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Exploring the Methodologies for Developing City Digital Twin for Sustainable Smart Cities: A Thematic Analysis

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Abstract

The growing complexity of urban challenges in the 21st century has spurred the need for innovative, data-driven tools in urban planning. One such emerging tool is the digital twin—a virtual replica of physical city systems that integrates real-time data, simulation models, and advanced analytics to support sustainable and resilient urban development. This paper conducts a systematic literature review (SLR) and thematic analysis of 548 recent studies to explore the methodologies and technological frameworks used to develop city digital twins. The analysis identifies two major themes: (1) models, frameworks, and tools for digital twin development and (2) data management strategies for effective implementation. By categorizing technological integrations such as GIS, BIM, remote sensing, machine learning, and IoT, this review highlights best practices and challenges in current urban digital twin applications. The findings suggest that while digital twins hold significant potential to advance Sustainable Development Goals (SDGs), gaps remain in terms of standardization, governance, interoperability, and bi-directional data flow. This study concludes with a call for more empirical research on bidirectional integration between the digital replica and its physical counterpart, particularly in developing countries, to unlock the full transformative potential of digital twins in smart urban governance.

1. Introduction

The 21st century has witnessed unprecedented urban growth, leading to increased challenges in infrastructure management, environmental sustainability, and resource allocation(Caprari et al., 2022a). As cities expand, the need for smarter, data-driven approaches to urban planning has become crucial(Azadi et al., 2025; Mazzetto, 2024a; Ogunkan & Ogunkan, 2025). Sustainable urban development, which seeks to balance economic growth, environmental protection, and social well-being, has gained significant attention among policymakers, researchers, and urban planners(Azadi et al., 2025; Mazzetto, 2024b). However, implementing sustainability in rapidly growing urban environments is a complex task requiring innovative solutions that integrate technological advancements with traditional urban planning methodologies(Weil et al., 2023)(Peldon et al., 2024). One such emerging technological advancement is the concept of digital twins. A digital twin is a virtual representation of a physical system that integrates real-time data, simulation models, and advanced analytics to enhance decision-making(*How the UAE Is Leading the Way in Digital Twin Integration*, n.d.)(Villani et al., 2025). Initially developed for manufacturing and aerospace industries, digital twins are now being explored for urban planning applications. In smart cities, digital twins offer the potential to optimize infrastructure, monitor environmental impacts, and enhance resilience against climate change and other urban challenges(Peldon et al., 2024). Despite these advantages, the adoption of digital twins in sustainable urban development remains limited due to technical, conceptual, and governance challenges(Haraguchi et al., 2024). The primary objective of this research is to investigate the role of digital twins in urban sustainability. This study will explore various methodologies for developing city digital twins, focusing on integrating technologies such as 3D modeling, Geographic Information Systems (GIS), remote sensing, and traffic simulation tools like Vissim. These technologies provide the foundation for creating accurate and dynamic urban digital twins, allowing planners to analyze various urban scenarios in real-time and make data-driven decisions(C. Chen et al., 2025). The integration of digital twins in urban planning is particularly relevant in the context of rapid urbanization and climate change. Cities worldwide face issues such as inefficient transportation systems, air pollution, energy consumption, and inadequate infrastructure planning. Traditional urban planning methods often fail to address these issues comprehensively due to a lack of real-time data and predictive analytics. Digital twins can bridge this gap by enabling cities to model different urban scenarios, optimize resources, and enhance sustainability through informed policy-making(Luo et al., 2025). Despite the potential benefits, several challenges hinder the widespread adoption of digital twins in urban planning. One of the key barriers is data integration. Digital twins rely on multiple data sources, including satellite imagery, IoT sensors, and spatial databases. Ensuring interoperability among these diverse data sources requires standardized frameworks and data management strategies(Jeddoub, Nys, et al., 2024). Additionally, computational complexity and the need for high-performance computing resources pose significant challenges. Many cities, particularly in developing countries, lack the technical infrastructure and expertise required to implement digital twins effectively.

Another critical issue is the governance and ethical implications of digital twins. As digital twins collect vast amounts of real-time data, concerns about data privacy and security have emerged. The ethical use of digital twins in urban planning requires clear policies and regulations to ensure responsible data management(X. Wang, 2025). Furthermore, the lack of a universally accepted definition and framework for digital twins in urban planning leads to confusion and ambiguity, making it difficult for cities to implement and scale these technologies

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effectively. In addition to addressing technical and governance challenges, this research highlights the need for a more comprehensive literature review on digital twins in sustainable urban development. While digital twins have been extensively studied in industrial applications, their role in achieving Sustainable Development Goals (SDGs) remains underexplored. This study aims to fill this gap by critically analyzing existing literature and identifying research gaps that need further investigation.

The research also seeks to compare the application of digital twins across different sectors. In industries such as aerospace and manufacturing, digital twins are used for predictive maintenance, performance optimization, and operational efficiency. However, their application in urban planning is more complex due to the dynamic nature of cities and the need for interdisciplinary collaboration among urban planners, data scientists, engineers, and policymakers. By examining case studies of digital twin implementations in different sectors, this research aims to draw parallels and identify best practices that can be adapted for sustainable urban planning. Furthermore, the COVID-19 pandemic has underscored the importance of resilient urban systems. The pandemic disrupted urban mobility, strained healthcare infrastructures, and highlighted inefficiencies in city management. Digital twins have demonstrated their potential in crisis management by enabling real-time monitoring, optimizing resource allocation, and enhancing emergency response planning. The lessons learned from the pandemic provide a compelling case for integrating digital twins into urban resilience strategies(Eumi, 2024).

In conclusion, digital twins represent a transformative approach to sustainable urban planning, offering innovative solutions to complex urban challenges. However, their successful implementation requires overcoming technical, governance, and conceptual hurdles. By critically analyzing methodologies, challenges, and research gaps, this study contributes to a deeper understanding of digital twins in sustainable city development and provides a roadmap for future research and implementation strategies.

2. Research Methodology

Research on applications of digital twin in urban planning is still in its early stages. Although some studies have explored the use of digital twin in developing smart cities, however, the literature relating to the use and application of digital twin technology in achieving Sustainable Development Goals (SDGs) in cities is still negligible. Therefore, to establish a comprehensive research agenda in this emerging field, a Systematic Literature Review (SLR) is essential, which will ensure rigorous reviews of the structured results. It is one of the most known approaches to conducting a literature review to provide insights and knowledge about a specific topic by ensuring the inclusion of only related literature and biases in the source selection. The quality of SLR depends on the clarity and completeness of the reporting process for which the study adheres to the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA) guidelines to conduct the literature review. As per PRISMA, the SLR consists of three steps: identification, screening, and eligibility. The search was carried out on the world's largest database Scopus using the following terms out of Title, Abstract, and Keyword:

("digital twin" OR "digital twinning" OR "virtual twin" OR "virtual twinning") AND ("urban" OR "urban planning" OR "urban development")

The above search resulted in 1522 documents out of which documents relating to "social science" and "environmental science" subject areas were considered, which led to 592 documents. Further screening was done using document type, in which the search was limited to articles, conference papers, book chapters, review papers, conference reviews, and books written in the English language, which narrowed the search to 586 documents. Following this, three levels of screening were done: title and keywords screening, abstract screening, and full-text screening. In title and keywords screening and abstract screening, the title of the document, index keywords, and author keywords were searched for the words "digital twin", "virtual twin" or "urban" to ensure that all the studies related to the studied topic are considered at the preliminary level, which limited the search to 570 documents. This was followed by a full-text screening in which all studies were categorized into three types:

1. studies that depict the direct application of digital twin in any urban planning aspect,
2. studies that depict the use of technology in any urban planning aspect or contribution of technology to the creation of urban digital twin and,
3. studies that do not include any mention of the use of digital twin or technology for urban areas or mention the use of digital twin for other sectors, i.e. architecture, construction, aerospace, manufacturing, etc.

Thus, the studies that that are irrelevant to the studied topic, i.e. studies that do not include any mention of the use of digital twin or technology for urban areas or mention use of digital twin for other sectors, i.e. architecture, construction, aerospace, manufacturing, etc. (point 3) were excluded. Accordingly, 548 documents or studies were selected to be included in this study. After identifying the appropriate research papers for the present study, these were arranged in Microsoft Excel to identify different characteristics of literature like year of publication, keywords, abstract, document type, and others. Following, bibliometric analysis was carried out using the VOSviewer (will be explained in detail in the section). Additionally, to answer the research questions mentioned in the section, thematic analysis was conducted which included analyzing the qualitative set of data and searching for meaning in patterns of data to identify themes. Accordingly, the thematic analysis of the study was based on the application of digital twin technology in sustainable urban planning and development along with challenges and solutions in the data management aspect.

2.1 Characterization in Literature and Bibliometric Analysis

In the table 1, three main characteristics of 548 documents are present which are the year-wise number of published research papers, type of document, and type of study. As the table indicates, interest in the city digital twin research started very recently in 2018, with one journal article, and has increased tremendously for six years to 93 journal articles, 3 books, 43 book chapters, 83 conference papers, and 16 review papers in 2024. The present study was conducted in April 2025, and

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therefore the number of studies is 36 in number which is expected to rise to 300 - 400 by year-end.

It was also noted from literature characterization that almost more than half of the studies are journal articles (n=247), followed by conference papers (n=171), the number of which are also increasing from 2018 to 2024. At last, the third characteristic of literature, i.e., type of study shows that 280 studies depict the direct application of digital twin in any urban planning aspect which is a significant number, and 268 studies depict the use of technology in any urban planning aspect or contribution of technology to the creation of urban digital twin. A keyword co-occurrence analysis was conducted on VOS viewers to identify the relationship between publications. The software allows the extraction of keywords from the title and abstract of the publication, or they can be taken from the author-supplied keyword list of publications using natural language algorithm and text mining methods.

Characteristics of Literature	Categories	Frequency
Year-wise number of published studies	2018	2
	2019	9
	2020	24
	2021	43
	2022	91
	2023	106
	2024	237
	2025	36
Type of document	Journal Article	247
	Conference Paper	171
	Book	9
	Book Chapter	68
	Review Paper	35
	Conference Review	18
Type of Study	Studies that depict the direct application of digital twin in any urban planning aspect	280
	Studies that depict the use of technology in any urban planning aspect or contribution of technology to the creation of urban digital twin	268

Table 1: Characteristics of Literature

To carry out keyword co-occurrence analysis, the minimum number of keyword occurrences was kept at two. Also, before carrying out the analysis the similar meaning keywords like “digital twin” or “city digital twin” or “urban digital twin and “smart cities” or “smart city” and “BIM” and “building information modeling” and “CIM” or “city information modeling”, etc. were merged. The result of the analysis showed that out of 670 keywords from the studies, 94 met the threshold and the most repeated keywords were city digital twin (134 occurrences), followed by smart city/smart cities (39 occurrences), 3D city model (25 occurrences), and urban planning (21 occurrences).

3. Results

The thematic analysis of 548 studies related to exploration of methodologies for developing city digital twin for sustainable smart cities result in two broad themes: Model/framework/technique/tool that has been developed/suggested in terms of developing digital twin technology and data management for digital twin technology.

3.1 Models/Frameworks/Techniques/Tools that have been developed/suggested in terms of developing Digital Twin Technology

The analysis of the studies showed that city digital twin and 3D models for various urban planning aspects were suggested and developed with assistance from various platforms frameworks networks algorithms tools techniques technology or apps. This section of the study addresses the following key points:

1. Studies suggest developing digital twins to address urban-related issues.
2. Studies suggest developing 3D models for addressing urban-related issues.
3. Studies suggest the integration of advanced technologies for enhancing the capacity of digital twins or 3D models to address urban issues.

3.1.1. Studies suggest developing digital twins to address urban-related issues.

There are almost 180 studies suggesting developing digital twins for addressing urban-related issues/aspects. For instance, developing digital twin for investigating importance of participatory process in urban park management(Luo et al., 2022), assessing the quantity and quality of urban greenery in the city(Zhukova et al., 2021), predicting changes in air quality(Hamada et al., n.d.; Logachev & Korotun, 2023), facilitating defect management in building at urban renewal and conservation scale(J. Chen et al., 2022), enhancing energy efficiency of building and reducing the carbon emission from it(Benedetti et al., 2022; Santhanavanich et al., 2022; Veisi & Shakibamanesh, 2023), assessing pedestrian-level thermal comfort in urban environments(Gholami et al., 2022), enhancing the flexibility and efficiency of the electric grids and network(Gholami et al., 2022; Zhong & Li, 2024), managing energy consumption at urban scale(Srinivasan et al., 2020), assessing the impact of infrastructure projects before their implementation(Shirowzhan et al., 2020), monitoring and preserving the complexity of various landscapes(Gabriele et al., 2023), addressing the current problems of water supply systems(Zhou et al., 2024), improving the urban logistics(Lozzi et al., 2023; Marcucci et al., 2020; Taniguchi et al., 2023), enhancing the operation of freeway systems(Fu et al., 2023), creating and validating the traffic models(Argota Sánchez-Vaquerizo, 2022), managing of urban road infrastructure(Zhu et al., 2024), improving vehicle fuel efficiency, mobility and reduced congestion and emissions(Aguiar et al., 2022; Kapusta & Trúchly, 2023), managing the geo-spatial aspects of public administration assets(Sammartano et al., 2021), collecting and processing data for urban monitoring systems and supporting urban operations centre (Dou et al., 2020; Gitahi & Kolbe, 2024; Supangkat et al., 2023), mitigating the Urban Heat Island(Bulatov et al., 2022; Elnabawi & Raveendran, 2024), improve the robustness of cities to external disturbances(Li et al., 2021), monitoring, defect inspection, and condition assessment of sewer pipelines(Y. Wang et al., 2022), integration of social aspects into the technology(Yossef Ravid & Aharon-Gutman, 2023), and conversion from 2D to 3D property valuation(Y. Ying et al., 2023).

In addition, the research also revealed that there are few case studies in which a digital twin platform is developed for solving city issues with advanced technology such as:

1. 3D City Digital Twin for Italy to address the challenge of insufficient pedestrian-level greenery using the Rhinoceros platform, Energy Plus, Honeybee, and Ladybug components in Grasshopper software(Gholami et al., 2022),
2. Digital geoTwin, a CityGML-Based data model for Vienna to capture various aspects of urban environments, including buildings, infrastructure, terrain, vegetation, and administrative boundaries, among others, in a structured and interoperable way(Lehner et al., 2024),
3. Digital Twin for Barcelona to conduct traffic studies such as evaluating traffic counts, trip distributions, and other metrics evaluating traffic counts, trip distributions, and other metrics using the Simulation of Urban Mobility tool(Argota Sánchez-Vaquerizo, 2022),
4. Digital twin for the city of Rostov-on-Don to maintain the new green spaces using cutting-edge technologies like GIS, unmanned aircraft, mobile laser scanning, and automated data recording and transmission(Zhukova et al., 2021),
5. Digital twin for Lyon city for comparison of scenarios from now to 2040 to help the decision-maker to make the best strategic decision for their cities using Digital Making Decision Software(Malé & Lagier, 2021),
6. Digital twin for the city of Kermanshah in Iran for enhancing energy efficiency of buildings in terms of consumption and generation using two-dimensional GIS data and a three-dimensional BIM model(Veisi & Shakibamanesh, 2023),
7. Digital Twin for the City of Zurich for simulating urban scenarios, planning infrastructure, and managing city services using real-time data(Schrotter & Hürzeler, 2020),
8. Digital Twin for Helsinki city for engaging with citizens, visualizing urban changes, and facilitating better decision-making using Open Cities Planner application(Hämäläinen, 2021),
9. Urban Digital Twin for Herrenberg, Germany aiming to aim to facilitate participatory and collaborative urban planning processes using Virtual Reality(Dembski et al., 2020), Additionally, some studies have explored the integration of human aspects into urban digital twins for better management and operational efficiency in urban environments(Abdeen et al., 2023; Lei et al., n.d.; Ye et al., 2023a).

3.1.2. Studies suggest developing 3D models for addressing urban-related issues.

There are 100 studies suggesting developing 3D models for addressing urban-related issues. For instance/aspects, developing 3D model for providing up-to date information about urban environments(Tamort et al., 2024), detecting automatic changes in the city over time and providing user or stakeholders interpretation of these changes(Nguyen & Kolbe, 2020, 2021, 2022), encouraging inclusivity and democracy in community design and policy making process(Najafi et al., 2023a; Nguyen & Kolbe, 2021), contributing to urban analytics and water sensitive urban design(Langenheim et al., 2022), enhancing the assessment process for building energy performance(Anselmo et al., 2023), managing and mitigating the effects of earthquake(Yu et al., 2023), levee management through extraction of detailed and accurate levee surface model(Lee et al., 2023), technological advancement in in survey procedure(Luhmann et al., 2022), evaluating and managing the sustainability of public buildings(Kaewunruen & Xu, 2018), digitizing water distribution systems(Bonilla et al., 2023a), sustainable development and management of urban heritage buildings(Zaker et al., 2021), managing and evaluating carbon emission sustainability in urban areas(Park & Yang, 2020a), enhancing urban services and addressing the social, economic, and environmental challenges of urban growth(Avezbaev et al., 2023a), integrating bout indoor and outdoor scenes of building(Shao et al., 2022a), application of modern design techniques in retrofitting projects(Duch-zebrowska & Zielonko-jung, 2021a), visualizing landscape(Kikuchi et al., n.d.-a; Vinasco-Alvarez et al., 2021a), supporting various environmental analysis and strategic urban forest management(C. Chen et al., 2024a; Gobeawan et al., 2018a; Münzinger et al., 2022a), real-time modelling and management of urban and natural drainage networks(Bartos & Kerkez, 2021), and improving solid waste management practices(Cárdenas et al., 2024).

3.1.3. Studies suggest the integration of advance technologies for enhancing the capacity of digital twins or 3D models to address urban issues.

The application of city digital twin is still in the early stages, and there are still debates on what a fully developed city digital twin should entail. Therefore, various studies have been carried out by researchers to enhance the capacity of digital twin technology such as:

1. combining digital twin with machine learning(Abdeen et al., 2023; Kumi et al., 2023), artificial intelligence(Bellini et al., 2023; Castelli et al., 2019; J. Chen et al., 2022; Jeddoub, Ballouch, et al., 2024; Taniguchi et al., 2023; Urban Freight Analytics, n.d.; Ye et al., 2023b), virtual reality(Michalik et al., 2022; Thuvander et al., 2022), robotics(J. Chen et al., 2022), big data analysis(Fu et al., 2023; Li et al., 2021), internet of things(Aguiar et al., 2022; Bazazzadeh et al., 2022; Castelli et al., 2019; Charitonidou, n.d.; Li et al., 2021; Taniguchi et al., 2023; S. ming Wang & Vu, 2023; Yossef Ravid & Aharon-Gutman, 2023), building information modeling (J. Chen et al., 2022; Dou et al., 2020; Sammartano et al., 2021; Veisi & Shakibamanesh, 2023; Xia et al., 2022), geographic information system(Digital Twin Enabled Sustainable Urban Road Planning, n.d.; Shariatpour et al., 2024; Veisi & Shakibamanesh, 2023; Xia et al., 2022; Yossef Ravid & Aharon-Gutman, 2023), user interfaces(Abdeen et al., 2023), visualization portals(Aguiar et al., 2022), intelligent prediction[136], [174], multi-criteria decision making(Digital Twin Enabled Sustainable Urban Road Planning, n.d.), advanced statistics(Bellini et al., 2023), behavioral models(Marcucci et al., 2020), agent based model(Logachev & Korotun, 2023), system dynamics model(Logachev & Korotun, 2023), social sensing(Kumi et al., 2023), procedural modeling (Shariatpour et al., 2024), and gamification(Taniguchi et al., 2023).
2. enhancing building modelling using geo-typical prototypes(Bulatov et al., 2022; Li et al., 2021),
3. facilitating 3D video transmission by optimal deployment strategies for edge computing servers(Liu et al., 2023),
4. enabling bidirectional data exchange for accurate modeling, optimization, and control of the network(Ghosh et al., n.d.;

Tomin et al., 2020),

5. using open standards like CityGML for 3D city modelling for making data produced transparent and easily accessible(Caprari et al., 2022b; S. Ying et al., 2023),
6. integrating deep learning into CityGML format with semantic information for automated façade object detection(S. Ying et al., 2023),
7. augmenting geospatial data representing the capacity of CityGML by using the concept of Application Domain Extension(S. Ying et al., 2023),
8. integrating local information with Earth Observation data(Gabriele et al., 2023; Merlo & Lavoratti, 2024),
9. shifting from 2D representations to more complex and dynamic 3D digital models(Merlo & Lavoratti, 2024),
10. creation of a central data repository/digital archive using GIS software by pairing the municipal geodatabase for infrastructure monitoring, condition assessment, and inventory management(Benedetti et al., 2022; Richter et al., 2024; Yossef Ravid & Aharon-Gutman, 2023),
11. employing advanced modeling techniques such as sonar scanning, laser 3D scanning, LiDAR, and visual inspection robots equipped with stereo vision(Y. Wang et al., 2022),
12. using enriched 3D point clouds with semantics collected using LiDAR for representing static structures and time series of sensor data for representing dynamic aspects(Jeddoub, Ballouch, et al., 2024; Richter et al., 2024),
13. collection of geospatial data using hybrid sensors combining camera systems with topographic LiDAR into an integrated aerial mapping system(Bacher, 2022),
14. increasing accuracy of geospatial localization by integrating mobile crowdsensing integrated into a Digital Geotwin-based platform(Supangkat et al., 2023),
15. solving the occlusion problem by integrating drone cameras with virtual cameras so that virtual objects will correctly appear in front of real objects in artificial intelligence(Kikuchi et al., n.d.-b),
16. allowing data transfer between digital and physical realms by integrating machine learning with the Internet of Things(Elnabawi & Raveendran, 2024; Srinivasan et al., 2020),
17. enhancing efficiency in the decision-making process by integrating data from various sources and using decision-making software (Malé & Lagier, 2021; Zhu et al., 2024),
18. emphasizing the use of big data and IoT/IOE technologies in creating more holistic 3D digital twin representations(Alberti et al., 2023),
19. utilizing cutting-edge technologies like unmanned aircraft, mobile laser scanning, and automated data recording and transmission for developing digital twins(Zhukova et al., 2021),
20. employing VGI3D, a web-based interactive system for 3D building modelling using geographic information images(S. Ying et al., 2023),
21. improving the quality of datasets by using a high-performance portable Mobile Mapping System (MMS) for creating digital twin(Blaser et al., 2021),
22. exploiting blockchain technology for sharing sensor data among application providers and ensuring data immutability and consistency in the development of digital twins(Bazazzadeh et al., 2022; Charitonidou, n.d.; Takahashi et al., 2022),
23. incorporating geometric layers in a virtual representation of city features using pre-existing data, digital elevation models from regional aerial surveys, and open street maps (Scalas et al., 2022),
24. addressing and simplifying the scalability challenge of digital twin by using automated procedural workflow(Thuvander et al., 2022),
25. integrating computational fluid dynamic simulations and suitability analysis with a digital twin platform for assisting in the data analysis stage(Hamada et al., n.d.),
26. using advanced statistical methods, optimization algorithms, and forecasting methods for optimal resource allocation(Zhong & Li, 2024),
27. enhancing the satellite image classification process by using segmentation models and U-Net network(Ahmadi et al., n.d.; Veisi & Shakibamanesh, 2023),
28. employing advanced computer modeling and simulation techniques, spatial analysis, and numerical simulations for solving problems related to urban planning, infrastructure, and sustainability(Dembski et al., 2019),
29. identifying and solving urban planning issues by creating virtual urban models on Gather or using serious gaming techniques or grid-based design techniques(S. ming Wang & Vu, 2023),
30. optimizing data management in digital twin using Open Geospatial Consortium web services such as OGC SensorThings API, OGC API 3D GeoVolumes, OGC CityGML, OGC API Features, Web Feature Service, and Web Map Service(Santhanavanich et al., 2022),
31. integrating mobile mapping systems with various sensors such as GNSS, INS, 3D laser scanners, and panoramic cameras to gather LiDAR point cloud data for applications such as large-scale topographic mapping(Castelli et al., 2019; Guo et al., 2021),
32. advancing the visualization aspect of urban digital twins by using game engines like Unreal and Unity complemented by OGC standards such as 3D Tiles, GeoVolumes API, and SensorThings(Würstle et al., 2022),

3.2 Data management for digital twin technology

The success of a digital twin largely hinges on how well the underlying data is handled and managed. Efficient data management is crucial to ensure that digital twins operate as expected, delivering accurate insights and useful predictive capabilities. This article presents recommended approaches for managing data in digital twin initiatives, aiming to optimize their effectiveness and operational performance. This section of the research paper identifies four stages in data management:

3.2.1 Data Acquisition, Processing, and Analysis

Data acquisition represents the first crucial step for creating a digital twin and there are numerous ways to acquire data such as the use of satellite imageries(Gobeawan et al., 2018b; Shariatpour et al., 2024; Zaker et al., 2021), unmanned aerial vehicles (drones)(Bonilla et al., 2023a; C. Chen et al., 2024b; Karim et al., 2022a; Kushwaha et al., 2022; Y. Wang et al., 2023; Zaker et al., 2021), and LiDAR(Karim et al., 2022a; Lee et al., 2023). However, the convergence of LiDAR technology with diverse data sources, including aerial thermography and real-time sensor networks, is crucial for precise ground representation and detailed data collection, especially when integrated with

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multispectral imaging and building models(Karim et al., 2022b; Münzinger et al., 2022a). City Information Modeling (CIM) enhances this integration by combining CAD files, OpenStreetMap (OSM) data, Airbus datasets, and SketchUp models, supported by AI, machine learning, GIS, BIM, and IoT for real-time insights(Avezbaev et al., 2023b; Bartos & Kerkez, 2021; Duch-zebrowska & Zielonko-jung, 2021b; Gil, 2020; Park & Yang, 2020b). Dynamic 3D urban modeling is further enriched by IoT sensors and UAVs, alongside satellite imagery for GIS and open data accessibility(Rantanen et al., 2023a).
However, challenges arise in data quality assessment specifically in completeness, consistency, and accuracy of building attributes, when data is obtained from open street maps (OSM) as the data is highly variable (Camacho et al., 2021). Standardizing geospatial data around CityGML and employing Free and Open-Source Software for Geo-spatial (FOSS4G) tools for data management and visualization can mitigate these issues(Seto et al., 2023a).
Data integration faces challenges such as semantic data loss and the need for consistent identifiers across datasets, necessitating ontology-based integration methods to minimize semantic loss during the transformation into unified semantic graph formats(Vinasco-Alvarez et al., 2021a). CityGML 3.0 datasets serve as interoperable semantic RDF graphs, facilitating improved integration of heterogeneous spatial-temporal data, while graph-based change detection methods offer solutions for tracking objects across various city snapshots(Vinasco-Alvarez et al., 2021a).

3.2.2 Data Modelling

Data modeling for city digital twins is crucial for developing a comprehensive and dynamic representation of urban environments through diverse data sources. This modeling facilitates the simulation, analysis, and visualization of various scenarios, thereby enhancing decision-making and urban planning processes(Ketzler et al., 2020). City Information Modelling (CIM) is instrumental in integrating multiple data sources and models, resulting in a unified digital representation of urban areas(Gil, 2020). Despite its benefits, this approach faces challenges, such as the fusion of data from different sensors and perspectives, as well as the intelligent modeling of complex urban objects(Shao et al., 2022b). The incorporation of game engines significantly boosts accuracy, offering high-fidelity visualizations and interactive simulations that engage stakeholders effectively(Rantanen et al., 2023a).
Additionally, predictive systems like Pipedream can assess correlations for accuracy and forecast behaviors, effectively integrating with common Artificial Neural Networks to enhance predictive capabilities(Bartos & Kerkez, 2021; Nguyen & Kolbe, 2022). Improved modeling and data assimilation techniques contribute to superior system performance and cost-effective operations, mitigating risks that traditional methods often identify too late. Furthermore, adaptive modeling and parameterization ensure that the digital twin remains relevant and responsive to ongoing changes within the urban landscape, making it an invaluable tool for contemporary urban management(C. Chen et al., 2024a).

3.2.3 Data Visualization

Data visualization is a fundamental component of city digital twins, significantly enhancing the understanding and communication of complex urban data. By transforming raw data into intuitive graphical representations, stakeholders can gain valuable insights into city dynamics, which facilitates improved decision-making and urban planning.
To accommodate users with varying levels of expertise, it is essential to develop user-friendly interfaces that simplify complex data visualization and analytics(Bonilla et al., 2023b; Najafi et al., 2023b). Visualization techniques are instrumental in topography development, employing mapping, and spatial statistics to accurately depict urban landscapes(Bonilla et al., 2023b; Park & Yang, 2020b).
The data visualization process incorporates a multi-level approach known as Semantic Enrichment that involves data comparison, pattern capture, and change interpretation, which are crucial for managing the intricacies of updating urban digital twins(Nguyen & Kolbe, 2024). Additionally, a web interface plugin can effectively handle IoT data, providing interactive visualizations as a foundational step for future simulations(Boumhidi et al., 2024). High-accuracy visualization of future landscape changes from an aerial perspective is possible after addressing occlusion challenges(Kikuchi et al., 2021). The combination of LiDAR with multispectral imagery and building models further enhances both data collection and visualization accuracy(Münzinger et al., 2022b).
Moreover, advances in modern game engines significantly improve visualization capabilities, positioning them as suitable platforms for constructing digital twins(Rantanen et al., 2023b). The standardization of geospatial data around CityGML, coupled with the use of Free and Open-Source Software for Geo-spatial (FOSS4G) tools, fosters effective data visualization(Seto et al., 2023b). Ultimately, integrating 3D visualization with semantic information enriches the representation of urban environments, offering deeper insights into their structure and functionality(Shariatpour et al., 2024).

3.2.4 Data Integration and Harmonization

Data integration and harmonization are pivotal in developing city digital twins, enabling the consolidation of diverse datasets into a cohesive framework that facilitates comprehensive urban modeling. This process involves synthesizing information from various sources, such as Geographic Information Systems (GIS), Internet of Things (IoT) sensors, satellite imagery, and existing urban databases, thereby providing a holistic view of city dynamics encompassing transportation, infrastructure, and environmental conditions. However, challenges such as varying data quality, measurement inconsistencies, and differences in data collection methodologies must be addressed to ensure the reliability of the digital twin.
Collaborative 3D Building Information Modeling (BIM) technologies can enhance information sharing and efficiency in construction projects, while tools like the “Dynamizer” extension of CityGML allow for real-time data integration(Kaewunruen & Xu, 2018). Open-data integration approaches, including static data methods, MQTT protocols, and game engine environments, further improve accessibility(Rantanen et al., 2023b). Effective interoperability between BIM and GIS necessitates standardized workflows for City Information Modeling (CIM) implementation(Omrany et al., 2023; Vinasco-Alvarez et al., 2021b). Additionally, the consolidation of heterogeneous spatial-temporal data into 3D and 4D models poses challenges related to semantic data loss, which can be mitigated through ontology-based integration methods(Vinasco-Alvarez et al., 2021b). Ultimately, utilizing

CityGML 3.0 datasets as interoperable semantic RDF graphs enhances the integration process, supporting informed decision-making and strategic urban planning(Vinasco-Alvarez et al., 2021b).

4. Findings and Discussion

The systematic review and thematic synthesis of 548 documents reveal a growing interest and diversity in digital twin applications for urban sustainability. The first key finding is that most studies are focused on developing models and tools to address specific urban challenges such as air quality management, transportation optimization, infrastructure resilience, and energy efficiency. Case studies from cities like Zurich, Helsinki, and Barcelona demonstrate successful implementation of digital twin platforms using integrated tools such as GIS, BIM, simulation engines, and real-time sensors.
Secondly, the role of emerging technologies—especially artificial intelligence, Internet of Things (IoT), big data, and machine learning—is central to enhancing digital twins' predictive and operational capabilities. However, technological sophistication is not without complications. Issues of interoperability, data harmonization, and the lack of standardized ontologies were frequently noted. CityGML, CIM, and other frameworks have emerged to bridge this gap, but there is limited consensus on universal standards for city-scale digital twins.

Furthermore, the literature highlights substantial interest in data management processes, including acquisition, modeling, visualization, and integration. The importance of semantic enrichment and visualization through game engines or web-based platforms was emphasized in improving decision-making and stakeholder communication. However, ethical and governance issues—such as privacy, data ownership, and policy limitations—are still underexplored, especially in low-resource settings.

A particularly novel insight from the reviewed studies is the potential of digital twins to act not merely as visualization tools but as active agents in participatory planning, urban resilience, and dynamic policy-making. The COVID-19 pandemic further reinforced the need for cities to build adaptive systems, where real-time feedback and simulation can support emergency response, infrastructure resilience, and citizen engagement.

5. Conclusion

Digital twins represent a transformative tool in the evolution of sustainable smart cities. Their capacity to integrate multi-source data, simulate urban dynamics, and support real-time decision-making offers promising avenues for addressing complex urban challenges. However, despite their conceptual appeal and growing body of literature, several gaps remain in their effective implementation and scalability.

The most pressing limitation lies in the bidirectional flow of information between the digital model and the physical city. Most current applications are still unidirectional—data flows into the model, but actionable insights are not consistently fed back into the physical systems. Future research should focus on establishing real-time feedback loops, dynamic model calibration, and automated control systems that can actively influence urban environments based on digital insights. Other research priorities should include:

1. Development of universal data standards and interoperability protocols.
2. Integration of citizen-generated data and social sensing into digital twin platforms.
3. Ethical frameworks and policies to govern data usage, privacy, and transparency.
4. Empirical studies evaluating the impact of digital twin implementation on achieving SDGs.

In conclusion, while the potential of digital twins in urban sustainability is immense, realizing this potential requires interdisciplinary collaboration, governance innovation, and continuous technological evolution. Strengthening the link between physical systems and their digital counterparts will be crucial for creating resilient, inclusive, and adaptive cities of the future.

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