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Digital Twins in Smart Cities

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ABSTRACT

The rapid acceleration of global urbanization has forced municipal authorities to confront unprecedented challenges in infrastructure management, environmental sustainability, and resource allocation. The paradigm of the "smart city digital twin" has emerged to address the challenges. A smart city digital twin is a cyber component that mirrors the physical urban system through real-time monitoring and simulation. The urban digital twin (UDT) represents a paradigm shift in how modern cities are planned, managed, and experienced. It is a cyber-physical system that mirrors the physical urban environment through continuous, bidirectional data exchange. Unlike traditional static 3D city models, a UDT is a living, dynamic replica that synthesizes real-time data streams from Internet of things (IoT) sensors, mobile devices, and municipal infrastructure. Several pioneering cities worldwide have transitioned the concept of the UDT from academic research into practical, operational systems. This paper delves into the realm of digital twin technologies and their role in shaping smart cities.

***KEYWORDS:** digitalization, digital twins, smart cities, city/urban digital twins (UDTs).*

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INTRODUCTION

The twenty-first century is defined by an unprecedented wave of urbanization. By 2050, approximately 68% of the world's population is projected to reside in urban areas. This rapid growth places extraordinary pressure on municipal governments to optimize resource allocation, maintain critical infrastructure, mitigate environmental degradation, and enhance the overall quality of life for residents. The rapid global urbanization has introduced unprecedented challenges to municipal administration, resource allocation, infrastructure resilience, public safety, and environmental sustainability. However, the emergence of the "smart city" paradigm has paved the way for a more holistic, data-driven approach to urban governance. At the vanguard of this technological evolution is the concept of the digital twin (DT). Figure 1 shows a typical digital twin [1]. It is regarded as the next generation of digitalization for decision making support. The current development of digital technologies has dramatically increased the adoption of digital twin (DT) systems into the automotive sector, turning conventional manufacturing practice into a smart and data-driven model. Figure 2 shows the conceptual model of a digital twin [2].

Smart cities are emerging as a solution to address modern urban challenges such as population growth, environmental sustainability, and resource management. They are transitioning from passive data collection to active, predictive simulation. This technological leap is powered by the urban digital twin (UDT), which may be regarded as a cyber-physical component that mirrors the physical urban system through real-time monitoring and advanced simulation, creating a continuous, bidirectional flow of data between the virtual and physical worlds. UDTs have emerged as a cornerstone of modern smart city strategies. For smart cities, urban digital twins (UDTs) have been a revolutionary paradigm at the intersection of the Internet of things (IoT), artificial intelligence (AI), and geographic information systems (GIS). By bridging the physical, social, and digital dimensions of the urban environment, UDTs provide municipal leaders with the predictive insights necessary to navigate the complexities of rapid urbanization and climate change [3].

CONCEPT OF DIGITAL TWIN

The concept of the digital twin was introduced in 2002 by Michael Grieves of Florida Institute of Technology. He applied the concept in manufacturing and proposed the digital twin as the conceptual model underlying product lifecycle management (PLM). The concept was being practiced since the 1960s by NASA. The concept of digital twin consists of three distinct parts: the physical product, the digital/virtual product, and connections between the two products [4]. Figure 3 shows the historical evolution of DT technology [5].

A digital twin is much as it sounds: creating a digital duplicate of the physical entity.

It has two sides, one pertaining to a physical device and the other to a digital rendition of this device. DT is a real time digital replica of a physical device using 3D modeling and sensors. The DT is an emerging paradigm focusing on an enterprise asset such as a system, product or process. Its core goal is to virtually represent this asset as close to reality as possible. A digital twin may exist before its physical counterpart is made. Technologies enabling DT include AI, IoT, 5G, virtual reality, augmented reality, wearables, and cloud computing. Figure 4 shows some of the fundamental technologies [6]. Realizing the full potential of DTs requires a convergence of these technologies. Digital twins integrate AI, IoT, machine learning, and software analytics with spatial network graph to create living digital simulation models that change as their physical counterparts change.

The three main pillars of the digital twin technology are visualization, emulation, and simulation. The foundation of DT is the physical world, which may consist of devices/products, physical systems, process, or an organization. Service is an essential component of DT in view of the paradigm of everything-as-a-service. DT-related services include application service, resource service, knowledge service, and platform service. The process of implementing DT can be divided into four steps: digital representation, synchronous mapping, simulation and prediction, and virtual and physical fusion. Figure 5 depicts the digital twin conceptual architecture [7].

There are numerous requirements to describe "digital twin." To be considered a digital twin, the model must have some specific characteristics such as [8]:

1. Data is the carrier of information and the key driver of DT. Real-time data is important for knowing the status of the product. Data-driven digital twin can perceive, respond, and adapt to the changing environment.
2. Integration of the different nodes is essential for creating valuable data. Sensors communicate the data to the digital world through integration technology between the physical world and the digital world, and vice versa.
3. Scalability (ability to analyze different scales of information);
4. Interoperability (ability to convert, match and establish equivalence between representation models);
5. Expansibility (ability to integrate models);
6. Fidelity (ability to conform to the physical model); the core of any DT is a high-fidelity virtual model.
7. Connectivity that indicates the level of communication with its physical counterpart; connectivity by design through IoT which is a paradigm for ubiquitous connectivity. Connect the products/services to a central location with streaming, big data, in-memory, and analytic capabilities to capture sensor data and enrich it with business and contextual data.

These are the most frequent requirements of digital twins.

WHAT IS A SMART CITY?

The concept of smart city emerges as a major response to the rapid urbanization and socio-economic challenges faced by cities worldwide. Smart city is a relatively new concept, with several definitions. The word "smart" can be used to describe any device that can process information and can communicate with something. The term "smart cities" is a fuzzy concept and there is not a one-size-fits-all definition of the concept. The term has gained traction across sectors and has pervaded the fields of sustainability, urban planning, architecture, engineering, and computer science. The Institute of Electrical and Electronics Engineers (IEEE) defines a smart city as a city that brings together technology, government, and citizens to enable the following characteristics: smart economy, smart mobility, smart environment, smart people, smart living, and smart governance [9]. A typical smart city is shown in Figure 6 [10].

A smart city is a high-tech urban area that connects people, information and technologies in order to increase life quality. It integrates information and communication technology (ICT) in a secure manner so as to manage the city's assets, increase operational efficiency, share information with the public, and improve citizen welfare.

ICT is the key technology that weaves digital intelligence into cities' fabric. The main motivation for using ICT is the desire to eradicate human error. Smart cities are those communities that pursue sustainable economic development through investments in human and social capital and manage natural resources through participatory policies.

Characteristics that may be used to determine a city's smartness include [11]:

- A technology-based infrastructure, which includes a critical mass of smartphones and sensors connected by high-speed communication networks and ICT
- Environmental initiatives, e.g. green rooftops towards clean and green environment
- A functioning public transportation system
- Citizen engagement, humans living and working in the city and utilizing its resources
- Open government and citizen-centric governance, bridging gaps between citizen and administration

A smart city uses networking and computing technologies to create efficiencies, improve sustainability, create economic development, and enhance quality of life for those living and working in the city. It connects various items such as street lighting, smart buildings/homes, smart factories, smart hospitals, smart mobility, urban manufacturing, and urban farming [12]. It monitors the conditions and integrates critical infrastructures such as bridges, tunnels, roads, subways, airports, seaports, and buildings. Components of a smart city include smart people, smart governance, smart homes, smart infrastructure, smart technology, smart campus, smart economy, smart water, smart living, smart factory, smart health, smart parking, smart shopping, smart transportation, and smart environment [13]. Some of these components are illustrated in Figure 7 [14].

DIGITAL TWIN IN SMART CITIES

The accelerating complexity of urban environments has prompted cities to adopt digital technologies that improve efficiency, sustainability, and resilience. As urbanization accelerates globally, the need for smarter, more sustainable cities has become imperative. As urban populations grow, smart city initiatives have evolved from innovative solutions to essential frameworks for shaping the future of sustainable urban living. Integral to this urban transformation is the concept of digital twins (DTs), which focuses on creating virtual representations of physical products to enhance their design, manufacturing, and life-cycle maintenance. The DT is a complex system of integrated technologies that creates a virtual model of a physical entity, either a product, process, or system, with continuous feedback between them.

In the realm of smart city, DTs play pivotal roles in orchestrating the collection, processing, and analysis of vast streams of data sourced from diverse urban elements. The CPSs are at the core of smart city DTs integrating computational algorithms with physical components to create a seamless connection between the digital and physical realms. Urban digital twins (UDTs) (or city digital twins) enable multi-domain interactions, where insights from one sector such as traffic patterns influence decision-making in another domain (e.g., energy demand optimization). This interconnected approach enhances efficiency, sustainability, and resilience, allowing cities to transition from isolated digital models to intelligent, adaptive urban systems [15]. Figure 8 shows the cloud word for digital twin in smart cities [16].

An urban digital twin (UDT) is not merely a static three-dimensional computer-aided design (CAD) model. Rather, it is a living, bidirectional system characterized by three essential components: a physical urban entity, a virtual counterpart, and a continuous data connection that synchronizes the two in real-time. The core engine of an urban digital twin (UDT) lies in the integration of geographic information systems (GIS) and building information modeling (BIM). By fusing GIS and BIM data with real-time IoT feeds (a process known as data fusion), the digital twin bridges the gap between spatial representation and physical operations. The real-world value of a UDT lies in its capacity to simulate "what-if" scenarios, allowing planners to test policies, designs, and interventions in a risk-free virtual sandbox before executing them in physical space. Data is continuously ingested from a wide array of physical assets—including buildings, roads, water networks, and mobile devices—and processed through advanced mathematical models, machine learning algorithms, and physics-based simulations [3]. Figure 9 shows the relationship between physical twin and digital twin in a smart city [17], while Figure 10 shows city/urban digital twin [18].

APPLICATIONS OF DIGITAL TWIN IN SMART CITIES

By bridging the physical and virtual realms, UDTs act as strategic accelerators for public sector organizations. Urban digital twins hold immense promise for improving infrastructure management, optimizing energy use, monitoring the environment, and engaging citizens in democratic governance.

Common applications of UDT include the following [3,16]:

- *Predictive Prototyping:* Historically, urban development has been a slow, iterative process of trial and error. UDTs revolutionize this by enabling virtual prototyping and scenario simulation. City planners can design and refine new neighborhoods digitally, assessing their impact on the surrounding urban fabric before breaking ground. For example, planners can simulate how a proposed skyscraper will alter wind tunnel effects, block natural sunlight for neighboring buildings, or impact the overall aesthetic view of historic landmarks. This eliminates guesswork, minimizes expensive design errors, and accelerates the transition from concept to construction.
- *Urban Planning*: Traditional urban planning often relies on static demographic projections and manual impact assessments, which are prone to error and fail to capture the dynamic feedback loops of city life. It often suffers from unintended consequences, such as the creation of wind tunnels, excessive shadowing, or localized heat accumulation. UDTs mitigate these risks by enabling high-fidelity simulations of the physical environment. They enable planners to run "what-if" simulations before physical construction begins. Planners can import proposed architectural designs into the digital twin to analyze their impact on solar exposure, natural ventilation, and microclimate patterns. For example, a digital twin can simulate how a proposed skyscraper will affect local wind patterns, solar shading, and microclimatic temperatures.
- *Infrastructure Management:* The maintenance of critical municipal infrastructure—such as bridges, tunnels, water mains, and electrical grids—presents a massive financial and operational burden for local governments. Modern cities contain massive, aging networks of subterranean and surface infrastructure that are notoriously difficult to monitor and maintain. Historically, infrastructure management has been reactive, addressing failures only after they occur, or preventive, performing maintenance on fixed schedules regardless of actual wear. UDTs provide comprehensive "below-ground" and "on-the-ground" visualizations, mapping complex pipelines, electrical grids, and transit tunnels. By integrating acoustic sensors, flow meters, and thermal cameras into the digital twin, municipal engineers can transition from reactive repairs to predictive maintenance.
- *Urban Mobility:* Urban mobility is highly dynamic and directly impacts fuel consumption, economic productivity, and public health. Traffic congestion is a primary driver of urban carbon emissions and economic inefficiency. UDTs optimize urban mobility by integrating real-time traffic feeds with machine learning algorithms to predict congestion patterns and dynamically adjust municipal assets. A mobility digital twin integrates real-time GPS data from vehicles, public transit feeds, and camera-based traffic sensors to create an active map of urban congestion. For example, in New York City, researchers from Columbia University, in collaboration with the NYC Office of Technology and Innovation, developed a localized digital twin focused on traffic safety and congestion mitigation in West Harlem.
- *Environmental Sustainability*: Achieving carbon neutrality is a primary goal for modern smart cities, and UDTs serve as critical tools for environmental sustainability. Achieving this goal is important as cities account for the vast majority of global carbon emissions. UDTs serve as vital tools in energy management by mapping building energy footprints and simulating retrofitting strategies. Through tools like the Automatic Building Energy Modeling (Auto-BEM) system, digital twins can analyze millions of buildings simultaneously, estimating energy usage and recommending structural modifications to help properties achieve net-zero emissions.
- *Disaster Mitigation:* Natural disasters and extreme weather events present severe threats to urban resilience. UDTs enhance disaster preparedness by simulating catastrophic scenarios, such as floods, earthquakes, or urban fires, using high-resolution terrain and meteorological data. For coastal and riverine cities, digital twins model how floodwaters will interact with the built environment, taking into account underground spaces, historical landfill geologies, and stormwater drainage capacities.
- *Public Health:* Beyond physical infrastructure, UDTs are increasingly applied to social and environmental health. During public health crises, environmental health digital twins can integrate demographic, mobility, and epidemiological data to forecast disease transmission patterns and optimize the distribution of medical resources.

- *Traffic Management:* Urban congestion contributes significantly to economic losses, carbon emissions, and public frustration. UDTs provide dynamic traffic models that process live data from GPS devices, road sensors, and traffic signal controllers. Rather than relying on fixed-time traffic light cycles, AI-driven digital twins can dynamically adjust signal timings to match real-time demand, smoothing traffic flow and reducing idle times. During accidents or road closures, the digital twin can instantly calculate optimal detour routes and push notifications to smart vehicles, mitigating the risk of gridlock.
- *Climate Resilience:* As climate change accelerates the frequency of extreme weather events, UDTs provide critical tools for disaster preparedness and response. By integrating real-time meteorological forecasts with topological and hydrological data, cities can simulate flood scenarios and deploy emergency resources proactively. UDTs are instrumental in driving cities toward net-zero targets by modeling micro-climates, analyzing building energy performance, and identifying optimal locations for solar panel installations.

BENEFITS

The integration of UDTs into municipal operations yields substantial benefits, transforming how cities are planned, maintained, and governed. The benefits are clear: accelerated risk assessment, enhanced capital efficiency, optimized resource management, and robust climate resilience. Research indicates that deploying digital twins in public sector infrastructure and capital planning can improve capital efficiency, accessibility of services, and operational performance. Other benefits of UDT include the following [3,19]:

- *Cost Reduction:* Optimizing resources and predicting problems before they occur can significantly reduce operational and maintenance costs. The adoption of DTs in infrastructure exemplifies how initial investments in data acquisition and real-time monitoring can yield substantial operational cost reductions over time.
- *Sustainability:* Rapid global urbanization has introduced unprecedented challenges to municipal administration and environmental sustainability. As cities account for the vast majority of global carbon emissions, achieving carbon neutrality is a primary goal of smart city development. Digital twins help cities become more sustainable by optimizing resource use, reducing emissions, and improving waste management.
- *Predictive Maintenance:* When combined with building information modeling (BIM) and geographic information systems (GIS), the digital twin can alert engineers to microscopic structural anomalies long before they manifest as visible damage. The integrated nature of UDTs allows municipalities to coordinate subterranean utility repairs. Instead of repeatedly excavating streets for separate water, gas, and electrical repairs, planners can use the digital twin to schedule synchronized maintenance, minimizing disruption to residents and businesses.
- *Energy Efficiency:* In the pursuit of net-zero emissions, digital twins serve as vital tools for energy optimization. By utilizing tools like Automatic Building Energy Modeling (Auto-BEM), UDTs can estimate the energy consumption of thousands of buildings simultaneously. Property owners and municipal authorities can run simulations to identify structural inefficiencies, model the impact of retrofitting measures, and optimize local microgrids.
- *Democratization:* UDTs democratize the urban planning process by fostering citizen-centric governance. By hosting the digital twin on public-facing web platforms or utilizing virtual and augmented reality (VR/AR) interfaces, municipalities allow citizens to visualize proposed neighborhood developments, experience the visual and acoustic impacts of new infrastructure, and submit spatial feedback directly to planners. This interactive, transparent approach bridges the gap between policymakers and the community, fostering trust and ensuring that urban growth aligns with the actual needs of residents.
- *Scalability:* Developing UDT that can scale from buildings to megacities requires hierarchical approaches and flexible, microservices-based architectures. The creation of large-scale benchmark datasets is a critical step in addressing the scalability challenges of UDT creation and validation, providing the data needed to train and test models at an unprecedented scale.

CHALLENGES

In spite of the significant promise of urban digital twins, their widespread adoption is severely constrained by a complex array of technical, governance, computational, regulatory, ethical, and socio-political challenges. The challenges include data interoperability, institutional silos, and cybersecurity risks. These must be overcome to fully realize the potential of digital twins in shaping sustainable, resilient, and inclusive urban futures. Other challenges of UDT include the following [3,15,16]:

- *Technical Challenges:* The primary technical challenge in building a UDT is interoperability. Cities collect data from a vast array of heterogeneous sources, including legacy databases, proprietary IoT sensors, geospatial mapping software, and architectural BIM files. These systems often operate in isolated silos, utilizing different data formats, coordinate systems, and update frequencies. For a digital twin to function effectively, it must achieve seamless data fusion, integrating static historical records with high-frequency, real-time sensor streams. Without universal standards, digital twins remain fragmented, expensive, and difficult to scale.
- *Computational Challenges:* Managing a city-scale digital twin requires processing petabytes of dynamic data, demanding immense computational power and storage capacity. Running real-time, high-fidelity physics-based simulations is computationally intensive. To achieve the low latency required for real-time applications (such as autonomous vehicle navigation or emergency dispatch), cities must deploy hybrid computing architectures.
- *Organizational Challenges*: The implementation of a UDT is as much an institutional challenge as it is a technological one. Municipal governments are traditionally organized into strict departmental silos—such as transportation, water, housing, and public safety—each managing its own data and software systems. Fostering the cross-departmental collaboration required to build a centralized digital twin requires significant administrative restructuring and a cultural shift toward open data sharing.
- *Ethical Concerns:* The socio-ethical implications of digital twins are equally critical, determining whether these platforms serve the public good or exacerbate existing urban inequalities. Continuous tracking of vehicle movements, pedestrian flows, and smart-utility usage raises serious ethical concerns regarding mass surveillance and data privacy. Municipalities must establish strict data governance frameworks, ensuring compliance with regulations such as the General Data Protection Regulation (GDPR), by implementing robust anonymization, data minimization, and consent-management protocols.
- *Privacy Concerns*: Smart city DTs introduce significant privacy and security challenges due to the vast amount of sensitive data that they handle, and their interconnected nature. The continuous monitoring of urban spaces raises profound privacy concerns. Ensuring the protection of citizens' data while maintaining the integrity and security of city operations is paramount.
- *Lack of Standardization:* A primary technical bottleneck is the lack of standardized data formats and semantic models. A city's data is inherently heterogeneous, generated by diverse sensors, proprietary software, and legacy municipal databases. Fusing GIS data (which focuses on geographic coordinates and spatial features) with BIM data (which focuses on structural geometries and building elements) often results in data loss or misalignment due to proprietary formats and coordinate system discrepancies. To overcome this, the industry must transition toward open standards.
- *Data Quality:* Real-time sensor networks are prone to physical malfunctions, communication dropouts, and environmental interference, leading to incomplete or corrupted data streams. A UDT must possess robust data harmonization and imputation algorithms to detect anomalies, filter out noise, and accurately estimate missing data points. If the underlying simulation models are fed low-quality or inaccurate data, the resulting policy recommendations will be fundamentally flawed—a phenomenon encapsulated by the computer science adage "garbage in, garbage out."
- *Cybersecurity:* As cities transition into hyper-connected cyber-physical systems (CPSs), they expose themselves to profound security and privacy risks. Because a digital twin maps critical municipal assets (including power grids, water supplies, and transit tunnels), it represents a high-value target for state-sponsored cyberattacks and ransomware. Securing the digital twin's entire data lifecycle—from edge capture to cloud storage—requires advanced encryption, zero-trust architectures, and continuous vulnerability monitoring. By embedding Internet-enabled sensors across the physical landscape and aggregating vast amounts of real-time data, UDTs exponentially expand a city's cyberattack surface.
- *Talent Shortage:* The development and maintenance of a UDT require a rare combination of interdisciplinary expertise, bridging the gap between urban planning, civil engineering, computer science, data analytics, and public

policy. Many municipal governments lack the financial resources and technical capacity to recruit and retain such highly specialized talent.

- *Digital Divide:* There is a risk of a "digital divide" in public engagement. While digital twins offer immersive visualizations to facilitate public feedback on planning decisions, municipalities must ensure that these digital platforms are accessible and inclusive, preventing the marginalization of communities that lack digital literacy or high-speed Internet access.
- *Democratic Governance:* A significant risk of smart city technology is the rise of technocratic governance, where decisions are made solely by algorithms and software engineers, sidelining the public. To counter this, progressive urban scholars advocate for the "Right to the Digital Twin City." This concept asserts that a digital twin should not be an exclusive tool for municipal elites; instead, it must serve as an open, democratic space that enhances public participation. By making portions of the UDT accessible via user-friendly web applications, citizens can visualize proposed neighborhood developments, assess how a new project might affect their local environment, and actively participate in civic planning.

FUTURE OF DIGITAL TWINS IN SMART CITIES

The next frontier is the development of prescriptive digital twins to replace the predictive, forecasting trends. By integrating advanced generative AI and reinforcement learning, future UDTs will not only predict urban crises (such as traffic gridlock or grid failures) but will also autonomously generate and evaluate thousands of mitigation strategies, presenting optimized recommendations to municipal operators in real time. As technology continues to mature, the next generation of UDTs will be characterized by the integration of artificial intelligence, edge computing, and immersive visualization environments [3].

The future of digital twins in smart cities represents a profound evolution in the history of human settlement. By transcending the limitations of passive monitoring, the next generation of UDTs will leverage immersive spatial computing and agentic artificial intelligence to co-create adaptive, resilient, and highly efficient urban environments. UDTs will serve as the cognitive core of tomorrow's metropolises. However, the realization of this vision is not merely a technical challenge; it is a governance imperative.

CONCLUSION

Urban digital twins have emerged as a cornerstone of modern smart city development, offering real-time virtual replicas of complex urban environments to optimize resource allocation, enhance sustainability, and test policy scenarios. They represent a paradigm shift in how we conceptualize, plan, and govern modern cities. By synthesizing real-time IoT data, physics-based simulations, and advanced AI, UDTs provide municipal leaders with an unprecedented 360-degree view of their urban ecosystems. By bridging the gap between the physical and virtual worlds through real-time data synchronization, UDTs provide municipal authorities with unprecedented situational awareness, predictive power, and strategic agility.

Urban digital twins represent one of the most powerful technological innovations in the history of urban planning, holding the key to creating highly efficient, resilient, and sustainable smart cities. To unlock the full potential of UDTs for more efficient, connected, and sustainable urban environments, it is important to develop collaboration among government, academia, and private sectors. Ultimately, the true measure of a digital twin's success lies in the strength of its governance, the equity of its algorithms, and its capacity to improve the daily lives of the citizens it replicates. More information about digital twin in the automotive industry can be found in the books in [20-27] and the following related journals:

- Digital Engineering
- Smart Cities

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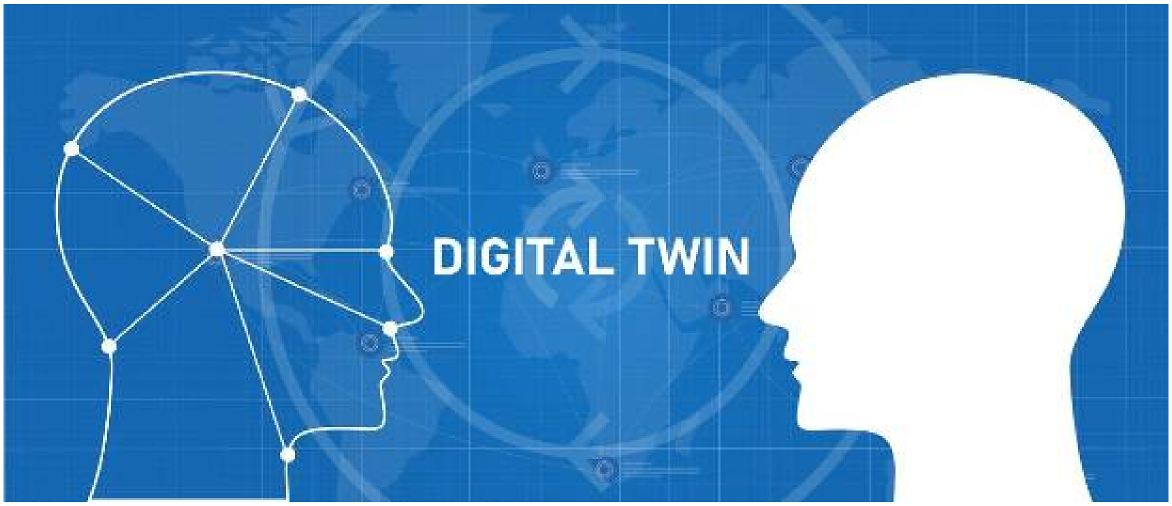

Figure 1 A typical digital twin [1].

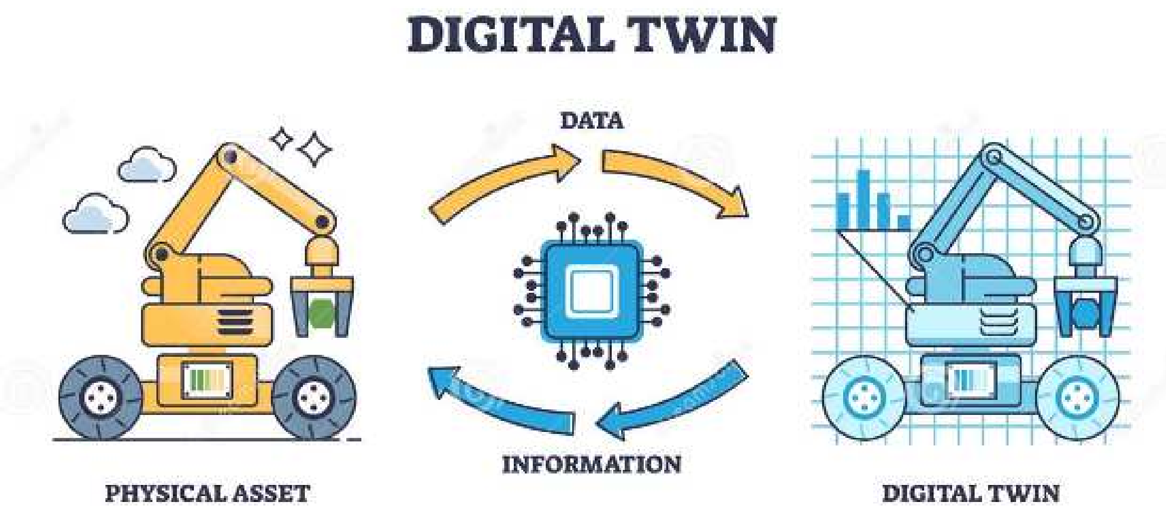

Figure 2 Conceptual model of a digital twin [2].

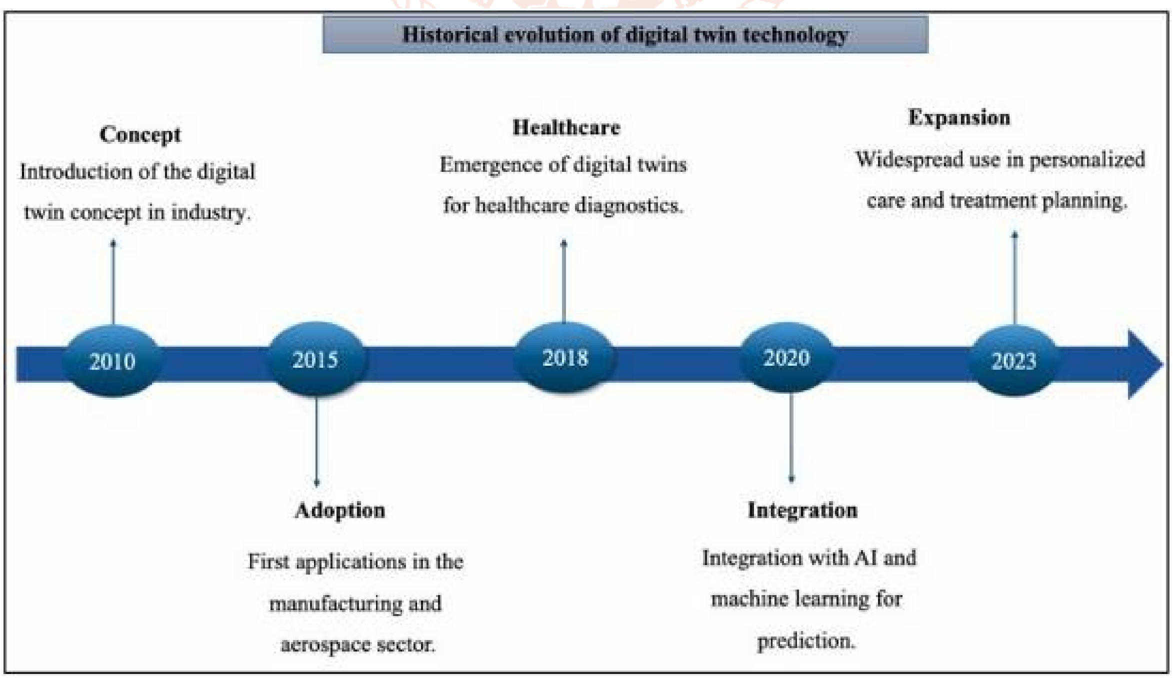

Figure 3 The historical evolution of DT technology [5].

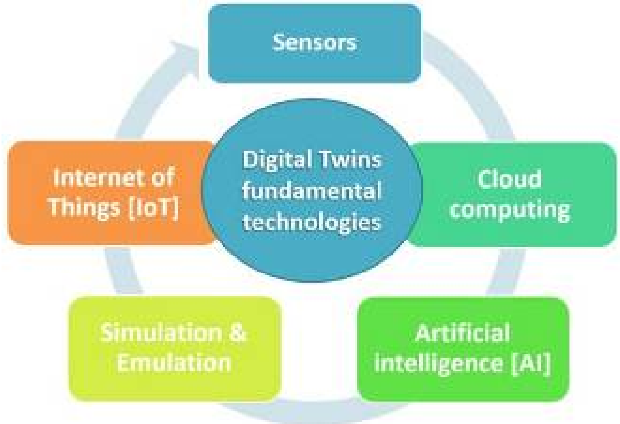

Figure 4 Some of the fundamental technologies [6].

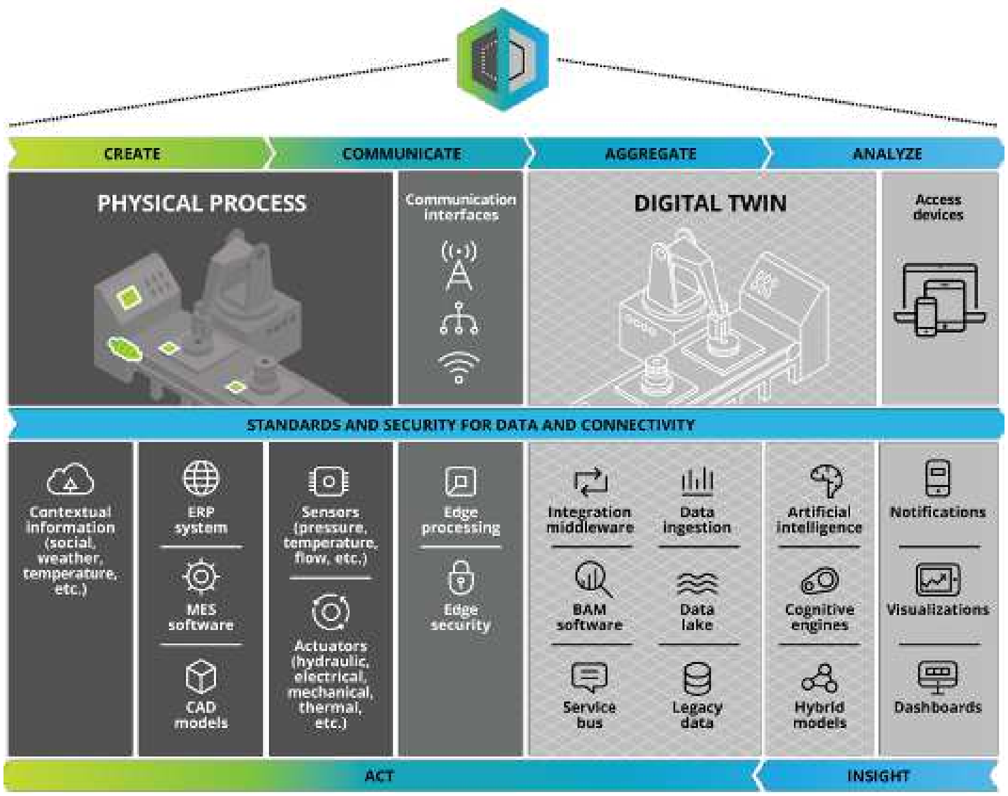

Figure 5 The digital twin conceptual architecture [7].

Figure 6 A typical smart city is shown in Figure 6 [10].

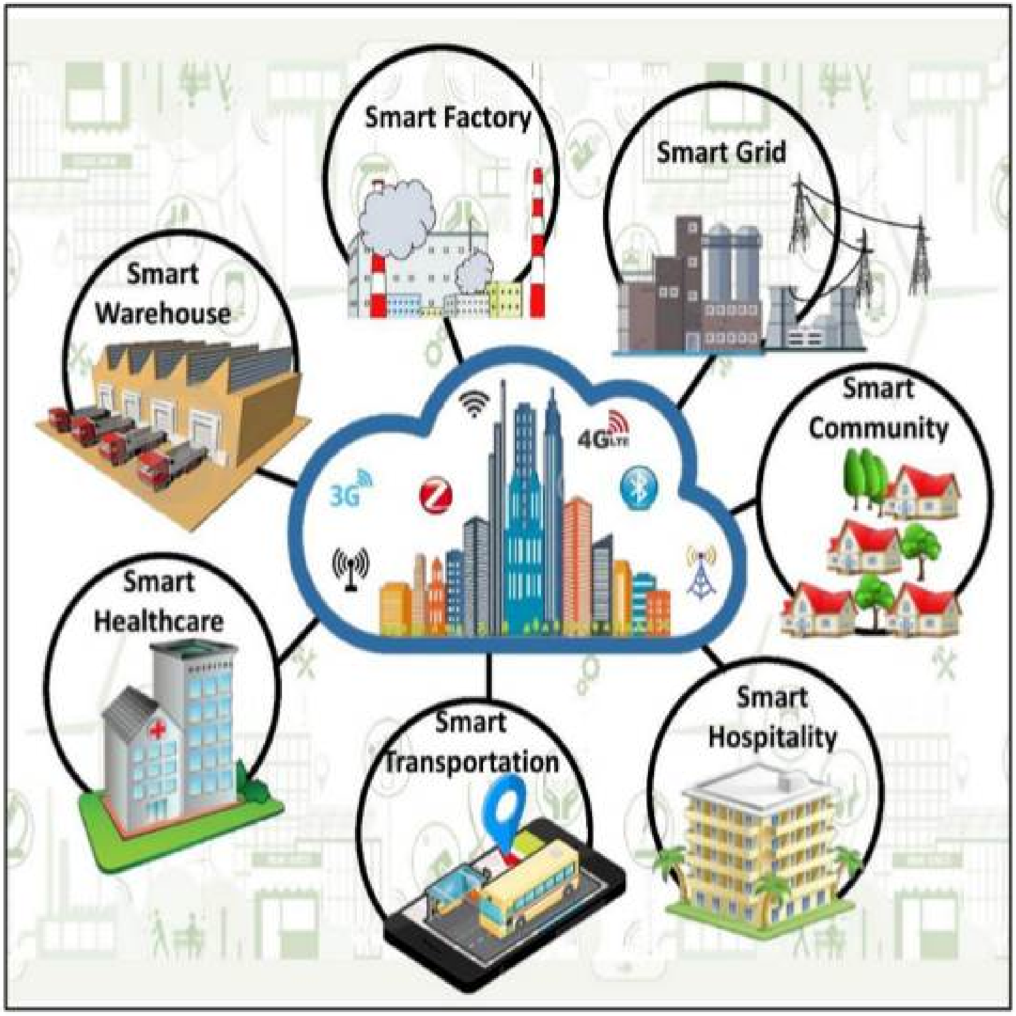

Figure 7 Some components of a smart city [14].

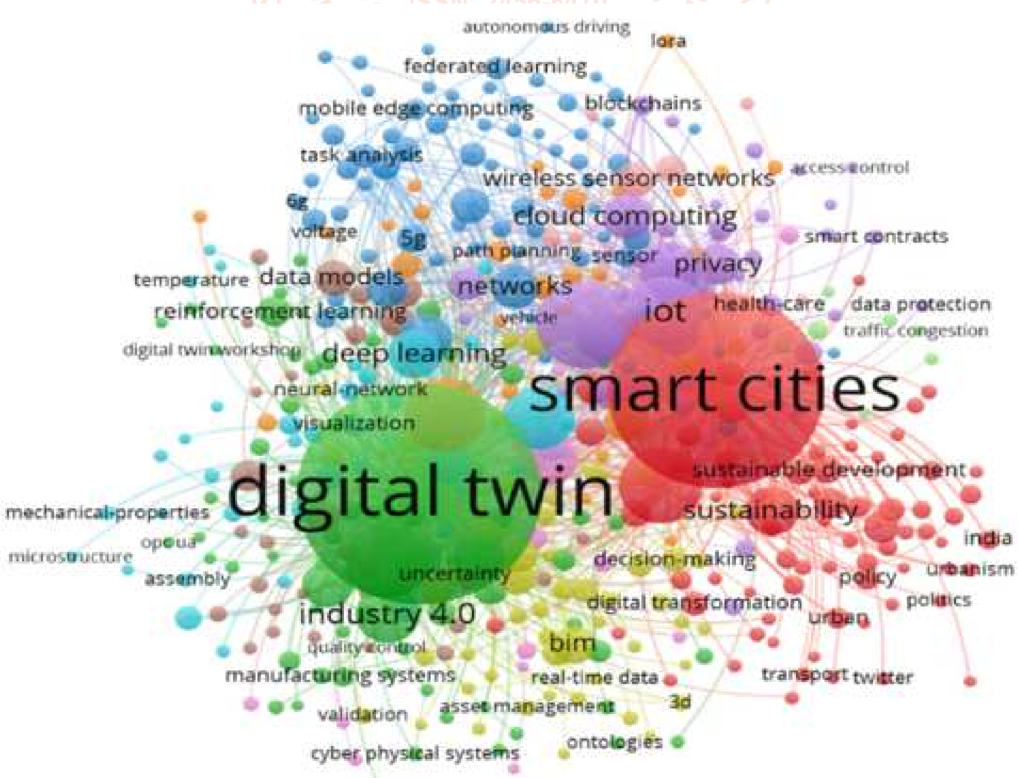

Figure 8 Cloud word for digital twin in smart cities [16].

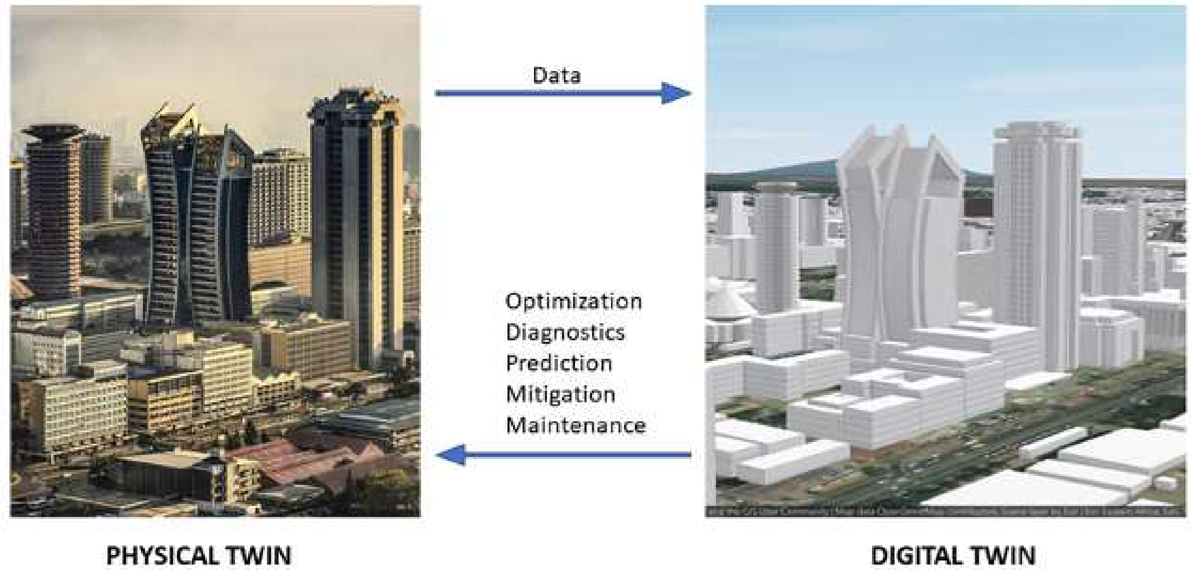

Figure 9 Relationship between physical twin and digital twin for a smart city [17].

Figure 10 City/urban digital twin [18].