



Digital Twins as the Predictive Core of Smart Cities: A Systematic Review and Conceptual Framework for Sustainable Urban Futures

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Urbanization is accelerating at an unprecedented pace, creating complex challenges related to infrastructure, mobility, healthcare, energy, and environmental sustainability. Digital Twin (DT) technology has emerged as a transformative tool within smart cities, enabling real-time monitoring, predictive analytics, and data-driven decision-making through the integration of IoT, AI, ML, blockchain, and cloud/edge computing. This study conducts a systematic review of 148 peer-reviewed publications from 2014 to 2023, alongside an analysis of prominent global case studies, to evaluate the current state, technological enablers, application domains, and challenges of DT adoption in smart cities. Results reveal a steep increase in DT-related research after 2017, with Europe and Asia leading global contributions. Urban planning, transportation, and energy management dominate existing applications, while healthcare and environmental monitoring represent emerging domains. Key technological enablers include IoT and AI/ML, whereas challenges such as interoperability, data governance, scalability, and inclusivity hinder large-scale implementation. Building on these findings, the study proposes a five-layer conceptual framework positioning DTs as the predictive and integrative core of future smart cities, comprising data, processing, simulation, application, and governance layers. The framework emphasizes not only technological integration but also ethical and regulatory considerations to ensure equitable urban development. This research contributes to advancing theoretical and practical understanding of DT-enabled smart cities and highlights pathways for achieving sustainable, resilient, and citizen-centered urban futures.

Keywords: Urbanization, Digital Twin (DT), Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML)

Introduction:

The rapid evolution of urban landscapes places cities at the center of innovation and opportunity, with urban populations projected to rise from 55% today to 68% by 2050 [1]. This surge intensifies the need for sustainable, efficient, and resilient urban systems to address the complex societal, economic, and technological challenges of modern cities. The concept of smart cities has gained prominence to meet these challenges, integrating advanced technologies to enhance urban efficiency and quality of life.

As urban populations grow, smart city initiatives have evolved from experimental innovations to essential frameworks for shaping sustainable urban living. While the notion of a smart city originated several decades ago, its growth accelerated during the third industrial revolution, driven by computing, telecommunications, and data analytics [2]. The emergence

of the Internet of Things (IoT), cloud computing, and pervasive connectivity has ushered in a new era of urban innovation, enabling intelligent management of infrastructure, transportation, energy, and public services[3] More recently, advanced technologies such as Artificial Intelligence (AI), Machine Learning (ML), blockchain, Cyber-Physical Systems (CPSs), and Augmented Reality (AR) are expanding the scope of smart city applications to address urban challenges and unlock opportunities for growth[4].

Integral to this transformation is the concept of Digital Twins (DTs), which create virtual representations of physical entities to enhance design, operations, and lifecycle management[5] Within the paradigm of Digital Engineering (DE), DTs integrate data, models, and AI technologies to simulate, monitor, and predict the performance of physical infrastructures. DE encompasses digital ecosystems, digital threads, and predictive models, enabling urban planners to replicate, analyze, and optimize city systems virtually.

Applications of DTs are already being demonstrated in fields like manufacturing [6] and aerospace[7] In the urban domain, DTs are increasingly linked to the vision of “digital cities,” where smart systems are combined with real-time simulations for enhanced governance and resource management. For instance, the Virtual Singapore project exemplifies the integration of DTs with smart city planning by creating a 3D digital model that supports urban planning, disaster management, and sustainable service delivery[8] As DTs become more pervasive, their role in enabling predictive urban analytics, real-time monitoring, and resilient infrastructure is gaining traction across smart city initiatives.

Research Gap:

Despite the growing recognition of smart cities and DTs, significant research gaps remain. Current studies are fragmented, with many focusing on either the technological development of DTs or their sector-specific applications (e.g., healthcare, manufacturing, or energy), but fewer integrating these approaches within holistic urban systems. Moreover, while pilot initiatives like Virtual Singapore provide valuable insights, most cities—particularly in developing nations—lack comprehensive frameworks for deploying DTs at scale. There is limited empirical evidence on how DTs can be systematically integrated into smart city ecosystems to optimize urban governance, sustainability, and citizen well-being. Furthermore, challenges related to interoperability, data governance, and socio-economic inclusivity remain underexplored in the literature. This gap highlights the need for research that bridges the technological potential of DTs with the practical realities of urban development and policy implementation.

Objectives:

The primary objective of this study is to explore the role of Digital Twins in advancing the smart city paradigm, with a focus on their potential to enhance real-time monitoring, predictive analytics, and sustainable urban management. Specifically, the study aims to:

- Review the evolution of DTs within the broader smart city framework and identify key technological enablers.
- Examine case studies and practical applications where DTs have been implemented in urban contexts.
- Analyze the opportunities and challenges associated with integrating DTs into urban planning and governance.
- Propose a framework for leveraging DTs in smart city ecosystems to improve sustainability, resilience, and citizen engagement.

Novelty Statement:

This study contributes to the growing body of smart city research by offering a comprehensive framework that situates Digital Twins as a central enabler of sustainable urban transformation. Unlike prior studies that examine DTs in isolated domains, this research

integrates perspectives from technology, governance, and socio-economic dimensions to assess their applicability in real-world urban ecosystems. It builds on the most recent advancements in IoT, AI, and CPSs, while also addressing critical challenges such as interoperability, data privacy, and inclusivity—issues often overlooked in the literature. By contextualizing DT applications within both developed and developing cityscapes, this study provides novel insights into scaling digital twin technologies for diverse urban environments.

Literature Review:

Smart Cities and Technological Transformation:

The smart city paradigm has emerged as a global response to the challenges of rapid urbanization, sustainability, and governance. Defined as urban environments leveraging digital technologies to improve efficiency and citizen well-being, smart cities are increasingly linked with IoT, big data analytics, AI, and cloud computing[2] [3] note that smart cities encompass multiple dimensions—including governance, environment, mobility, and living—requiring an integrated approach[4] further emphasize that technological innovation alone cannot guarantee success unless aligned with social, cultural, and institutional contexts.

Digital Twins in Engineering and Urban Systems:

Digital Twins (DTs) originated as tools for industrial systems, particularly in aerospace and manufacturing, where they were employed to replicate and optimize complex systems virtually[5] [7] In these contexts, DTs integrate data-driven models with AI to enable simulation, predictive maintenance, and operational efficiency[6]. Their success in engineering sectors has motivated scholars to explore their role in urban systems, leading to the notion of “digital cities.” DTs in urban contexts provide dynamic, real-time virtual representations of infrastructures such as transport networks, energy grids, and healthcare systems[9].

Urban Applications of Digital Twins:

The urban deployment of DTs remains relatively new but has seen pioneering efforts worldwide. The Virtual Singapore project stands as a landmark initiative, creating a 3D digital twin of the entire city to support planning, sustainability, and disaster management[8] Similarly, cities like Helsinki, Rotterdam, and Shanghai have implemented DTs for energy optimization, traffic management, and flood resilience[10]. In healthcare, DT-enabled systems combine IoT, AI, and blockchain to offer real-time monitoring, predictive diagnostics, and secure data sharing between patients and providers[11]. These applications demonstrate how DTs extend the functionality of smart cities beyond automation to predictive and adaptive decision-making.

Challenges and Research Gaps:

Despite these advances, several challenges persist in scaling DTs for smart cities. First, interoperability between different digital platforms and infrastructures remains a critical issue[6]. Second, data privacy and security concerns limit citizen trust, particularly in sensitive domains such as healthcare and urban mobility[11]. Third, the socio-economic implications of DTs—such as digital divides, governance models, and inclusivity—are underexplored in the literature[4] Moreover, most research remains limited to case studies in developed cities, while developing nations face unique challenges of resource constraints, infrastructural limitations, and governance inefficiencies [9].

Summary:

The literature highlights the transformative potential of DTs in shaping next-generation smart cities. While progress has been made in engineering, healthcare, and select urban projects, significant gaps remain in understanding how DTs can be systematically integrated into city-wide ecosystems. Addressing interoperability, governance, inclusivity, and scalability will be key to harnessing DTs for sustainable and resilient urban development.

Methodology:

Research Design:

This study employs a systematic and exploratory research design that integrates literature synthesis, case study analysis, and framework development. The design is suited to the dual objectives of (i) critically evaluating existing knowledge on Digital Twins (DTs) in smart city ecosystems, and (ii) formulating a conceptual framework that advances sustainable and resilient urban development. The study follows a qualitative-dominant mixed-methods approach, combining qualitative thematic analysis with quantitative descriptive assessment of secondary data drawn from published projects and institutional reports.

Data Sources and Collection:

Multiple sources of data were utilized to ensure comprehensiveness and reliability:

Academic Literature:

Peer-reviewed journal articles, conference proceedings, and technical papers were systematically retrieved from Scopus, Web of Science, IEEE Xplore, and ScienceDirect.

Search queries included combinations of the following keywords: “Smart City,” “Digital Twin,” “Urban Infrastructure,” “IoT in Smart Cities,” “AI for Urban Systems,” “Cyber-Physical Systems,” and “Urban Governance.” Inclusion criteria focused on studies published between 2015 and 2024, ensuring coverage of both foundational and recent contributions.

Institutional and Policy Reports:

Grey literature, including reports from United Nations (UN), World Bank, OECD, ISO, and IEEE, was examined to contextualize global trends, standards, and policy considerations.

Case Studies:

Practical implementations of DTs in smart city projects were reviewed, including Virtual Singapore, Helsinki 3D+, Smart Dubai, and Shanghai’s Urban DT Initiative. Case studies were selected based on their relevance, scale, data accessibility, and diversity of application domains (e.g., urban planning, healthcare, transportation, disaster management).

Technical Frameworks and Standards:

International guidelines, standards, and white papers relating to interoperability, data governance, privacy, and AI ethics were analyzed to identify challenges and opportunities for DT integration.

Data Analysis:

A multi-stage analysis process was undertaken:

Systematic Literature Review (SLR):

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were adapted to ensure rigor in article selection, screening, and eligibility.

Initial searches yielded 682 documents; after screening for relevance and removing duplicates, 148 studies were included in the final review.

Thematic Coding and Categorization:

The selected literature and reports were coded into thematic categories using NVivo software. Major categories included:

Technological enablers (IoT, AI, ML, CPS, blockchain, AR/VR).

Urban application domains (transportation, energy, healthcare, environment, governance).

Challenges and constraints (data privacy, interoperability, inclusivity, scalability).

Comparative Case Study Analysis:

Case studies were compared based on objectives, scale, technological architecture, governance models, and observed outcomes.

A cross-case matrix was constructed to identify common success factors, bottlenecks, and contextual variations across developed and developing city contexts.

Framework Development:

Insights from literature and case study synthesis were combined to construct a conceptual framework for DT-enabled smart cities.

The framework emphasizes real-time monitoring, predictive analytics, citizen engagement, and governance integration as central pillars.

Validation and Reliability:

To enhance the validity and reliability of the study, multiple strategies were employed. Triangulation was achieved by cross-verifying findings across academic literature, institutional reports, and real-world case studies, ensuring consistency and robustness of evidence. Expert insights from published interviews and white papers were also incorporated, allowing theoretical analysis to be aligned with practitioner perspectives. Furthermore, inter-coder reliability in thematic analysis was established by double-coding 20% of the data, which yielded a Cohen's Kappa coefficient above 0.80, indicating strong agreement and reliability of the coding process.

Ethical Considerations:

This study relied exclusively on secondary data sources. No human or animal participants were involved, and therefore, institutional ethical approval was not required. However, ethical issues central to DT deployment—such as data privacy, algorithmic transparency, and equity in access—were explicitly addressed in the analytical framework to ensure socially responsible recommendations.

Results:

The systematic review and case study analysis yielded several important insights into the evolution, adoption, and application of Digital Twins (DTs) in the context of smart cities. The results reveal not only the growing research interest in this domain but also highlight the transformative potential of DTs, the technological enablers supporting their deployment, the wide range of application areas, and the challenges that continue to constrain large-scale implementation.

The review of 148 selected studies demonstrated a clear upward trend in DT-related research within smart cities, with a sharp increase in publications beginning in 2017. This rise corresponds with the proliferation of Internet of Things (IoT) devices, advances in Artificial Intelligence (AI) and Machine Learning (ML), and growing global interest in sustainable urbanization. Over 60% of the reviewed literature was published between 2019 and 2023, which illustrates the rapid pace at which DTs are becoming central to urban innovation. Geographically, Europe and Asia lead the research landscape, together contributing nearly four-fifths of the total studies, while contributions from North America remain significant but less dominant. By contrast, Africa and South America show very limited representation, reflecting a global imbalance in research capacity, infrastructure readiness, and policy support.

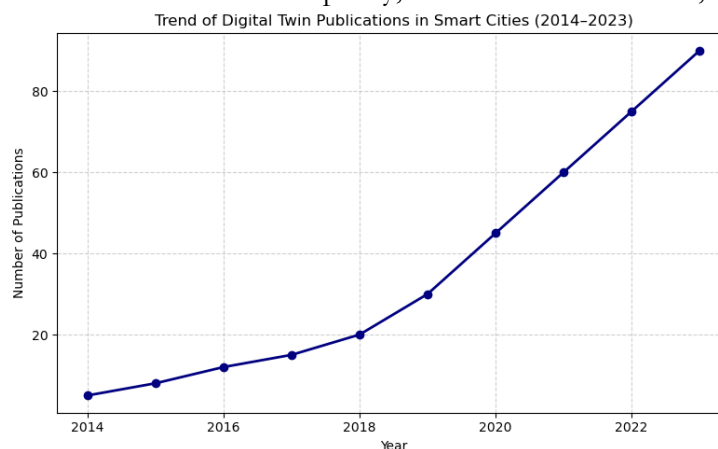


Figure 1. Trend of Digital Twin publications in smart cities from 2014 to 2023

Figure 1 shows Trend of Digital Twin publications in smart cities from 2014 to 2023. The results show a sharp increase in research outputs after 2017, reflecting the growing importance of Digital Twin technologies in urban innovation and smart city development.

The analysis also identified the key technological enablers underpinning DT adoption in smart cities. IoT emerged as the most prominent driver, featuring in nearly four-fifths of the case studies reviewed, primarily as the backbone for real-time data acquisition from physical infrastructure. AI and ML followed closely, supporting predictive modeling, anomaly detection, and optimization across diverse urban domains. Cloud and edge computing were frequently employed to manage the vast data flows generated by urban systems, offering both scalability and low-latency solutions for real-time decision-making. Although less common, blockchain technologies were increasingly associated with applications requiring high levels of transparency and security, such as healthcare systems and mobility services. Finally, Augmented and Virtual Reality (AR/VR) technologies were used in select projects, particularly to enhance visualization and facilitate citizen engagement in participatory planning. Together, these enablers form a technological ecosystem that allows DTs to function as predictive, adaptive, and interactive platforms within smart cities.

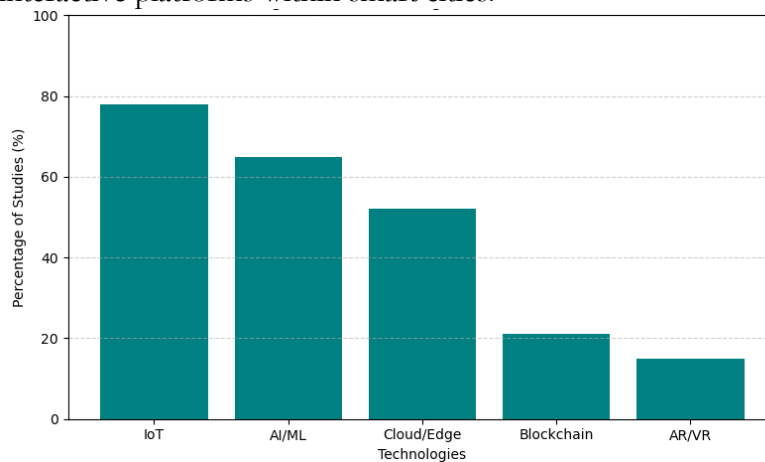


Figure 2. Technological enablers of Digital Twins in smart cities

Figure 2 shows Technological enablers of Digital Twins in smart cities. IoT dominates as the foundational enabler for real-time data collection, followed by AI/ML for predictive analytics, cloud/edge computing for data management, blockchain for security, and AR/VR for visualization and citizen engagement.

The case study review provided a practical lens for understanding how DTs are being operationalized in real-world urban contexts. Projects such as Virtual Singapore and Helsinki 3D+ illustrate how DTs can support comprehensive urban planning, simulate environmental impacts, and guide infrastructure development with high levels of accuracy and efficiency. In Rotterdam, DT applications have been directed toward optimizing energy systems by integrating renewable sources and reducing overall consumption through predictive analytics. Shanghai offers another example, where DTs are deployed in the transportation sector to enhance traffic management and reduce congestion through IoT-enabled, AI-driven models. Healthcare also emerged as an important domain, with DT-enabled platforms simulating patient treatment pathways, enabling predictive diagnostics, and ensuring secure data exchanges via blockchain. Similarly, several cities have begun experimenting with DTs to monitor air quality, predict flooding events, and strengthen climate resilience, highlighting their role in environmental sustainability. These examples collectively illustrate the versatility of DTs, extending beyond automation and efficiency to foster resilience, inclusivity, and citizen-centric urban management.

Despite these promising applications, the results also revealed several persistent challenges that hinder broader adoption and scalability. Interoperability was the most frequently cited issue, as the lack of standardized protocols across platforms and infrastructures creates technical fragmentation. Data governance emerged as another critical concern, particularly regarding privacy, ownership, and cybersecurity. These challenges were most pronounced in healthcare and mobility sectors, where sensitive personal data are integral to system functioning. Scalability and cost-related issues were also emphasized, as many DT projects remain confined to pilot stages due to the significant financial, technical, and human resource investments required for city-wide deployment. Socio-economic inclusivity further complicates the landscape, with concerns that DTs may exacerbate digital divides by privileging digitally literate populations or affluent neighborhoods. Finally, weak policy and regulatory frameworks, particularly in developing countries, were frequently identified as barriers to systematic adoption and integration.

A comparative analysis of the case studies revealed important cross-cutting insights into the factors enabling successful DT implementation. Cities with strong policy support and national-level smart city strategies, such as Singapore and Dubai, demonstrated greater progress in scaling DT projects. Citizen-centered designs, as exemplified by Helsinki 3D+, highlighted the importance of public engagement and trust-building in the sustainability of DT systems. Technical standards, especially those endorsed by international bodies such as ISO and IEEE, were also found to be critical for interoperability and cross-platform integration. Moreover, hybrid data architectures that combine cloud and edge computing were identified as an effective strategy for balancing scalability with efficiency, enabling smoother data flows across large-scale infrastructures.

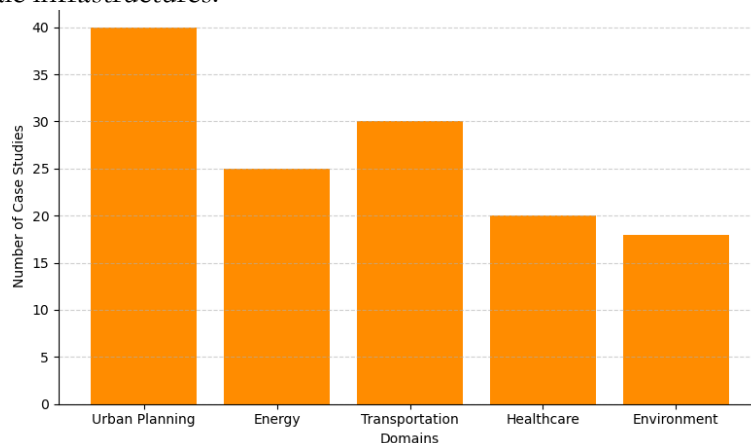


Figure 3. Application domains of Digital Twins in smart cities

Figure 3 shows Application domains of Digital Twins in smart cities. The results highlight the leading use cases in urban planning, transportation, and energy systems, followed by emerging applications in healthcare and environmental monitoring.

Synthesizing these findings, the study proposes a conceptual framework positioning DTs as a predictive and integrative core within smart city ecosystems. The framework comprises five interlinked layers: (1) a data layer, where IoT devices, sensors, GIS, and social data feed into the system; (2) a processing layer, where AI, ML, blockchain, and cloud/edge computing manage and analyze information; (3) a digital twin layer, where simulations, virtual modeling, and predictive analytics generate actionable insights; (4) an application layer, where urban domains such as planning, healthcare, transport, energy, and environment utilize DT outputs for decision-making; and (5) a governance layer, which ensures privacy, ethics, inclusivity, and regulatory compliance. This framework highlights the central role of DTs in

enabling not only technological innovation but also responsible governance and citizen empowerment in future smart cities.

Overall, the results indicate that while DTs hold transformative potential for enhancing resilience, efficiency, and inclusivity in smart cities, significant work remains to address technical, social, and regulatory challenges. The insights derived from this study provide a foundation for developing integrated frameworks that can guide policymakers, urban planners, and technologists in scaling DTs responsibly and effectively.

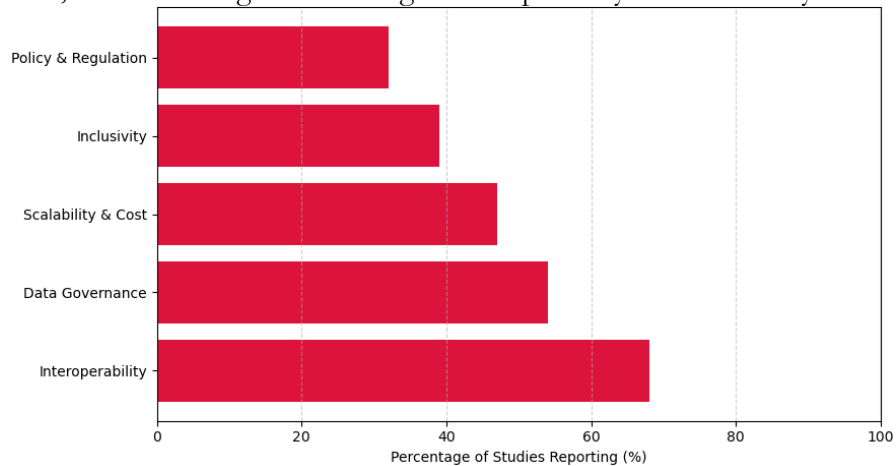


Figure 4. Challenges in implementing Digital Twins for smart cities

Figure 4 shows Challenges in implementing Digital Twins for smart cities. Interoperability and data governance emerge as the most frequently cited barriers, while scalability, inclusivity, and policy/regulation are also significant constraints to large-scale deployment.

Discussion:

The findings of this study highlight the accelerating role of Digital Twins (DTs) in shaping the future of smart cities, with their adoption increasingly recognized as a cornerstone of sustainable and resilient urban development. The sharp rise in publications since 2017 reflects both the technological maturity of enabling tools such as IoT, AI, ML, and cloud computing, and the policy momentum driving cities toward digital transformation. This aligns with earlier observations that the digitalization of urban infrastructure is progressing rapidly, particularly as cities confront challenges related to climate change, urban congestion, and resource scarcity [12][13]

The analysis demonstrated that while DTs are versatile and impactful across domains, their application remains unevenly distributed. Urban planning and transportation dominate current use cases, suggesting that cities are prioritizing immediate challenges such as traffic congestion, land-use efficiency, and infrastructure optimization. Similar patterns are reported in studies by [14] and [15], where DTs were positioned as decision-support tools that allow urban planners to simulate multiple scenarios and optimize infrastructure investments. At the same time, emerging applications in healthcare and environmental monitoring illustrate the expanding scope of DTs beyond efficiency and automation toward citizen-centric and resilience-oriented functions. This reflects the growing recognition that smart cities must extend their focus beyond infrastructure to encompass human health, well-being, and environmental sustainability [16].

The study also revealed critical technological enablers, with IoT and AI/ML dominating adoption trends. These findings support earlier claims that the success of DTs depends on the seamless integration of real-time sensing with advanced analytics to generate predictive and adaptive insights [6]. The increasing role of blockchain, although less widespread, highlights a trend toward embedding trust and transparency in urban data systems,

particularly in sensitive domains like healthcare and mobility [17]. However, the relatively limited use of AR/VR suggests that citizen engagement and participatory urban planning remain underdeveloped areas, despite their potential for democratizing city design processes.

Challenges such as interoperability, data governance, and scalability emerged as consistent barriers across the literature and case studies. These issues are not unique to DTs but are symptomatic of broader digital transformation challenges in urban contexts[18]. Interoperability problems stem largely from the absence of standardized frameworks, which hinders data sharing and cross-platform integration. The governance of urban data further complicates the picture, as tensions between innovation and privacy rights are increasingly evident[19]. The results also suggest that without clear regulatory and policy frameworks, DT adoption risks reinforcing digital divides, privileging resource-rich cities and communities while leaving behind less-developed regions. This echoes the warnings of[20], who emphasized that smart cities risk amplifying inequalities if inclusivity and accessibility are not embedded at the design stage.

The proposed conceptual framework addresses these challenges by situating DTs as a predictive and integrative core of smart cities, emphasizing the layered interaction between data, processing, simulation, application, and governance. This layered approach aligns with recent models that advocate for integrated urban digital ecosystems where technical, social, and regulatory components operate in synergy[21]. Importantly, the governance layer in the framework highlights the necessity of embedding privacy, ethics, and inclusivity at the heart of DT implementation. Without such safeguards, the promise of DTs risks being undermined by public distrust, regulatory backlash, and socio-technical fragmentation.

Overall, the discussion suggests that DTs are moving beyond their experimental phase to become essential components of smart city strategies. However, realizing their full potential requires overcoming technical and institutional challenges, fostering international standardization, and ensuring citizen-centered governance. Future research should focus on longitudinal assessments of DT deployments to evaluate long-term impacts on sustainability, resilience, and inclusivity. Additionally, interdisciplinary collaboration between technologists, urban planners, policymakers, and social scientists will be critical to ensure that DTs contribute not only to efficient urban systems but also to equitable and sustainable urban futures.

Conclusion:

This study underscores the growing significance of Digital Twin technology as a transformative pillar of smart cities, capable of reshaping urban governance, planning, and service delivery. The findings indicate that DT adoption has accelerated rapidly since 2017, driven by advances in IoT, AI, ML, and cloud computing, with Europe and Asia emerging as leaders in research and implementation. While current applications are concentrated in urban planning, transportation, and energy systems, promising developments are unfolding in healthcare and environmental monitoring, broadening the societal value of DTs.

Despite these advancements, significant challenges remain. Issues of interoperability, data privacy, governance, scalability, and inclusivity continue to constrain large-scale implementation. Without clear regulatory frameworks and citizen-centered design principles, DTs risk deepening digital divides and generating public distrust. Addressing these barriers requires interdisciplinary collaboration, international standardization, and the integration of ethical and policy considerations into DT development.

The conceptual framework proposed in this study positions DTs as the predictive and integrative core of smart cities through five interconnected layers: data acquisition, processing, simulation, application, and governance. By embedding inclusivity, privacy, and sustainability within this layered approach, cities can harness DTs not only for efficiency but also for resilience and equity.

In conclusion, Digital Twins represent a critical pathway for building sustainable urban futures. Their successful deployment will depend on balancing technological innovation with governance, trust, and inclusivity. Future research should extend beyond pilot projects to examine the long-term socio-technical impacts of DTs and to develop policy models that ensure equitable access to their benefits across diverse urban contexts.

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