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Review

From Digital Twins to Digital Twin Smart Cities: City Planning Using State-of-the-Arts Technology

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Abstract: In recent years, digital twin (DT) technologies have increasingly been adopted by cities seeking to evolve towards digitally enabled, data-driven urban systems. This article synthesises academic literature and practitioner reports to examine how digital twins have been used in the design, implementation, and ongoing development of digital twin smart cities. Methodologically, the study is using systematic literature review based on PRISMA, which is an integrative review of peer-reviewed research and leading real-world case studies from municipal practice. 43 literatures were screened covering 36 academic papers and 7 practitioner articles. After outlining key digital twin technologies and their role in urban transformation, the paper analyses prominent real-life implementations to illustrate current capabilities and practical applications. It then critically discusses the main challenges and limitations of digital twin smart cities, including data governance, interoperability, privacy, scalability, and citizen acceptance. The article concludes that while digital twins hold substantial potential for more resilient, efficient, and sustainable cities, their long-term success will depend as much on robust governance, social legitimacy, and participatory engagement as on technological innovation.

Keywords: digital twins; digital twin smart cities; citizen participation

1. Introduction

Digital Twin (DT) technology represents a transformative advancement in digitalization and data analytics. A DT is a virtual model of a physical entity—be it a product, process, or system—that integrates real-time data from the physical world with its digital counterpart using sensors, Internet of Things (IoT) devices, and advanced analytics. Originally used in aerospace, DTs now influence sectors such as manufacturing, healthcare, and urban planning [1].

DT functions by continuously receiving data from their physical counterparts, facilitating dynamic simulation and predictive analytics. This feedback loop enhances monitoring, optimization, and prediction of future performance, thereby reducing downtime and improving efficiency. By creating a digital replica, organizations can experiment with different scenarios without physical risk, leading to better decision-making and innovation [2].

In the past decade, we have observed more and more DT technology being used in urban planning in various cities. Through implementing different digital twin smart cities projects, we see how DT technology can transform these cities into smart cities [3]. According to the definitions provided by the Smart Cities Council, "a smart city uses information and communications technology (ICT) to enhance its livability, workability and sustainability." Therefore, in this review, we will focus on looking into how DT technology is used to implement the goals for smart cities, i.e., to develop digital twin smart cities. Through reviewing the latest research articles and practitioners' reports on digital twins and digital twin smart cities, we hope to get more insights about the latest developments in digital twin smart cities, how they are implemented, what challenges and limitations they are facing, and last but not least, the future directions of them.

In this review, we focus on the following three research questions (RQs), which help to deepen the analysis and align with the systematic review's goal of identifying gaps and synthesizing knowledge in the field of DT technology for smart cities.

RQ1. How does DT technology integrate with existing urban infrastructure to enhance real-time data-driven decision-making in smart cities?

RQ2. What are the critical factors influencing the scalability of DT technology across different urban environments?

RQ3. What are the challenges and limitations of DT smart cities?

2. Methodology

This manuscript now fully adheres to systematic-review standards, following PRISMA 2020 principles and incorporating explicit quantitative reporting at each stage.

2.1. Systematic Review

As DT technology and smart-city applications are now established fields, a systematic review, rather than a thematic or narrative review, is appropriate to ensure broad coverage, transparency, and reproducibility. Systematic reviews minimise bias by using predefined inclusion criteria, structured search strategies, and quality assessment frameworks.

The systematic review method is widely recognized for its rigor, transparency, and replicable approach, making it suitable for synthesizing research in established fields, such as DT technology and smart cities.

According to Khan et al. [4], systematic reviews use explicit methods to identify, select, and critically appraise relevant research, which minimizes bias and enhances the validity of findings. This method contrasts with thematic reviews, which are more interpretive and subjective, as noted by Braun and Clarke [5], who highlight the exploratory nature of thematic analysis, often better suited for nascent fields. Furthermore, Moher et al. [6] emphasize that systematic reviews follow a structured approach, including predefined criteria for inclusion and exclusion, which aids in selecting only the most relevant and high-quality studies, enhancing the reliability of the findings, and thereby ensuring comprehensiveness and reproducibility.

By focusing on clear research questions and employing a systematic approach, this method can effectively identify gaps in the literature, as suggested by Higgins and Green [7]. While thematic reviews offer flexibility and depth in exploring themes, the systematic review's structured approach is more appropriate for providing a robust foundation in a well-established field, ensuring that all relevant studies are included and assessed comprehensively. Given the established nature of DT technology and its applications in smart cities, a systematic review provides a more robust framework for analyzing the breadth and depth of the literature, ensuring that key studies are not missed and that the review process is transparent and reproducible. Additionally, the systematic approach allows for the identification of research gaps and inconsistencies across studies, which can guide future research directions.

Overall, the systematic review method is preferred in this context for its rigor, comprehensiveness, and ability to provide a strong foundation for identifying gaps and opportunities in the current body of knowledge. Therefore, we use it to investigate the three research questions mentioned.

2.2. The Review Process

The literature review in this manuscript follows a structured approach to ensure a thorough and systematic exploration of DT technology and its application in smart cities [8]. The process involved several steps, including database selection, criteria for inclusion and exclusion, and the use of key search terms. The aim was to create a robust foundation for the study by integrating both seminal works and the latest advancements in the field.

Step 1. Database Selection: The literature review was conducted using reputable academic databases, including IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar. In addition, practitioner sources are covered (e.g., PwC, government reports, mobility-tech blogs). They were treated separately and used only for describing real-world applications, not for scientific evidence synthesis.

These databases were chosen for their extensive coverage of engineering, technology, and urban planning topics, ensuring a comprehensive collection of relevant literature.

Step 2. Search Terms: Key search terms were carefully selected to capture the broad scope of digital twin technology and its applications in smart cities.

Searches used Boolean combinations of terms where the primary keywords including: “Digital Twin”, “Digital Twin City”, “Smart Cities”, “Cyber-physical Systems”, “Urban Analytics”, “Urban Simulation”, “City Digital Twin”, “Urban Planning”, “Digital Urbanism”, “Built-environment Modelling”, “City Management” and “Sustainability”.

The combinations of these terms were used to refine the search, such as “Digital Twin AND Urban Planning” and “Smart Cities AND City Management.”

Timeframe: **2013–2024**, with seminal earlier works included selectively.

Step 3. Inclusion and Exclusion Criteria: To ensure relevance, the literature included in this review was selected based on specific criteria. Articles published in the last ten years were prioritized to capture the most recent developments. However, seminal works that have significantly influenced the field were also included, regardless of publication date. Peer-reviewed journal articles, conference papers, and key industry reports were selected, while non-peer-reviewed sources, opinion pieces, and articles lacking rigorous methodology were excluded.

Step 4. Data Extraction and Analysis: The selected articles were systematically analyzed to extract key themes, methodologies, findings, and gaps in the literature. This analysis focused on identifying the evolution of DT technology, its integration with smart city frameworks, and emerging trends in the field.

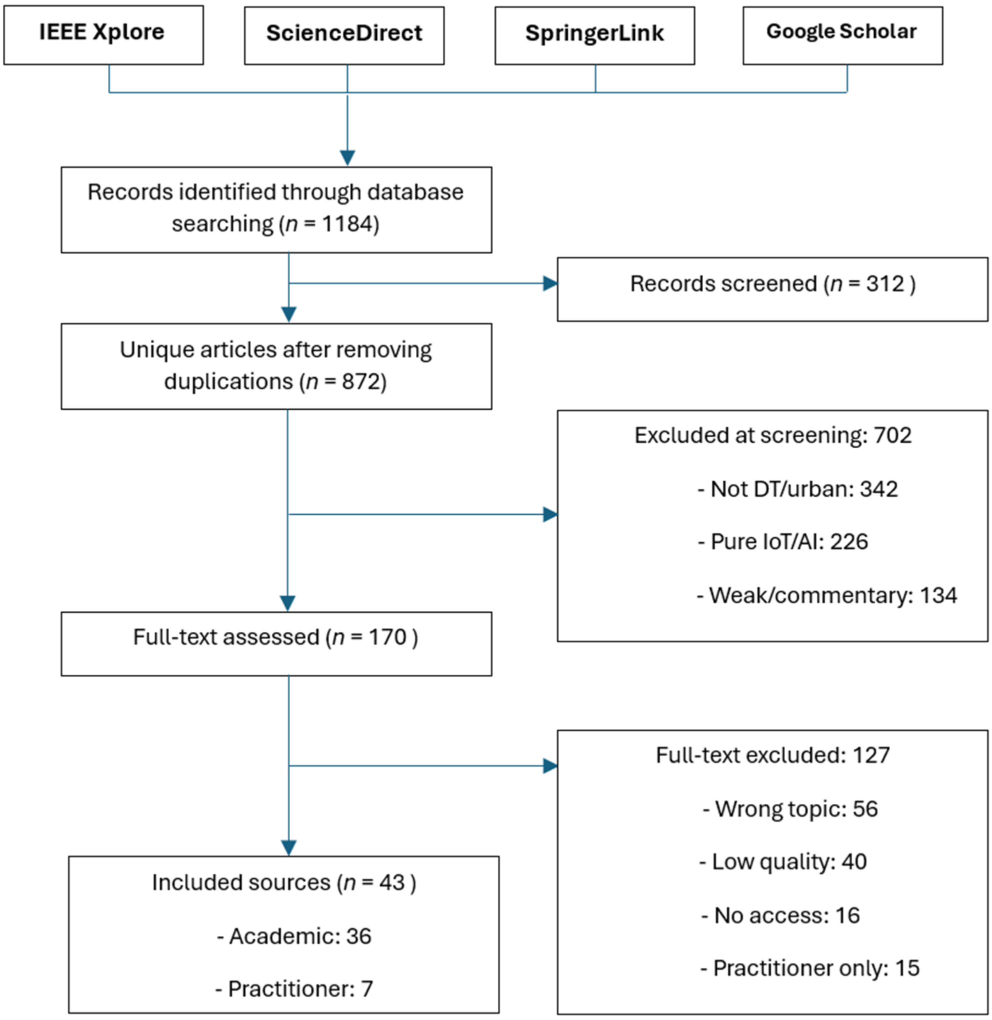

Figure 1. Systematic literature review flowchart.

The literature review and selection process ensures a thorough, unbiased, and reproducible analysis of the existing literature on DT technology and smart cities. Figure 1 presents our systematic review process to reflect the above procedures, and our findings are presented in the following sections, while the process at different PRISMA stages is summariised in the Appendix A. The list of screened literature is summarised in Appendix B.

2.3. PRISMA-Aligned Literature Identification and Screening

A total of 1184 records were identified where screening and coding were performed using Rayyan QCRI. Below is the PRISMA Breakdown:

- Records identified across all databases: 1184
- Duplicates removed (via Zotero 6.0): 312
- Records screened (title/abstract): 872
- Excluded at screening: 701
    - Not focusing on DT/urban systems (*n* = 341)
    - Pure IoT or AI studies unrelated to smart cities (*n* = 226)
    - Commentary pieces or insufficient methodological detail (*n* = 134)
- Full-text assessed: 171
- Full-text excluded: 128
    - Wrong domain (manufacturing-only, aviation-only, etc.): 54
    - Insufficient methodological clarity: 42
    - Non-English or inaccessible full texts: 17
    - Practitioner reports without academic grounding: 15

Final Included Studies: 43

- 36 peer-reviewed journal articles
- 7 practitioner sources (separately categorised)

2.4. Methodological Quality Assessment

Studies were appraised using a simplified CASP-inspired framework:

1. Clear aims
2. Transparent and replicable methods
3. Valid data / modelling approach
4. Relevance to digital twin urbanism
5. Limitations acknowledged

Studies failing at least three criteria were excluded.

2.5. Data Extraction and Synthesis

Extraction fields included:

- Research aims
- Conceptualisation of DT
- Technological components
- Urban domain (transport, environment, governance, etc.)
- Findings and implications
- Limitations

Synthesis followed thematic grouping aligned to RQ1–RQ3.

3. From Digital Twins to Digital Twin Smart Cities

DT technology enables virtual replication of physical entities using real-time data. In smart-city applications, DTs model complex urban systems, enabling simulation, prediction, and optimisation. Existing research highlights applications in AI-enhanced analytics, IoT integration, predictive maintenance, 5G-enabled communication, sustainability optimisation, and cybersecurity. Core components include real-time sensor integration, GIS/BIM data fusion, cloud-based cyber-physical systems (C2PS), and multilayer digital architectures. They allow us to understand the entity and test for predictive analysis and decision-making.

Nowadays, various forms of DT technology are developed with the following applications: (i) the integration with artificial intelligence (AI) and machine learning (ML) techniques, (ii) the expansion of the use of IoT and related sensor deployments, (iii) the enhancement of the predictive maintenance, (iv) the use of 5G technology, (v) the adoption in the healthcare technology, (vi) the optimization of resources for sustainability, and (vii) the development of cybersecurity systems for protecting digital assets of the cities and its occupants [1]. Table 1 presents a description of some examples of DT applications.

Digital twin smart city technologies are developed based on digital twin concepts, and they are sophisticated models that integrate multiple technological advancements to reflect the dynamic nature of urban environments. According to Lehtola et al. [9], the foundation of a digital twin is a comprehensive back-end system that stores all relevant data, visualized and interacted with through various front-end applications. This integration enables a continuous feedback loop where real-time data from IoT devices and other sensors update the digital twin, providing an evolving and accurate representation of the city. Vessali et al. [10] emphasize that digital twins leverage AI and advanced analytics to process data from numerous sources almost immediately, offering invaluable insights into city performance and facilitating effective decision-making.

Table 1. Some examples of DT applications [1].

DT Application	Description
(1) Integration with AI and ML Techniques	The integration can enhance data analytics and decision-making processes.
(2) Expansion of the Use of IoT and Related Sensor Deployments	This expansion can help generate more comprehensive data streams for the DT system.
(3) Enhancement of the Predictive Maintenance	This enhancement aims to improve maintenance scheduling and reduce costs.
(4) Use of 5G Technology	It can facilitate faster and more real-time data transmission and updates.
(5) Adoption in Healthcare Technology	The adoption can create precise models for the system.
(6) Optimization of Resources for Sustainability	Sustainability can be achieved through the optimization of resources and the reduction of cities' carbon footprints.
(7) Development of Cybersecurity Systems	The development of cybersecurity systems can be used to protect the digital assets of the cities and their occupants.

Indeed, DT technology encompasses a complex and integrated framework that combines multiple technological components to create virtual replicas of physical entities. In the case of digital twin smart cities, they are virtual replicas of those cities concerned. At its core, DT technology utilizes real-time data to establish a dynamic link between the physical and digital realms. It facilitates continuous monitoring, simulation, and optimization of various systems and processes within smart cities. Usually, the following components are included in the digital twin smart cities system.

3.1. Core Components and Data Integration

DT technology relies on advanced data integration and real-time analytics. Key components include sensors, IoT devices, and data processors that continuously capture and transmit data from the physical environment to a digital model. Integrating diverse data sources, like geographic information systems (GIS) and building information models (BIM), is crucial for creating accurate digital representations of urban systems [11]. This real-time data collection allows DTs to reflect the current state of their physical counterparts, providing valuable insights for urban planning and management.

3.2. Technological Layers and System Architecture

DTs consist of several interconnected layers that together provide a complete view of the urban environment. These include the physical layer, comprising the actual objects and systems being monitored; the data layer, which involves data collection and processing; and the application layer, where simulations and analytics are conducted [12]. The connection between physical and digital entities allows for continuous updates and predictive analysis in real-time. In addition, due to the large amount of real-life data to be collected and integrated, prior research also suggests that it may be necessary to develop cloud-based cyber-physical systems (C2PS) for digital twin systems to handle data management issues [13].

3.3. Simulation and Predictive Capabilities

A key feature of DT technology is its ability to run complex simulations and predictive models. Using real-time data and sophisticated algorithms, DTs can forecast future scenarios and assess the impact of various urban interventions. These capabilities allow city planners to explore different strategies and make informed decisions that enhance urban sustainability and resilience [14].

3.4. Integration with Emerging Technologies

DT technology integrates with emerging technologies like AI, ML, and 5G. AI and ML enhance the analytical capabilities of DTs, enabling them to identify patterns, predict issues, and suggest solutions autonomously. The advent of 5G supports faster and more reliable data transmission, crucial for real-time monitoring and response [12].

4. Digital Twin Smart Cities: Redefining Urban Development: A Comparison

While the technology used in digital twin smart cities provides an edge in the development of smart cities, some existing technologies also provide similar functionalities. The following is a comparison of digital twin smart cities with them.

4.1. Digital Twin Smart Cities vs. 3D City Models

While 3D city models provide detailed visual representations, Jeddoub et al. [11] argue that DTs offer more comprehensive tools by integrating real-time data and supporting simulations, which enhance urban management. DTs go beyond static visualizations by enabling dynamic interactions between various urban systems. For example, while a 3D model might show a building's structure, a DT could simulate the building's energy consumption in real-time, integrating data from sensors to predict future usage patterns and optimize efficiency.

4.2. Digital Twin Smart Cities vs. City Information Models

City Information Models (CIM) manage urban data and facilitate stakeholder collaboration. Jeddoub et al. [11] note that DTs offer advanced capabilities by integrating real-time data and supporting dynamic simulations, making them more potent for addressing modern cities' challenges. Unlike CIMs, which are typically static and focused on data integration, DTs can simulate urban scenarios in real-time, such as traffic flow or environmental changes, offering a more interactive and predictive tool for city planners.

4.3. Digital Twin Smart Cities vs. Spatial Data Infrastructure

Spatial Data Infrastructure (SDI) provides a framework for geospatial data management. Jeddoub et al. [11] highlight that while SDIs support DTs' data needs, they lack the dynamic features of DTs, which integrate real-time data for simulations and analytics. For example, while SDI might store and manage large datasets about urban infrastructure, DTs actively use this data to run simulations that can predict the impact of new developments on traffic congestion or pollution levels.

4.4. Are Digital Twin Smart Cities Better Than Other Methods?

As presented above, digital twin smart cities are able to provide better services and functions compared with the three commonly used methods, i.e., 3D city models, city information models, and spatial data infrastructure. In addition, digital twin cities can handle the functions presented by all these three systems. Jeddoub et al. [11] further emphasize that DTs bring a level of interactivity and predictive capability that traditional methods cannot match, allowing for more informed decision-making in urban planning and management. This capability makes DTs a superior choice for developing and managing smart city initiatives. As a result, we can argue that digital twin smart cities would be a better option for moving the development of smart city concepts.

5. Common Usage of Digital Twin Smart Cities

Nowadays, digital twin smart city projects have been developed in many countries. As reported by Boučková [15], the implementation of digital twin smart cities can achieve an average saving of US$280 billion by 2030 in the form of savings arising from energy, infrastructure, etc. We can anticipate that more and more city administrations will use digital twin smart city technology to improve their planning and services. The following are a few common examples of digital twin smart city applications.

5.1. Urban Planning and Infrastructure

DT technology is crucial in urban planning and infrastructure management, which helps perform traffic optimisation and energy modelling. DTs enable the visualization and simulation of urban environments, assisting planners in making data-driven decisions to address challenges such as traffic congestion and environmental sustainability. Jeddoub et al. [11] highlight that DTs integrate data from various sources, such as GIS and BIM, to create comprehensive 3D city models that support efficient urban planning. Boučková [15] also reported that by collecting data from public transportation systems and construction schedules and analyzing these data using digital twin smart city applications, town planners can make better plans and policies for improving the city environment.

One important town planning issue is the development of an efficient transportation management system. In the transportation aspect, DTs are used to optimize traffic flow and enhance public safety. By simulating different traffic scenarios, city authorities can develop strategies to improve mobility and reduce congestion using historical and real-time traffic data to maintain better traffic management and reduce traffic congestion [15]. Halúsková [12] also emphasizes the potential of DTs to synchronize with other urban systems, thereby improving overall transport management and safety. In addition, Feng et al. [16] propose using an Internet of Vehicles (IoV) system and blockchain to improve and resolve data sharing and related issues.

5.2. Environmental Monitoring and Sustainability

DTs play a vital role in environmental monitoring and sustainability, which forms the foundation of modern renewable energy systems. They integrate real-time data from environmental sensors to monitor air quality, water levels, and energy consumption. Jeddoub et al. [11] note that DTs support strategies to mitigate climate change impacts by providing a holistic view of environmental data. Halúsková [12] explores DTs' application in energy management, where they optimize renewable energy deployment and enhance urban energy systems' resilience.

5.3. Public Safety and Emergency Management

There is a rich content of literature focused on studying how digital twin smart cities can be used for public safety and, in particular, disaster risk management, which is the essential element for real-time risk modelling. Ariyachandra and Wedawatta [17] conducted a detailed review. They reported that technologies, such as unmanned aerial vehicles (UAVs), mobile crowd sensing, IoT, AI, geo-parsing, and convolutional neural networks (CNN) using data from social media, have been studied as digital twin smart cities tools for disaster risk management. Furthermore, Ford and Wolf [18] propose to use the concept of a digital twin smart city to develop a community disaster management model. As such, we can argue that DT technology can enhance public safety and emergency response. These technologies can be used to develop simulations of emergency scenarios, allowing authorities to develop and test response strategies. In addition, Jeddoub et al. [11] emphasize that DTs improve urban resilience by integrating data to predict and manage risks from natural disasters and other emergencies.

Peldon et al. [14] also elaborate on the ability of DTs to support urban resilience by providing early warnings of potential threats and enabling real-time monitoring of critical infrastructure. This capability is crucial for enhancing the city's preparedness and response to emergencies, thereby ensuring the safety and well-being of its citizens.

6. Selected Case Studies of Digital Twin Cities

Digital twin technology has been used to implement smart cities in various locations across the globe. The following are a few representative cases (see Table 2).

Our first case is Zurich, Switzerland. As one of the major European financial hubs with the rapid growth of the city's population, the administration of Zurich incorporated the digital twin concept as one of the six smart city programs for implementing its city administration and development, i.e., the digital twin of the City of Zurich. With the help of the digital and spatial image of Zurich, the city administration uses it as a tool for bringing digital transformation in urban planning. Its scope includes the use of spatial data and 3D city models, with continuous updates from time to time, to provide the most up-to-date data inventory and, most importantly, to put these data as open government data [19].

Table 2. Examples of digital twin smart cities projects.

Location (Alphabetical Order)	Examples
Amsterdam, Netherlands	Urban Development (3D printed bridge) [2]
Chattanooga, Tennessee	Traffic Management [15]
Herrenberg, Germany	Town Planning and Participatory and Collaborative Processes [20]
Los Angeles, California	Transportation Management [2]
Seoul, Korea	Traffic Management, Urban Development, Emergency Services, Urban Sanitation, Facilities Management, and City revitalization [15]
Shanghai, China	Urban Planning, Optimize Land Use, and Enhance Disaster Preparedness [2]
Singapore	Urban Planning and other public services [21]
Zurich, Switzerland	Urban planning, Open Government Data initiatives [19]

Another case is Herrenberg, Germany. With the idea of empowering the citizens by incorporating participatory and collaborative processes in town planning, the digital twin smart city of Herrenberg is developed. It is a digital twin smart city equipped with various state-of-the-art data models to present the city's built environment, street networks, mobility simulation, wind flow simulation, etc. This virtual platform provides information for her citizens to engage with the town planning process and becomes the communication channel for town planning officials and citizens [20].

As mentioned, transportation management is a key usage of digital twin smart cities, and there are a few cases, too. Boučková [15] reported that digital twin smart city applications had been used in Chattanooga, Tennessee, to develop models to reduce traffic congestion. The city management used data collected from traffic cameras, weather stations, and emergency services to develop their model. Based on the simulation results, better traffic light patterns were developed to reduce traffic congestion. Another digital twin smart city project in Los Angeles, California, has also been developed and used for improving traffic flow, planning road construction works, and optimizing public transportation routes based on a data-driven decision-making process [2]. These two examples showcase the success of using digital twin smart city systems in transportation management.

Concerning its use in urban planning, the 3D printed bridge pedestrian bridge in Oudezijds Achterburgwal canal in Amsterdam is a showcase of how digital twin smart city technology can be used to improve the well-being of the residents [2]. With the help of the technology, it is the first 3D-printed bridge of its kind.

Last but not least, more cities are now using the digital twin smart cities to support various aspects of the city's needs. For example, Seoul, Korea, used the digital twin smart city technology in traffic management, urban development, emergency services, urban sanitation, facilities management, and city revitalization [15]. At the same time, Shanghai has also implemented a DT to support urban planning, optimize land use, and enhance disaster preparedness [2]. These two examples show a holistic approach to city management, fostering sustainable urban growth. Furthermore, Singapore also implemented "Virtual Singapore", a digital twin smart city incentive for providing information to all the stakeholders of the community [21].

Integrating DT technology in smart city initiatives to form the digital twin smart city represents a significant leap toward creating more efficient, sustainable, and resilient urban environments. By leveraging real-time data and advanced analytics, cities can optimize operations, improve resident's quality of life, and achieve long-term sustainability goals. As this technology evolves, its potential to transform urban living and infrastructure will grow, making it a cornerstone of future smart cities.

7. Result Analysis

Using the findings presented above, we further review how DT technology is transforming our society based on our three RQs. Table 3 at the end of this section summarizes the key points of our discussions based on the three RQs proposed.

Table 3. Findings Listed Based on Research Questions.

Research Question	Findings
RQ1: How does DT technology integrate with existing urban infrastructure to enhance real-time data-driven decision-making in smart cities?	There are cases showing that DT technology can enhance real-time data-driven decision-making in smart cities.
RQ2: What are the critical factors influencing the scalability of DT technology across different urban environments?	IT infrastructure and interoperability are two critical factors affecting the scalability of DT technology across different urban environments.
RQ3: What are the challenges and limitations of DT smart cities?	The key challenges and limitations include data integration and management, technological infrastructure and scalability, information security and data privacy, interoperability, and evolving emergent technology.

7.1. RQ1. How Does DT Technology Integrate with Existing Urban Infrastructure to Enhance Real-Time Data-Driven Decision-Making in Smart Cities?

As showcased by the above case studies [22,23], we can see that DT technology can integrated into urban infrastructure and enhance real-time data-driven decision-making, such as traffic and transportation management in Chattanooga, Los Angeles and Seoul. Such real-time data collected helps city officials make prompt decisions in both day-to-day and emergency management. In addition, the data collected cannot only be used for real-time decision-making but also be fed into other systems for urban planning and development (such as in Seoul, Shanghai, Singapore and Zurich), which are for long-term development and emergency preparedness (such as in Shanghai). Such data can also be shared with members of the public through open government data initiatives (in Zurich) and improve the efficiency and competitiveness of society as a whole.

7.2. RQ2. What Are the Critical Factors Influencing the Scalability of DT Technology across Different Urban Environments?

This question addresses the scalability issue, aiming to identify the factors that either facilitate or hinder the widespread adoption of digital twins in diverse city settings [24,25]. To answer this RQ, several key factors emerge:

(1) Data integration and interoperability: The ability to integrate diverse data sources, such as IoT devices, GIS, and real-time sensor data, is essential for scaling digital twins in varied urban environments. Inconsistent data formats and standards can hinder scalability [26].
(2) Infrastructure and resource availability: The availability of computational resources, such as cloud computing and edge devices, directly influences the scalability of digital twins. For example, the application of cloud-based platforms in smart cities like Singapore and Barcelona has demonstrated how robust infrastructure can facilitate scalability [27].
(3) Regulatory and privacy concerns: Legal frameworks around data privacy and urban planning regulations can either enable or limit the scalability of digital twins. Regions with stringent data protection laws may face challenges in implementing real-time, large-scale digital twin models [28].
(4) Public-Private Partnerships: Collaboration between government entities, private companies, and research institutions is crucial for sharing resources and expertise. Successful examples include the collaboration between Siemens and the city of Berlin to develop scalable digital twin solutions [20].

These factors highlight the complexity of scaling digital twin technology, emphasizing the need for a multidisciplinary approach to address technical, regulatory, and social challenges.

7.3. RQ3. What Are the Challenges and Limitations of DT Smart Cities?

There are several challenges and limitations of DT smart cities, which include data integration and management, technological infrastructure and scalability, information security and data privacy, interoperability, and evolving emergent technology that concern about:

- data governance
- platform interoperability
- citizen trust
- privacy-preserving AI
- federated learning
- blockchain-enabled transparency

(a) Data Integration and Management

One of the primary challenges in deploying digital twin smart cities is data integration. While we have found cases of DT twin city as mentioned above, it is evident that such successes are grounded on a successful data integration, which is not easy to achieve. Effective DT deployment requires robust data management frameworks to ensure accuracy, reliability, and security [11]. This challenge includes integrating data from various urban systems, which often use different platforms and data formats.

Peldon et al. [14] highlight the importance of developing interoperable data systems to support the integration of DT technology in urban environments. To keep up with this requirement, continuous investment in technological infrastructure and the development of standards to facilitate data sharing and integration across different systems are needed.

(b) Technological Infrastructure and Scalability

One significant challenge is the need for advanced technological infrastructure to support DT operations. Jeddoub et al. [11] highlight that the availability of high-speed communication networks, powerful computing resources, and sophisticated sensor systems often limit the scalability of DT technology. Continuous investment in technological infrastructure is necessary to meet the growing demands of smart cities [12].

Another significant challenge is scalability. Current studies often focus on small-scale or isolated implementations of DTs, such as specific buildings or infrastructure elements, rather than city-wide systems [29,30]. Scaling DTs to manage entire cities involves complex challenges, including data integration across diverse urban systems and maintaining real-time synchronization between physical and digital entities.

(c) Information Security and Data Privacy Concerns

Throughout the past few years, researchers have asked questions about who the users of smart city services are and what exactly these services can provide to the public [31]. They argued that many users, even with better educational backgrounds, expressed their concerns about data security and privacy. This may be a reflection of the lack of digital literacy skills of most people to understand how digital twin smart city works [17]. While we should not undermine the data security and privacy risks faced by the digital twin smart city service, the development of digital literacy skills in society as a whole is an essential task for making people generally accept this technology.

In addition, as DTs rely on massive amounts of data collected from various sources, ensuring the privacy of sensitive information and securing these systems against cyber threats is paramount. However, there is limited research on robust privacy-preserving techniques and security frameworks tailored for DTs in urban settings [32].

(d) Interoperability

The lack of standardized protocols and frameworks hinders seamless integration between different DT systems and other smart city technologies, limiting their potential to work cohesively [33]. Addressing these gaps requires interdisciplinary collaboration and the development of new methodologies, tools, and standards to ensure that DTs can be effectively scaled, secured, and integrated into the complex ecosystems of smart cities.

(e) Evolving Emerging Technologies

Emerging technologies like Artificial Intelligence (AI), Blockchain, and the Internet of Things (IoT) are poised to revolutionize the implementation and capabilities of digital twin technology in smart cities. AI can significantly enhance the predictive capabilities of DTs by processing vast amounts of data and learning from patterns, thereby enabling more accurate simulations and decision-making processes in urban management [34]. Blockchain technology offers a solution to some of the data privacy and security concerns mentioned earlier. By providing decentralized and immutable ledgers, blockchain can ensure secure data transactions and transparency across DT systems, fostering trust among stakeholders [35]. The integration of IoT devices into DTs can further improve real-time data collection and synchronization between the physical and digital worlds, allowing for more responsive and adaptive urban systems [29].

8. Concluding Remarks

Integrating DT technology into smart city frameworks offers transformative opportunities for smart-city planning, sustainability, public safety, and infrastructure optimisation. However, cities must confront challenges surrounding:

- data standardisation
- secure data governance
- transparent privacy safeguards
- equitable digital participation
- long-term scalability through interoperable architectures

Digital twins (DTs) are increasingly recognised as foundational infrastructure for next-generation smart cities, offering advanced capabilities for urban planning, environmental monitoring, disaster resilience, and public safety through real-time simulation and predictive analytics. Nevertheless, their transformative potential will remain constrained unless structural challenges related to data integration, technological fragmentation, governance, and scalability are systematically addressed. Future research and policy development should therefore prioritise the design of scalable, interoperable, and governance-centred DT architectures, embedding clear frameworks for data ethics, privacy, ownership, and lifecycle management across public authorities, private technology providers, and citizens.

The global diffusion of digital twin smart cities is likely to accelerate due to demonstrated cost efficiencies, improved service delivery, and enhanced transparency [2,15,19–21]. However, this transition is fundamentally socio-technical rather than purely technological; its success will depend on institutional capacity, regulatory coherence, and sustained public trust in how urban data are governed and deployed.

Persistent concerns around data security and privacy continue to undermine citizen acceptance of digital twin systems [31]. While emerging approaches such as federated learning offer promising pathways to reconcile data utility with privacy protection [36], future DT implementations should institutionalise privacy-preserving AI as a default design principle rather than an optional add-on. Embedding decentralised learning architectures, secure data enclaves, and differential privacy mechanisms can materially reduce risks while preserving analytical functionality, thereby strengthening public legitimacy.

Equally critical is the governance of data quality, accessibility, and accountability throughout the urban data lifecycle [17]. Cities should establish formal digital twin governance frameworks that define standards for data acquisition, validation, sharing, retention, and deletion, alongside transparent rules on data ownership, third-party access, and commercial use. Such frameworks must align with national data protection regimes while also articulating clear municipal responsibilities for stewardship and oversight.

From a systems perspective, interoperability must be treated as a non-negotiable policy requirement rather than a technical preference. Municipal authorities should mandate common standards across IoT sensor networks, GIS platforms, Building Information Modelling (BIM), AI analytics, and cyber-physical infrastructures to prevent siloed systems, vendor lock-in, and fragmented urban intelligence. Standardisation is essential for ensuring that digital twins can operate as integrated, city-wide decision-support systems rather than isolated pilot projects.

Beyond technical and regulatory considerations, the social sustainability of digital twin smart cities hinges on citizen capability and participation. Municipalities should invest in structured digital literacy programmes that translate complex DT concepts into accessible narratives, clearly demonstrating practical benefits in areas such as mobility optimisation, air quality management, and climate resilience. This aligns with the growing recognition that socio-economic dimensions must be embedded within digital twin design rather than treated as peripheral [37,38].

Finally, participatory governance should be positioned at the core of digital twin development. The experience of Herrenberg, Germany [20] illustrates how co-creation between citizens, planners, and technologists can enhance both legitimacy and functionality. Continuous feedback mechanisms, deliberative engagement processes, and participatory design practices should become standard components of digital twin implementation, ensuring that these systems evolve in ways that are socially responsive, democratically accountable, and genuinely public-serving.

Collectively, these policy and research directions point towards a more resilient, trustworthy, and inclusive model of digital twin smart cities—one that integrates technological innovation with robust governance, interoperability, privacy protection, digital literacy, and citizen participation.

Author Contributions

Conceptualization, K.H.; methodology, S.S.; validation, K.H. and S.S.; investigation, K.H. and S.S.; writing—original draft preparation, K.H. and S.S.; writing—review and editing, K.H. and S.S.; supervision, K.H.; project administration, K.H. All authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were generated in this study.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

Appendix A. PRISMA Summary

PRISMA Stage	Count	Notes
Records identified	1184	IEEE Xplore, ScienceDirect, SpringerLink, Scopus
Duplicates removed	312	Zotero 6.0
Records screened	872	Title/abstract
Excluded at screening	702	Irrelevant, weak methods
Full-text assessed	170	Eligibility
Full-text excluded	125	Not DT/urban; poor quality; no access
Included (academic)	36	Peer-reviewed
Included (practitioner)	7	Context only

Appendix B. List of Screened DT Literature

Authors	Title	Journal/Publisher	Year
Alam, K. M., & El Saddik, A.	C2PS: A digital twin architecture reference model for the cloud-based cyber-physical systems.	IEEE Access	2017
Alva, P., et al.	Use cases for district-scale Urban Digital Twins.	International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences	2022
Alvi, M., et al.	Global perspectives on digital twin smart cities: Innovations, challenges, and pathways to a sustainable urban future	Sustainable Cities and Society	2025
Ariyachandra, M. R. M. F., & Wedawatta, G.	Digital twin smart cities for disaster risk management: A review of evolving concepts.	Sustainability	2023
Barresi, A.	Urban Digital Twin and urban planning for sustainable cities.	TECHNE – Journal of Technology for Architecture and Environment	2023
Batty, M.	Digital twins.	Environment and Planning B: Urban Analytics and City Science	2018
Biljecki, F., & Stouffs, R.	City digital twins: From vision to reality.	ISPRS Journal of Photogrammetry and Remote Sensing	2021
Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y.	Towards a semantic construction digital twin: Directions for future research.	Automation in Construction	2020
Braun, V., & Clarke, V.	Using thematic analysis in psychology.	Qualitative Research in Psychology	2006
Dawelbait, G., & Zhang, W.	Urban digital twins for smart city modelling: A review.	Sustainable Cities and Society	2022
Dembski, F., Wössner, U., Letzgus, M., Ruddat, M., & Yamu, C.	Urban digital twins for smart cities and citizens: The case study of Herrenberg, Germany.	Sustainability	2020
Deng, T., Zhang, K., & Shen, Z.-J. M.	A systematic review of a digital twin city: A new pattern of urban governance toward smart cities.	Journal of Management Science and Engineering	2021
El-Agamy, R. F., et al.	Comprehensive analysis of digital twins in smart cities: Technologies, applications, and challenges.	Artificial Intelligence Review	2024
Feng, H., Lv, H., & Lv, Z.	Resilience towarded digital twins to improve the adaptability of transportation systems.	Transportation Research Part A: Policy and Practice	2023
Ford, D. N., & Wolf, C. M.	Smart cities with digital twin systems for disaster management.	Journal of Management in Engineering	2020
Fuller, A., Fan, Z., Day, C., & Barlow, C.	Digital Twin: Enabling technologies, challenges and open research.	IEEE Access	2020
Higgins, J. P. T., & Green, S. (Eds.).	Cochrane handbook for systematic reviews of interventions (Version 5.1.0).	The Cochrane Collaboration	2011
Huzzat, A.	A comprehensive review of digital twin technologies in urban management.	Digital Engineering	2025
Jeddoub, L., Nys, G.-A., Hajji, R., & Billen, R.	Digital twins for cities: Analysing the gap between concepts and current implementations with a specific focus on data integration.	International Journal of Applied Earth Observation and Geoinformation	2023
HamaMurad, Q., & Jusoh, N. M.	A Literature Review of Smart City: Concept and Framework.	Journal of Advanced Geospatial and Science Technology	2022
Khan, K. S., Kunz, R., Kleijnen, J., & Antes, G.	Five steps to conducting a systematic review.	Journal of the Royal Society of Medicine	2003
Ketzler, B., Paulheim, H., & Niemann, H.	Data integration challenges for digital twins of smart cities.	IEEE Access	2020
Khajavi, S. H., Motlagh, N. H., Jaribion, A., & Holmström, J.	Digital twin: Vision, benefits, boundaries, and creation for buildings.	IEEE Access	2020
Kitchin, R.	Data Lives.	Bristol University Press	2021
Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … Moher, D.	The PRISMA 2020 statement: An updated guideline for reporting systematic reviews.	BMJ	2021
Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … McKenzie, J. E.	PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews.	BMJ	2021
Lehtola, V. V., Koeva, M., Elberink, S. O., Raposo, P., Virtanen, J.-P., Vahdatikhaki, F., & Borsci, S.	Digital twin of a city: Review of technology serving city needs.	International Journal of Applied Earth Observation and Geoinformation	2022
Lei, B., et al.	Challenges of urban digital twins: A systematic review and a Delphi expert survey.	Automation in Construction	2023
Lytras, M. D., & Visvizi, A.	Who uses smart city services and what to make of it: Toward interdisciplinary smart cities research.	Sustainability	2018

Authors	Title	Journal/Publisher	Year
Mazzetto, S., et al.	A Review of Urban Digital Twins Integration, Challenges, and Future Directions in Smart City Development.	Sustainability	2024
Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G., & The PRISMA Group.	Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement.	PLoS Medicine	2009
Pang, Z., Chen, Q., Han, W., & Zheng, L.	Value-centric design of the internet-of-things solution for food supply chain: Value creation, sensor portfolio and information fusion.	Information Systems Frontiers	2015
Paul, J., Khatri, P., & Kaur Duggal, H.	Frameworks for developing impactful systematic literature reviews and theory building: What, why and how?	Journal of Decision Systems	2023
Peldon, D., Banihashemi, S., LeNguyen, K., & Derrible, S.	Navigating urban complexity: The transformative role of digital twins in smart city development.	Sustainable Cities and Society	2024
Qi, Q., Tao, F., Hu, T., & Anwer, N.	Enabling technologies and tools for digital twin.	Journal of Manufacturing Systems	2020
Ramu, S. P., Boopalan, P., Pham, Q.-V., Maddikunta, P. K. R., Huynh-The, T., Alazab, M., Nguyen, T. T., & Gadekallu, T. R.	Federated learning enabled digital twins for smart cities: Concepts, recent advances, and future directions.	Sustainable Cities and Society	2022
Schrotter, G., & Hürzeler, C.	The digital twin of the city of Zurich for urban planning.	PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science	2020
Shahat, E., Hyun, C. T., & Yeom, C.	City digital twin potentials: A review and research agenda.	Sustainability	2021
Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C.	Digital twin in industry: State-of-the-art.	IEEE Transactions on Industrial Informatics	2019
Treiblmaier, H., & Beck, R.	Business transformation through blockchain.	Springer	2021
Van Zoonen, L.	Privacy concerns in smart cities.	Government Information Quarterly	2020
Weil, C., et al.	Urban Digital Twin Challenges: A Systematic Review and Perspectives for Sustainable Smart Cities.	Sustainable Cities and Society	2023
White, G., Zink, A., Codecá, L., & Clarke, S.	A digital twin smart city for citizen feedback.	Cities	2021

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