collaborate on projects, and build communities in a fully immersive digital environment. As technology continues to evolve and mature, it has the potential to transform the way we live, work, and play, creating new possibilities for human connection and expression on a global scale. According to *Roblox*[6], the characteristics of the Metaverse are mainly reflected in the composition of eight elements: identity, friends, immersion, low latency, diversification, anywhere, economic systems, and civilization [49]. The description of these eight elements of the Metaverse is shown in Table 2.

Table 2
Eight elements of the Metaverse.

Elements	Description
Identity	In the Metaverse, users will have a new and arbitrary virtual identity [73], and each user will participate in the virtual world as a virtual person. In the future, with the development of modern technology, we can also predict that each virtual human's needs will correspond to the needs of the physical robot. Human identity, virtual identity, and machine identity are integrated with multi-sensor interaction, space-time jumping, and data interconnection.
Friends	Human beings are social animals, and social behavior is an indispensable activity for human beings to connect and form a social form. With time elapsing, the modes of social communication are also changing [3], from early letters and modern faxes to Twitter, emails, etc. in the Internet age. As for the Metaverse, social networking also exists [114]. The Metaverse's social contact is more authentic than virtual social networking in the Internet era.
Immersion	The immersive [31]experience is one of the most important characteristics of the Metaverse. Immersion is the key to breaking the real- and virtual- dimensional walls between the Metaverse and the real world. People can perceive the world through vision, hearing, touch, smell, etc. Regarding sight and hearing, users can experience various scenes in the Metaverse using modern technologies such as augmented reality (AR), virtual reality (VR), and mixed reality (MR). In the future, touch will become the third perception dimension for users in the virtual world, in addition to vision and hearing [124].
Low latency	The Metaverse requires high synchronization and low latency [101] so that users can get a real-time, smooth, and perfect experience. The emergence and development of 5G gradually make this concept possible.
Diversification	The Metaverse has rich user-generated content (UGC) [33], which means users generate content. Users are both players and creators. The Metaverse's diversity is dependent on their imagination. Its achievement requires the Metaverse to have good openness and a sufficiently low operating threshold. This requirement can enable a considerable number of users to participate in constructing the Metaverse and enriching its ecology. Furthermore, with the development of AI-generated content (AIGC) [111], the Metaverse is expected to become an autonomous society.
Anywhere	The concept requires human beings to realize a vision in which people can enter the Metaverse anytime and anywhere [24], eliminating the limitations of time and space. To achieve its objectives, the concept still requires our continued efforts and development.
Economic systems	As a virtual world independent of the real world, the Metaverse also needs a set of economic systems [4] similar to those in the real world but belonging to the Metaverse. This digital asset does more than belong to a game world. It can also be connected to the Metaverse and exchanged for real currency.
Civilization	In this virtual digital world, the emergence of its culture is one of the signs of its maturity. From the innovation and application of new technologies to the formation of an economic system and business model that match them, and then to the popularity of the public, forming a unique social structure, formulating the rules belonging to the Metaverse, and finally stepping into maturity This process will gradually create a civilized system in the Metaverse and promote the development of modern society.

2.2. Key technologies of Metaverse

The Metaverse is a combination of the real and virtual worlds that requires various new technologies to create an immersive experience and build an exclusive economic system. The integration of critical technologies makes the Metaverse more immersive, diverse, and low-latency. We have divided the technologies involved in the Metaverse into four categories: network infrastructure, fundamental technology, virtual reality space convergence, and virtual reality object connection, as shown in Fig. 2. We provide a detailed explanation of each element below.

Communication and computing infrastructure. The foundation of connectivity is the Internet. Many innovations, such as 5G and 6G, have been made through continuous Internet research. 5G offers advantages such as low latency, high speed, and low power consumption, enabling the realization of the Metaverse. 6G has the potential to transcend time limitations and extend services from the physical world to the virtual world, providing the network foundation for the Metaverse. Additionally, quantum communication technology ensures communication security in 5G and 6G network environments. The Internet of Things (IoT) plays a vital role in the Metaverse, providing users with a seamless and authentic interactive experience. Cloud computing, edge computing, and other computing paradigms promote the development of computing power to meet the low threshold requirements of the Metaverse.

Fundamental technology. AI algorithms play a crucial role in

[6] https://www.roblox.com.

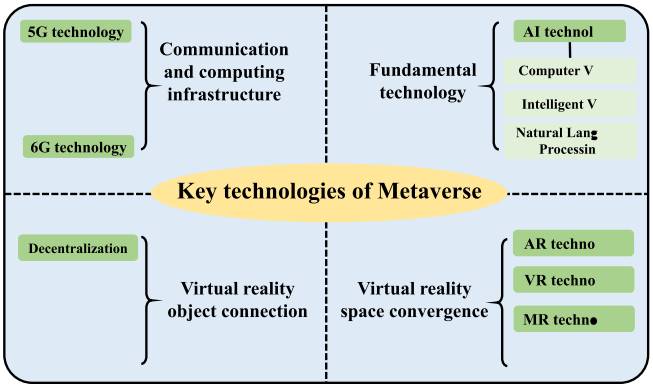

Fig. 2. The key technologies of the Metaverse.

bridging the virtual and real worlds. AI enables the breakdown of natural language and facilitates language conversion, allowing users from around the world to access the Metaverse without language barriers. Furthermore, technologies such as computer vision, intelligent voice, and natural language processing provide users with visual and auditory experiences similar to those in the real world. Consistent spatio-temporal data is essential for mapping between the real world and the Metaverse, as spatio-temporal consistency is a fundamental feature of the Metaverse. Spatio-temporal algorithms aid users in understanding how to navigate and move within the Metaverse.

Virtual reality object connection. Decentralization is a concept in which every component of the system incorporates the core. The Metaverse utilizes four decentralization technologies: decentralized computation, decentralized storage, decentralized databases, and blockchain. Blockchain, the most commonly applied decentralization technology in the Metaverse, ensures the trustworthiness of the other three technologies and grants ownership of virtual world assets exclusively to Metaverse citizens.

Virtual reality space convergence. Augmented reality (AR), virtual reality (VR), mixed reality (MR), and brain-computer interface (BCI) are indispensable for achieving the convergence of the virtual and real worlds. AR utilizes real-world entities as its main focus and enables users to explore the real and virtual worlds more effectively through digital technology. VR provides users with a highly immersive experience within the Metaverse. MR integrates virtual objects into the real world, allowing users to interact with them in their physical environment. BCI offers users a more convenient and rapid mode of interaction.

2.3. Application of Metaverse

Metaverse enables the virtualization of events that would typically require face-to-face interaction, allowing them to take place online. Activities that were traditionally only possible offline are now being converted into virtual reality and rapidly expanding into various fields, such as medical care [96], education [64], and smart cities [60]. In the medical field, a specific type of Metaverse known as extended reality (ER) is utilized to simulate the entire radiotherapy process and identify and address issues that may arise during the process [123]. In addition, in the future, nurses will collaborate with the Metaverse to develop innovative solutions to enhance the efficiency, capacity, and quality of cancer care [120]. By leveraging the capabilities of the Metaverse, educational institutions can create virtual campuses or replicas of their institutions, providing immersive learning experiences like never before. This technology allows for the gamification of lessons, virtual travel to explore historical and cultural sites, and a new level of enjoyment in the field of science [25]. Moreover, the Metaverse enables the creation of digital twins in 3D format for cities or landscapes. It allows for the prediction and assessment of various factors, such as climate, traffic dynamics, and energy production, enabling proactive resource management practices. Storing resource-intensive products in virtual environments reduces the impact on landfills, water bodies, and sensitive ecosystems while enhancing city assets such as green spaces, water bodies, and cultural heritage sites [4]. The Metaverse is a powerful tool with the potential to revolutionize our interactions with the world. It offers new avenues for learning, working, and socializing, ultimately improving our quality of life. As technology continues to advance, it can be anticipated that even more innovative applications of the Metaverse in the future.

3. Smart cities

The concept of the smart city, initially proposed by IBM in 2008 as part of their concept of the Smart Earth, has evolved to encompass the application of new-generation information technologies in various aspects of city development. These technologies include the Internet of Things (IoT), cloud computing, and big data analysis [12,88]. To monitor water, electricity, and transportation systems in the city, a diverse range of sensors are deployed [45]. These sensors collect data that is transmitted to the elastic compute service (ECS), which is a cloud computing platform [67,92]. Within the ECS, the collected data is analyzed using big data analytics to promptly identify existing problems.

Currently, the concept of the smart city is widely accepted worldwide. Governments can utilize big data analysis to make informed decisions, promote economic development, and ensure sustainable resource utilization in cities. For enterprises, the smart city concept provides opportunities for technological development and encourages digital transformation. Residents benefit from the implementation of smart city technologies as they gain access to convenient life services that improve their quality of life and overall happiness.

3.1. Smart city construction

The construction of a smart city involves the integration of new technologies, the effective utilization of data, and the establishment of a comprehensive one-stop platform, as shown in Fig. 3. By leveraging these factors, cities can achieve improved efficiency, sustainability, and quality of life for their residents.

New technologies. Cutting-edge technology plays a pivotal role in the advancement of smart cities [85]. It hinges on the utilization of advanced infrastructure and the seamless integration of cutting-edge information technology. Among the foremost technologies driving smart cities, the Internet of Things (IoT) stands out as a linchpin. IoT enables the interconnection and seamless communication among a myriad of devices and sensors. This interconnected network empowers the collection and swift exchange of data, enabling real-time monitoring and dynamic control of city systems. Cloud computing, another indispensable technology woven into the fabric of smart cities, offers scalable and on-demand access to computing resources. This allows for the efficient storage, processing, and analysis of vast volumes of data generated by a multitude of sensors and devices. Leveraging cloud platforms facilitates the deployment of smart city applications and services, underpinning data-driven decision-making and amplifying the overall efficiency of city management. In addition to IoT and cloud computing, intelligent search and big data analysis methods are harnessed within smart cities to manage the immense troves of collected data. Intelligent

Fig. 3. The three important factors of smart city construction.

search algorithms empower rapid and precise retrieval of pertinent information from diverse sources, streamlining decision-making processes for city planners and administrators. Meanwhile, big data analysis techniques unveil invaluable insights and patterns hidden within extensive datasets, empowering predictive modeling and the optimization of city operations. To ensure well-informed decisions and preempt potential pitfalls, governmental regulators can harness computer simulations. By crafting virtual models of the city and its intricate systems, regulators can simulate assorted scenarios and meticulously evaluate potential outcomes before implementing changes in the physical environment. This simulation-centric approach permits the thorough assessment of the impact of various decisions, profoundly aiding in the development of efficient and sustainable smart cities.

Data. Data is a vital asset in smart city development, playing a crucial role in driving innovation and growth across industries. The sharing of information among different stakeholders can eliminate knowledge barriers and foster collaboration, leading to the rapid advancement of various sectors. In the ongoing development of smart cities, data-sharing protocols are actively pursued to enhance the circulation of data. These protocols aim to establish standardized frameworks and mechanisms for seamless and secure data exchange. By enabling efficient data sharing, these protocols facilitate the integration of disparate datasets from various sources, unlocking new insights and opportunities for city development. However, as data circulation expands, ensuring data security becomes paramount. Researchers and experts are actively exploring solutions to protect the privacy and integrity of large-scale data circulation. Among the technologies being investigated, blockchain stands out as a promising solution. Blockchain provides a decentralized and tamper-resistant framework for data storage and transactions, enhancing trust and security in data exchanges. By utilizing cryptographic techniques and distributed consensus mechanisms, blockchain can enable secure and transparent data sharing within the ecosystems of smart cities. In addition, privacy computing techniques are being developed to address privacy concerns in data circulation. Privacy-preserving algorithms and protocols allow data to be analyzed and processed while protecting sensitive information. These techniques enable data owners to retain control over their data while still contributing to the collective intelligence of the smart city. Current technologies have made significant progress in exploring the application of blockchain and privacy computing in smart city contexts [46,106,122]. These technologies offer promising solutions for ensuring data security and privacy while facilitating the flow of information necessary for smart city development.

One-stop platform. The intelligent transportation system utilizes advanced technologies such as real-time data analysis, traffic monitoring, and smart routing to optimize transportation networks, improve traffic flow, and enhance overall efficiency and safety [85]. The energy system focuses on the intelligent management and utilization of energy resources, incorporating technologies like smart grids, energy monitoring systems, and renewable energy solutions to optimize energy distribution, reduce waste, and promote sustainable practices. The logistics and building service systems leverage IoT sensors, automation, and data analytics to streamline logistics operations, enhance supply chain management, and improve building maintenance and services. A city command center serves as the nerve center for monitoring and managing various city functions in real time. It integrates data from different sources, enabling authorities to monitor and respond promptly to emergencies, coordinate public services, and ensure efficient city operations [35]. Intelligent healthcare utilizes technologies such as telemedicine, wearable devices, and health data analytics to enhance healthcare services, promote preventive care, and improve the overall well-being of residents. City environmental management employs sensors, data analysis, and predictive modeling to monitor and manage environmental factors such as air quality, waste management, and water resources. This enables authorities to make informed decisions and implement effective measures to create a sustainable and eco-friendly city environment. The government's public service platform provides a unified interface for residents to access various government services. This digital platform enables the efficient delivery of public services such as permits, licenses, payments, and information dissemination, enhancing convenience and accessibility for citizens.

3.2. Combination of Metaverse and smart cities

Combined with the current concept of the Metaverse, the development of smart cities can be significantly enhanced. The Metaverse represents a vision where diverse technologies are utilized to create virtual representations of the real world, enabling real-time perception of data and dynamic adjustments based on these changes [44,94]. By integrating the Metaverse with the concept of smart cities, there is tremendous potential for expansion and advancement. The Metaverse can offer solutions to existing technical challenges in smart cities, such as high energy consumption of sensors, communication delays, algorithmic perception errors, and IoT security concerns [4,13]. The emergence of the Metaverse transcends the boundaries of physical city space, allowing for the experience of virtual scenes within the real world and promoting the integration of virtual and physical realms in city governance. This integration brings three significant characteristics when combining the smart city concept with the Metaverse, as illustrated in Fig. 4.

Expanded data perception and analysis. The combination of the Metaverse and smart cities enables a more comprehensive and detailed perception of real-world data, leveraging advanced technologies. By integrating virtual and physical data sources, smart cities can gain deeper insights into various aspects of city life, including transportation patterns, energy consumption, and citizen behavior. These enhanced data perception and analysis capabilities support more accurate decision-making, efficient resource allocation, and improved city management. In the context of the combination of Metaverse and smart cities, the abundance of intelligent devices distributed throughout the city generates a vast amount of data. To create a future-proof smart city, it is crucial to analyze and utilize this data effectively. Big data analysis plays a pivotal role in converting raw data into actionable insights for city managers [2,12]. The results of such analysis provide a reliable foundation for city management, allowing decision-makers to formulate plans and implement targeted strategies based on the data-driven findings. This iterative process of utilizing data to inform decision-making creates a virtuous circle, fostering continuous improvement and development within the city. Furthermore, the integration of the Metaverse and smart cities necessitates the construction of a robust data integration and sharing platform. This platform serves as a centralized repository for collecting, processing, and sharing data across various domains and stakeholders. By establishing such a platform, cities can break down data silos, promote collaboration, and enable the seamless flow of information. This integrated approach to data management facilitates more efficient and effective city governance, fosters innovation, and enables

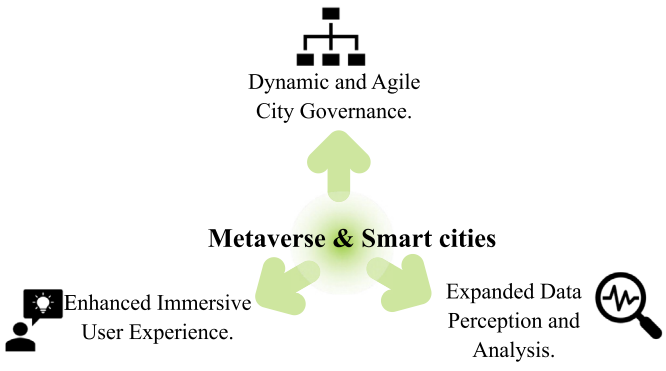

Fig. 4. Significant characteristics of the combination of Metaverse and smart cities.

the implementation of data-driven solutions for city challenges.

Enhanced immersive user experience. The integration of the Metaverse and smart cities introduces an enhanced user experience by offering immersive and interactive virtual environments. Residents have the opportunity to engage with virtual city spaces, access various services, participate in social activities, and experience simulated scenarios. By leveraging virtual reality (VR) and augmented reality (AR), individuals can immerse themselves in virtual replicas of their cities. They can explore different areas, interact with virtual representations of buildings and infrastructure, and visualize proposed city planning and design concepts. This immersive experience not only enhances user engagement but also enables citizens to provide valuable feedback and input during the planning and decision-making processes. Virtual environments within the Metaverse also facilitate community engagement and citizen participation. Residents can participate in virtual meetings, discussions, and collaborative activities, regardless of their physical location. This inclusivity promotes a sense of belonging and encourages active involvement in shaping the future of their cities. By leveraging virtual platforms, city authorities can gather diverse perspectives and incorporate community insights into city development plans. Furthermore, the integration of the Metaverse and smart cities enables the testing and validation of city planning and design concepts in virtual environments before implementation in the physical world. City planners and architects can create virtual replicas of proposed projects, simulate their impact on the city landscape, and gather data-driven insights to inform decision-making. This iterative process allows for more efficient and informed city development, reducing the risk of costly mistakes and enhancing the overall quality of the built environment.

Dynamic and agile governance. The integration of the Metaverse with smart cities facilitates dynamic and agile governance approaches. Through virtual simulations and real-time data analysis, city authorities can make well-informed decisions quickly, evaluate the impact of policy changes, and monitor the effectiveness of interventions. This flexibility in governance enables adaptive and responsive city management, empowering cities to address emerging challenges and seize opportunities for continuous improvement. Smart cities in the Metaverse serve as comprehensive management platforms for cities, offering a more intelligent and integrated approach to city development. These cities embrace a model that incorporates all essential systems, including production, commerce, transportation, communication, and healthcare [20,91]. The platform makes full use of technologies such as big data, cloud computing, and the IoB to intelligently respond to various public service needs, such as social management and industrial operations [72]. In this integrated platform, information from various professional systems is gathered and centralized in a command center in real-time, ensuring accurate and timely decision-making. City decision-makers can develop precise and effective scheduling plans based on the comprehensive situational awareness provided by the platform. Real-time and all-directional remote command and scheduling capabilities empower city authorities to ensure efficient response and deployment during major emergencies, offering strong support for city management and public security [95]. The integration of the Metaverse and smart cities enhances the coordination and efficiency of city management activities. By leveraging advanced technologies and real-time data, decision-makers can gain a holistic understanding of city dynamics and optimize resource allocation accordingly. This dynamic and agile governance approach enables cities to respond proactively to changing circumstances, improve service delivery, and enhance the overall quality of life for residents.

3.3. Future expectation of smart cities

The concept of a smart city revolves around achieving real-time monitoring of city resources and implementing scientific management and scheduling practices to promote sustainable development. Sensors play a crucial role in collecting real-time information about various aspects of the city, which is then used to generate a comprehensive map of the city's operations [81]. Through the analysis of this data, security risks can be identified promptly, leading to improved management efficiency and enhanced emergency response capabilities. The implementation of smart city initiatives involves the utilization of information technology across different sectors and industries within the city. Intelligent upgrades have been applied to various fields, including transportation, energy, ecology, and security. In the realm of intelligent transportation, real-time traffic monitoring systems enable the capture of accurate data on travel speeds [121]. Path algorithms like Contraction Hierarchies can predict and prevent traffic congestion, allowing drivers to receive timely navigation updates and avoid large-scale congestion [40]. Intelligent security systems provide real-time access to the status of alarm forces in different regions, enabling timely responses and effective allocation of police resources in emergencies [34]. By integrating surveillance and response mechanisms, smart cities enhance public safety and security.

Furthermore, smart cities emphasize sustainability and environmental management. Implementing smart grids and energy-efficient systems allows cities to optimize energy consumption, reduce carbon emissions, and promote renewable energy sources. Waste management systems integrated with smart technologies enhance the waste collection, recycling, and disposal processes. In intelligent energy systems, three-dimensional visualization techniques enable the analysis of data related to pipe networks, such as thickness, buried depth, and type [48]. This visualization aids in optimizing energy distribution and management. In the context of the intelligent ecosystem, real-time monitoring of weather conditions, air quality indicators like the air quality index (AQI)[7], and water resources help assess and visualize the city's ecological environment [9].

Smart cities also incorporate intelligent solutions in other areas to enhance overall city management. In the domain of intelligent healthcare, advanced technologies such as electronic health records, telemedicine, and wearable devices enable remote monitoring and personalized healthcare, leading to more efficient and accessible healthcare services for residents. The concept of smart cities also encompasses intelligent governance and public service delivery. By integrating data and information systems, government agencies can provide better and more efficient public services to residents. This includes online platforms for government services, digital citizen engagement tools, and data-driven decision-making processes. The combination of smart city technologies with the Metaverse offers even greater possibilities for city development. The Metaverse provides immersive and interactive virtual environments that allow residents to engage with the city and its services in new and exciting ways. Virtual simulations can be used to test and refine city planning strategies, while augmented reality applications enhance the overall user experience in various aspects of city life.

4. Applications

From the perspective of city development, cities can be categorized into three distinct eras: the era of horsepower, the era of electricity, and the era of computing power. The concept of the smart city emerged as a result of the transition from the era of electric power to the era of computing power. The relatively new idea of the Metaverse has the potential to empower smart cities and infuse them with renewed vitality [13]. As the Metaverse gains popularity, many people are envisioning the kind of life and work experiences it could offer humanity [41]. Furthermore, the Metaverse is poised to become a key trend in smart city development, representing the future trajectory and direction [14]. It is reasonable to predict that the Metaverse will find diverse applications in the smart cities of the future [4]. Some of the potential application scenarios are depicted in Fig. 5.

[7] https://en.wikipedia.org/wiki/AQI.

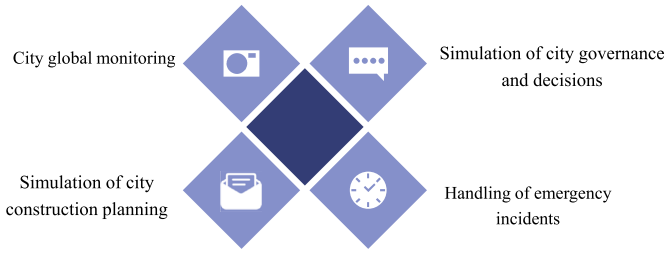

Fig. 5. The future applications of the Metaverse combined with smart cities.

City global monitoring [53]. One of the main functions of a smart city is the ability to monitor the entire city. Through the monitoring of city law enforcement, sanitation, greening, municipal administration, lighting, gas, etc., problems can be identified in time. In addition, on the premise that the responsible units for various city management issues and the divisional boundaries of city management departments are standardized and clarified, coordinated handling is achieved. It brings great convenience to city governance and helps regulators to find problems in cities and solve them in time, such as lighting failures, destruction of greenery, and more. However, city managers' grasp of the basic information and status of the city are limited by the time of data collection and statistics, which have delays and inaccuracies. If the real-time, immersive, and low-latency features provided by the Metaverse are fully used, city managers can be placed in the cities they manage, comprehensively obtain city information, and give full play to the capabilities of city managers [4,63].

Incorporating IoT into city global monitoring applications within the Metaverse can enable real-time data collection from various sensors placed throughout the city. These sensors can provide instant updates on various aspects, such as traffic, air quality, energy consumption, and more. The IoT's role in seamlessly connecting these sensors and devices should be emphasized to showcase how it enhances the Metaverse's capacity for comprehensive city monitoring. Apart from IoT, it is essential to mention the integration of additional technologies. For instance, real-time data from IoT sensors can be combined with geospatial technology, enabling precise location-based information. Geographic information systems (GIS) can help visualize data spatially, making it easier for city managers to understand and act upon the information. This holistic approach, involving IoT and GIS technologies, enhances the immersive experience in the Metaverse, allowing city managers to navigate and interact with the city more effectively.

Simulation of city governance and decisions [99,102]. City governance and decision-making relied on government data. Today, with the gradual application of smart cities, municipal governance is becoming more and more refined. On the timescale, some scenes need to be able to be updated in real-time; on the spatial scale, it is hoped to be finer to a more detailed grid. It requires more socialized big data to participate. By providing multivariate big data, new tools, and new methods through smart cities, the traditional post-assessment approach can be transformed into a more comprehensive assessment that combines before, during, and after an event occurs. Before the event occurs, conduct simulation analysis and do analysis and comparison of multiple scenarios and comparisons of multiple plans; when the event occurs, conduct dynamic monitoring and evaluation; and after the event occurs, conduct a full-chain evaluation and analysis of the event. It forms a full-lifecycle spatial governance closed loop for the operation, monitoring, diagnosis, performance evaluation, and simulation decision-making of the entire city. The concept of the Metaverse makes city governance and decision-making easier and more comprehensive. In the Metaverse, all people and things, in reality, can be embodied based on their real-time mapping properties with the real world [73]. In addition, the Metaverse can realize spatial data visualization [69]. Therefore, by fully mapping all city problems into the Metaverse, and observing the dynamics of events in the Metaverse, changes in the situation can be discovered in advance and problem-solving can be simulated, thereby providing better decision-making for the cities in the real world [105].

Discussing the handling of emergency incidents within the Metaverse, it is important to emphasize how IoT technology plays a vital role in real-time monitoring and early warning systems. IoT sensors can detect anomalies, such as waterlogging or fires, and relay this information to the Metaverse. Highlighting the integration of IoT data sources and the seamless transfer of information from the physical world to the Metaverse will showcase the Metaverse's capability to improve emergency response and preparedness. In addition, the integration of AI and other technologies plays a critical role in data analysis and scenario planning. These technologies can process vast datasets from sensors and other sources to identify trends and predict outcomes.

Handling of emergency incidents [55]. In the real world, city systems can handle emergency events through monitoring. When the smart city system is perfect, as part of the city operation management service platform, it can warn of the arrival of emergencies such as waterlogging, fire, and earthquakes and take corresponding countermeasures. Taking waterlogging as an example, the smart city system marks the key flood prevention points on the large-screen map, and the coordinates of each point are visible. In addition, the on-site video can be sent back in real-time, and the attribute information of the responsible person can be seen at a glance. Among them, some important points are equipped with water level monitoring devices, which can collect and report the situation of water accumulation on-site in real-time. As long as the monitored water level is higher than the warning value, the system will immediately sound an alarm to remind relevant flood control personnel to deal with it in time. Through the Metaverse, in addition to responding to related emergencies, it is also possible to simulate real emergency events such as waterlogging and fire. it is hard to experience this immersive experience in the real world, but it is a breeze in the Metaverse. With the help of Metaverse, real scenes, changing situations, and the participation of all staff can be fully reflected, thereby greatly improving the emergency response capabilities of all staff.

It is important to emphasize how IoT technology plays a vital role in real-time monitoring and early warning systems. IoT sensors can detect anomalies, such as waterlogging or fires, and relay this information to the Metaverse. Highlighting the integration of IoT data sources and the seamless transfer of information from the physical world to the Metaverse will showcase the Metaverse's capability to improve emergency response and preparedness. In addition to IoT, spotlight the synergy of augmented reality (AR) and virtual reality (VR). These immersive technologies can provide real-time visualizations and simulations of emergencies. For example, firefighters can use AR goggles to see vital information overlaid on their field of view during a fire response. The combination of IoT data and AR/VR enhances situational awareness and decision-making in emergency scenarios within the Metaverse.

Simulation of city construction planning [112]. With the maturity and popularization of smart city technologies, it is expected to use digitalization, data intelligence, grid processing, and other technologies to play a guiding role in city construction planning in the future [52]. Entering the era of rapid city renewal, the scale of city renewal is becoming more and more refined, down to a street or even a building. For example, when a street is being updated, in addition to the analysis of population, industry, and public service facilities, some street view data can also be used to learn what the business configuration of a vibrant block in the world looks like through artificial intelligence. For the renewal of a building, multivariate data can also be used for auxiliary analysis on how to configure different floor types more accurately. With the concept of Metaverse becoming more mature, the application of Metaverse in city construction planning is bound to make greater progress. Planners can plan new facilities in the city, like in the game *Minecraft*, and have a powerfully immersive experience in the city, which is conducive to making better planning decisions.

IoT devices can offer data on traffic patterns, population movements,

and infrastructure usage, which can be used to inform city planners within the Metaverse. Stress the importance of real-time IoT data streams in enabling immersive city planning simulations and more informed decision-making processes. Additionally, the tools of 3D modeling and city planning software enable planners to create detailed 3D models of city infrastructure and visualize proposed changes in a realistic environment. The integration of these technologies with the Metaverse provides planners with a dynamic and interactive platform for exploring different construction scenarios. Emphasize how IoT data, 3D modeling, and city planning software converge to facilitate informed decision-making and immersive city planning experiences.

5. Key technologies of Metaverse for smart cities

The Metaverse plays a pivotal role in integrating the real world and the digital world [119]. It offers captivating interactive experiences in the virtual realm that appeal to various industries. Accelerating the adoption of the Metaverse can effectively support the integration of the virtual and real worlds, and it also has significant implications for the advancement of smart city construction. The Metaverse is not a single technology but rather a fusion of multiple technologies applied in diverse scenarios [23]. These Metaverse technologies have the potential to drive the development of smart cities. Smart cities that embrace Metaverse technologies serve as crucial platforms for digital governance and the growth of the digital economy, ultimately enhancing the long-term competitiveness of future cities [103]. The operational processes of smart cities, as illustrated in Fig. 6, are primarily categorized into data sourcing, data aggregation, and project delivery. When analyzing connectivity with the following key technologies, a special emphasis on the relationship with IoT will help to better understand the role of these technologies in Metaverse and smart cities. Thus, we illustrate the connection between these technologies and IoT in Table 3. In these processes, Metaverse technologies can empower and support smart cities, providing robust capabilities. In the following context, we delve into how these technologies impact and foster the growth of the Metaverse.

5.1. Interactive technologies

The interactive technologies we introduce includes AR and VR [86]. From the perspective of technological evolution, the Metaverse is most likely to be realized by relying on AR/VR interactive technologies at this stage. The immersive experience is one of the basic features of the Metaverse, and AR/VR equipment is the necessary hardware to support the immersive experience [76]. Similarly, for smart cities, interactive technologies that provide immersive experiences can also offer broad application possibilities [58]. Interactive technologies play an important role in terms of data sourcing and project delivery in smart cities.

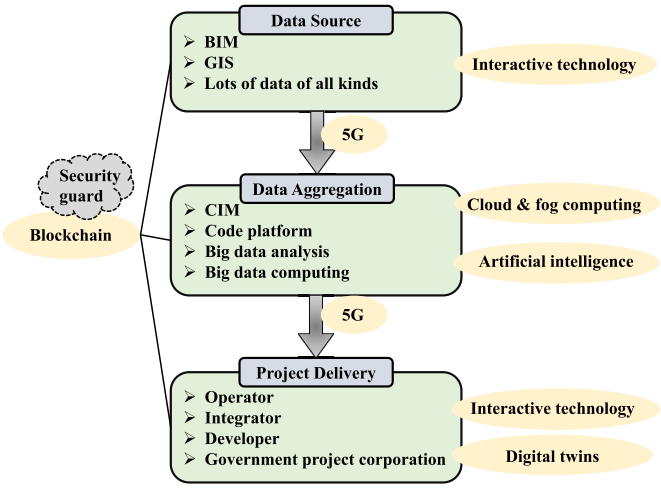

Fig. 6. The operation processes of smart cities and the technologies in Metaverse.

Table 3
The connection between the technologies of Metaverse and IoT.

Technology	Connection
Interactive	IoT sensors and devices can provide real-world data that enhances the immersive experience in AR and VR applications. For instance, IoT data can be used to augment real-world objects in AR environments.
Cloud computing and fog computing	IoT devices generate vast amounts of data that require efficient processing and storage. Cloud computing provides the scalability and resources needed to manage this data, while fog computing brings computation closer to IoT devices for faster real-time processing.
Artificial intelligence	IoT data serve as valuable input for AI algorithms. Artificial intelligence can analyze and derive insights from IoT-generated data, enabling predictive maintenance, anomaly detection, and intelligent decision-making in smart cities.
5G	5G's high-speed and low-latency characteristics are fundamental for seamless IoT device communication. It facilitates the rapid and reliable exchange of real-time data, which is crucial for applications like autonomous vehicles and responsive smart infrastructure.
Digital twins	Digital twins are virtual replicas of physical objects or systems. IoT data continuously updates digital twins, ensuring they reflect the real-world state. This integration of IoT data is invaluable for simulation, analysis, and informed decision-making.
Blockchain	Blockchain enhances the security and trustworthiness of IoT data. It provides an immutable ledger for IoT data transactions, ensuring data integrity and authenticity, which is vital for applications requiring data traceability and security.

In terms of the data source, smart cities are bound to generate a lot of data, thus data redundancy is an inevitable phenomenon [100]. The most representative data in smart cities are building information modeling (BIM) [8] and geographic information system (GIS) [21] data. In traditional cities, two-dimensional drawings are often used to represent designs, which have a high error rate, and many designs can only be imagined. Nowadays, with BIM, relevant software can be used to carry out three-dimensional modeling of multiple data and construction projects, quickly resolving drawing problems and solving technical issues in a visual way [97]. GIS applied to the construction of smart cities can provide technical support for the innovation and transformation of smart cities by virtue of its advanced information level, spatial sense, three-dimensional sense, and other advantages [5]. With the continuous deepening of city informatization and intelligent development, there are higher requirements for real-time visualization of geographic information [68]. GIS will directly affect, or even determine, the construction quality and efficiency of smart cities. GIS can effectively make up for the shortcomings of traditional geographic information systems and better meet the requirements of spatial data processing. Because the data in BIM and GIS are different from data in traditional forms, it is not intuitive to interpret these data in smart cities, and it is not easy to reduce and eliminate useless information and redundant data through traditional data analysis methods [98]. The interactive technologies of the Metaverse can make the interpretation of this spatial data more intuitive and convenient, which is also conducive to reducing redundant data. In this way, some useless information transfer can be reduced at the data source, thus reducing unnecessary waste of resources.

Furthermore, the interactive technologies of AR/VR are used to highly simulate and visualize the data, which is also helpful for decision-makers to make better decisions and for workers to better deal with situations according to reality. It has great application in the project delivery process. In general, in the Metaverse, smart cities can be more targeted, iconic, and humanized. In the Metaverse, some useful tools, such as BIM and GIS technology, can continuously create new and more

reasonable dimensions in the model. Physical information such as length, width, and height in the building, time-consuming, cost simulation, and a humanistic atmosphere can all be simulated in the virtual model world for decision-making and judgment as a reference for real-world decision-making. The combination of the Metaverse, BIM, and GIS brings new inspiration and experience to designers or decision-makers through an immersive experience. In addition, in the real world, relying solely on human imagination to operate is not only time-consuming but also prone to errors in the construction management process, which will affect efficiency. If the interactive technologies of the Metaverse are utilized, the construction process will be much easier. As long as maintenance workers wear VR glasses and adjust the appropriate scale, they can see every corner of the underground, zoom in and out in equal proportions, and check the status of every mechanical device and even every screw. It can not only save costs but also achieve high-efficiency delivery of high-quality architectural effects. Most of them are applied to large-scale industrial building models.

5.2. Cloud computing and fog computing

The Metaverse relies on crucial technologies to increase computing power and data storage capacity, and two of these technologies are cloud computing and fog computing [1]. Cloud computing refers to centralized computing that efficiently processes large amounts of data within a short period of time [65]. It leverages the Internet to upload data to remote centers for analysis, storage, and processing, providing services on a global scale. From another aspect, edge computing, which is closer to the device side, allows data processing to occur locally without the need for uploading to the cloud. Edge computing can be performed on devices like smartphones, ATMs, and smart homes. Fog computing, in turn, can be seen as localized cloud computing [57,79]. It not only eases the load on cloud computing but also benefits from its distributed nature, resulting in faster computing speed and lower latency [38]. These technologies are vital backend infrastructure for the realization of the Metaverse, especially considering the substantial data processing requirements, image rendering needs, and high-fidelity user experience they demand. Both cloud computing and fog computing are indispensable in the development of the Metaverse [29].

In smart cities, cloud computing and fog computing play an essential role in data aggregation. In this process, data from various sources is collected, analyzed, and computed. Traditional data centers are unable to cope with the data needs of smart city applications. The growing volume of data transmitted, stored, and accessed by IoT devices in cities necessitates a new infrastructure to handle this load [71]. With the tremendous amount of data that needs processing, the technologies of cloud computing and fog computing have become essential in smart cities. Cloud computing enables the upload of city data to remote centers for analysis, storage, and processing through the Internet. Fog computing serves as an intermediary computing layer between edge devices and the cloud. By providing computing power in close proximity to edge devices, fog computing enhances overall operational efficiency. This framework plays a crucial role in various applications, such as wearable devices for healthcare and fitness tracking, smart grids, smart cities, and ambient assisted living, among others.

5.3. Artificial intelligence

As one of the key technologies of the Metaverse, artificial intelligence (AI) is a technology that is able to make the Metaverse more dynamic. AI works with real users to be able to build characters in the Metaverse, which can create and aid economic activity and turn the barren Metaverse into an active and creative world. The generation of text, pictures, videos, and other content in AI-generated content (AIGC) [19,111] will also increase the content richness of the Metaverse [93]. In these years, artists and AI have created non-fungible token (NFT) artworks together [54,87]. The foundation of AI, deep learning, has greatly improved the experience of the Metaverse [108]. For example, making computers do better in gesture recognition and eye movement tracking makes it possible for machines to better understand human emotions and body language [125], which will further enhance AI's creative cooperation with humans. Software based on deep learning is also integrated into the virtual world, such as autonomous driving [43], robots making decisions in virtual activities [113], etc.

AI can better perform analysis and prediction of the data through data aggregation. Through AI, cities will become more intelligent. Specifically, it can be reflected in the following points:

- *Traffic management.* Intelligent traffic management systems can help alleviate congestion by informing drivers of roadblocks and delays. These systems utilize deep learning algorithms to predict and optimize traffic flow, which in turn reduces carbon emissions. Moreover, the integration of traffic violation detection systems and AI-powered cameras can significantly decrease the number of traffic accidents.
- *Parking.* Using the license plate recognition technology, the parking lot can impose a fine on vehicles that have stopped for more than the due time.
- *Environmental protection.* AI can be used to analyze the energy use data of citizens and determine where renewable energy can be used. In addition, it can show cities where energy is wasted and put forward measures to save energy. AI can also analyze and predict the level of pollution, which will help the relevant departments to make decisions that are most suitable for the environment.
- *Healthcare.* The patient monitoring system can detect chronic diseases in advance and help prevent them. It can analyze citizens' health reports and conduct medical consultations. Chat robots can provide medical assistance, provide information, and make appointments.
- *Public transport.* With the help of AI, users can learn about public transport in real-time and improve time and customer satisfaction. Automated buses in cities can reduce emissions and improve routes.
- *Garbage management.* AI can distinguish different types of garbage, track their nearest location, and monitor their filling volume to prevent overflow. AI can classify recyclable items more efficiently and quickly.
- *Identify crime.* Cameras supporting AI can detect criminal acts and immediately report them to the authorities. The unmanned aerial vehicle (UAV) can recognize the face, compare it with the database, track its identity, and verify the identity of the person entering the city or restricted area.

The application of AI in smart cities has the following points. Firstly, the application of AI in cities will enhance the personalized provision of services, help predict future trends, and simulate the adoption of various policies before the implementation of policies [75]. Secondly, AI can enhance financial management in cities by providing precise forecasting and expenditure management. By leveraging machine learning algorithms, city officials can better anticipate revenue streams and allocate resources more effectively, leading to improved financial sustainability and efficiency [78]. Thirdly, AI will enhance the fairness of cities and towns by making suggestions and taking action on welfare systems such as public distribution, primary health care, and education [59]. Fourthly, AI will positively impact the environment through energy, waste, and traffic management [51]. Finally, AI can boost worker productivity by providing efficient products and services, which in turn promotes economic growth in cities. By optimizing processes and automating tasks, AI can help cities' workforce achieve greater output with less effort, leading to increased economic activity and development [6].

5.4. 5G

Metaverse is parallel to the real world, reacts to the real world, and has a variety of high-tech integrations. It is a virtual world, but it is closely connected with the real world [117]. In this context, 5G mobile

communication will be crucial in facilitating the connection channel and enabling the efficient exchange of data and information [22]. Judging from the characteristics of 5G, it can meet many needs of the Metaverse [77]. On the one hand, it depends on the characteristics of 5G itself, such as its large bandwidth, low latency, high reliability, and wide connection. From another aspect, it depends on the organic combination of 5G and new technologies such as cloud computing, artificial intelligence, and blockchain.

In smart cities, the amount of data is larger than that of traditional city systems [80]. Because of the combination of various technologies, one communication technology is needed to support the transmission of this data. Due to the characteristics of the large bandwidth, low latency, high reliability, and wide connection of 5G, it is bound to play a vital role in the data transmission of smart cities [82]. 5G can empower the development of smart cities, endow them with the characteristics of new smart cities, and drive digitalization, networking, and intelligence in all areas of the city from three directions [115]. These three characteristics exist at the same time and promote their evolution. The core of digitalization is data. All things, people, and activities in the 5G smart city can be perceived and marked in the whole area, to collect various data and information more deeply. Massive amounts of data and information will become the basis of smart city operations and management. With the underlying resources, accelerate the digitization of city functions and objects. Networking refers to 5G, extensively connecting digital intelligent bodies to form a smart scene connection network that can operate independently and realize intelligent collaboration. Based on digitization and networking, cities themselves can operate intelligently and efficiently, and city entities can enjoy intelligent services and experiences. Further, based on 5G, 6G is also slowly gestating and developing. At present, the industry is in the early vision research stage of 6G, and industry-related organizations are actively discussing the requirements of 6G and conducting research on key technologies. 6G is different from 5G, which will subvert people's perceptions of mobile networks. 6G will fully support the digital transformation of the whole society and realize the intelligent connection between the physical world and the digital world. In the future, 6G will become the driving force of smart cities, assisting the development of smart cities and even global digitalization and realizing fast communication between virtual and reality [42,66].

5.5. Digital twins

Digital twins, as described in Ref. [11], are virtual replicas of physical objects that accurately mirror their real-world counterparts in the digital realm. In other words, digital twins create a virtual replica of a physical object, effectively duplicating it in the digital realm. Digital reproduction and digital representation technologies have been around for quite some time. In digital twins, a digitally reconstructed object is also fed real-time data from a real-world object to accurately mimic its actions and reactions [7]. The object is fitted with sensors that collect relevant data and feed it to a processing system that forwards it to a digital representation. Using this system, users can mimic the actions of real-world objects and predict their actions and responses. Digital twins can be valuable in the Metaverse, despite some dissimilarities, by providing a virtual representation of physical objects or systems. Assuming users feed real, real data to components in the Metaverse, they can successfully run what-if scenarios. It can be said that digital twins are an important part of the Metaverse.

In smart cities, digital twins often play a key role in product delivery. The product delivery party can test the product before delivery, establish a virtual model consistent with the real-world model in digital twins, and test it to reduce the probability of error. In addition, during the operation of smart cities, data can also be synchronized to the digital twins to monitor and find problems in time. In digital twins, multiple projects can be carried out at the same time, achieving data isolation between different environments and improving the efficiency of project delivery and the speed of smart city operation. In addition, in the digital twins, after obtaining the license, data from multiple industries can also be used at any time, and various fields of the city can operate independently but cooperate with each other [28].

5.6. Blockchain

The establishment of the Metaverse, a virtual technology, requires the support of blockchain. As a digital living space with a new social system, Metaverse can solve the problem of data trust and help establish an open and transparent community autonomy model [107]. Moreover, Metaverse can build a safe and reliable economic system and non-fungible tokens (NFTs), and achieve unique identity verification [110]. In general, blockchain can solve some Metaverse security issues. Likewise, blockchain can also be used to address some security concerns in smart cities.

As an emerging technology, blockchain has great potential in many fields, including smart cities [74,89]. In terms of infrastructure, the use of blockchain can explore and realize the efficient exchange of data information between information infrastructure equipment and improve the coordination ability of information infrastructure. In terms of data resources, with the help of blockchain's own data characteristics, such as being non-tamperable and traceable, it is expected to break the original data circulation and sharing barriers and provide high-quality data sharing guarantees. In terms of intelligent applications, relying on the more credible cooperation environment provided by the blockchain, some bright applications have emerged. On this basis, to realize the organic combination of blockchain and smart cities, the most important part is to improve the security of the smart cities. These applications are reflected in the following points:

Credible and traceable data governance. In the era of big data, traditional city management methods are changing to data governance and service innovation based on data circulation and sharing. The use of blockchain helps to promote consensus among multiple government departments, foster efficient collaboration, and optimize city governance. The first is to build a shared data foundation. Using blockchain to synchronize data according to pre-agreed rules, establish new data update rules, and build a data foundation for circulation and sharing. The second is to establish a coordination and mutual trust mechanism. Through the local deployment of blockchain nodes, various government departments realize the localized verification of shared data and determine the source and authenticity of the data. The information on the chain does not involve the complete original data. From a technical point of view, data sharing that does not rely on third parties is realized. Based on the blockchain data-sharing mechanism, it can be applied in financial innovation, government affairs disclosure, property rights registration, collaborative governance, and other fields.

Improving the quality of services for the benefit of the people. Smart cities improve the quality of services for the benefit of the people and also improve the efficiency of citizens. For example, in the medical aspect of smart cities, recording information such as medical IoT device data and patient electronic medical records on the blockchain can provide relevant evidence for determining the responsible party in the accountability process for medical accidents. Public medical institutions or medical research and development institutions are authorized to extract non-identity information from all nodes to address the problem of isolated data islands in the medical field. In this way, it not only solves the problem of isolated data islands in the medical field but also protects personal privacy.

Precise governance. The refined and precise development of city governance is increasingly dependent on city data quality, sharing efficiency, and security capabilities. In terms of judicial evidence storage, the blockchain is used in the entire life cycle of electronic evidence generation, collection, transmission, and storage to protect electronic evidence, prevent tampering, and leave traces of data operations. Notarization, arbitration, and other authoritative institutions conduct multi-party evidence deposits to achieve evidence solidification and permanent

preservation. In terms of data sharing, blockchain meets the needs of information disclosure, government function flattening, and securing mutual trust in government services. Its asymmetric encryption technology and public-private key mechanism can effectively solve the information security problems derived from open data sharing and eliminate the concerns of all parties about privacy leakage.

6. Open problems and opportunities

As an emerging industry, the Metaverse is currently in its infancy, and its industrial base is relatively weak. In addition to technical constraints, the Metaverse still needs to break through a lot of practical bottlenecks in the scene landing. As shown in Fig. 7, there are also some problems and opportunities that need to be solved when the Metaverse lands in smart cities: a basic framework, data security and privacy issues, and energy supply issues.

6.1. Basic framework

There are several design challenges associated with the basic framework of the Metaverse in smart cities [58]. Firstly, the smooth operation of the economic and social system relies on a set of regulations and institutions that support and facilitate its functioning. The Metaverse is a digital replica of the real economy and society, which will be presented to users in a more vivid and detailed way. To achieve this, various fundamental frameworks must be established, such as system design, legal norms, and cultural customs. Secondly, selecting the appropriate city style for the Metaverse can be challenging, as there are various options to choose from, and it is difficult to determine which style would be most suitable and appealing to users. To address these challenges, it is important to consider the following factors. Firstly, the basic framework of the Metaverse in smart cities should be designed with a focus on efficiency and effectiveness, while also taking into account the specific needs and requirements of users. Secondly, it is necessary to establish a harmonious relationship between the real world and the Metaverse, emphasizing the importance of cross-cultural communication and collaboration. Thirdly, it is crucial to ensure the safety and security of the Metaverse, including the prevention of cybercrime and the protection of users' data. Thus, designing the basic framework of the Metaverse in smart cities represents a complex and challenging task, requiring careful consideration of a range of factors, including user needs, efficiency, effectiveness, cultural harmony, safety, and security. By addressing these challenges, we can ensure that the Metaverse becomes a powerful tool for promoting sustainable development and social progress in smart cities.

6.2. Data security and privacy issues

The Metaverse is a virtual world that combines elements of the real world and the digital world, creating a new type of social and economic ecosystem [23]. As the Metaverse becomes more popular, concerns about data security and privacy protection are increasing. The Metaverse requires a large amount of data to be collected and processed, which can include personal information such as names, addresses, and phone numbers. This data can be used for various purposes, including advertising, marketing, and even profiling. If the Metaverse is applied to smart cities, the scale of data collection will increase significantly. Data collected from smart city systems can include information about city infrastructure, public services, and citizens' daily lives. This data can be used to improve city planning, enhance public safety, and increase efficiency in public services. However, the collection and use of this data will also involve a large amount of personal and corporate privacy and information that must be protected. In the current context of stricter data regulation, the collection and use of Metaverse and smart city data will also face more restrictions. Many countries and regions have implemented regulations on the collection, storage, and use of personal data aimed at protecting personal privacy and information security. These regulations often include specific requirements for data minimization, transparency, and consumer rights. Therefore, when developing Metaverse and smart city systems, it is essential to consider compliance with these regulations and the protection of citizens' privacy and personal information. Researchers, developers, and policymakers need to work together to address these challenges and develop effective solutions that protect citizens' privacy and data security while promoting the growth of the Metaverse and smart city systems [15,36].

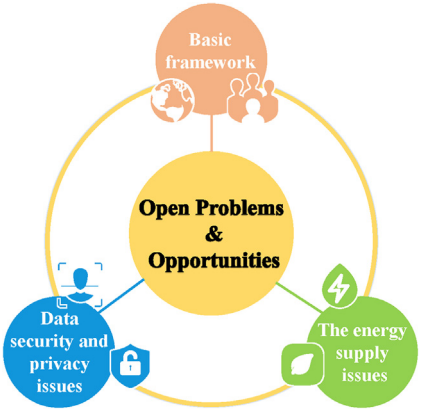

Fig. 7. Open problems in Metaverse for smart cities.

6.3. Energy supply issues

As the pace of the global green transformation continues to accelerate, there is a growing risk of an energy and resource supply crisis. The Metaverse, a large-scale connection between virtual and real application scenarios, requires a vast amount of energy to operate smoothly. Data centers, computing centers, network equipment, communication base stations, and other new infrastructure are all essential for the operation of the Metaverse, and these infrastructures require a larger energy supply to function. For smart cities built in the Metaverse, the energy supply problem will be even more serious, as the energy used to run the entire city is enormous. In the process of building and operating smart cities in the Metaverse, the contradiction between energy supply and demand is likely to become more prominent. This is because the energy required to run smart cities is much larger than that required to run traditional cities. To address this problem, it is essential to promote the development and application of clean and renewable energy sources, such as solar, wind, and hydrogen energy. Moreover, it is crucial to improve energy consumption efficiency, particularly in the context of smart cities. This can be achieved through the use of advanced technologies, such as energy storage systems and energy-saving measures. Moreover, it is important to consider the environmental impact of energy supply. The use of clean and renewable energy sources can help reduce greenhouse gas emissions and mitigate the effects of climate change. Additionally, developing effective and sustainable energy supply chains is essential. This can involve adopting a circular economy approach that focuses on the reuse and recycling of waste energy and materials [18,26].

7. Conclusions

The Metaverse and smart cities are two prominent subjects in the realm of emerging internet technologies. The Metaverse is anticipated to serve as the next evolutionary phase of the Internet, seamlessly blending virtual and physical realities. Smart cities, from another aspect, strive to enhance the quality of life for citizens, foster conducive environments for business development, and enable more efficient governance and management systems. In this article, we present a comprehensive overview of the Metaverse, encompassing its defining characteristics, key technologies, and diverse applications. Subsequently, we delve into the concept of

smart cities, exploring their prospects, proposed solutions, and the potential synergies between smart cities and the Metaverse. Furthermore, we propose how the integration of the Metaverse can empower smart cities, highlighting the pivotal technologies required for this convergence. In addition, we shed light on the pertinent questions and challenges that necessitate attention to establish the Metaverse as a viable solution for smart cities. These considerations encompass ensuring privacy and security in data utilization within both Metaverse and smart city systems, bridging the digital divide to ensure equitable access to Metaverse-enabled services, establishing interoperability standards for seamless integration of various platforms and technologies, and addressing the ethical implications associated with immersive experiences. Ultimately, we conclude by offering valuable insights to scholars to enhance the appeal of the Metaverse for smart cities. We emphasize the imperative need for interdisciplinary collaboration to address all kinds of challenges. By exploring these opportunities and challenges, scholars and practitioners can contribute to realizing a compelling and beneficial Metaverse for smart cities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This research was supported in part by the National Natural Science Foundation of China (Nos. 62002136 and 62272196), Natural Science Foundation of Guangdong Province (No. 2022A1515011861), the Young Scholar Program of Pazhou Lab (No. PZL2021KF0023), Engineering Research Center of Trustworthy AI, Ministry of Education (Jinan University), and Guangdong Key Laboratory of Data Security and Privacy Preserving.

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