The Uptake of Urban Digital Twins in the Built Environment: A Pathway to Resilient and Sustainable Cities

OMRANY, Hossein, MEHDIPOUR, Armin, OTENG, Daniel and AL-OBAIDI, Karam <http://orcid.org/0000-0002-4379-6964>

Omrany et al. Computational Urban Science (2025) 5:20
https://doi.org/10.1007/s43762-025-00177-x

Computational Urban Science

REVIEW

Open Access

The uptake of urban digital twins in the built environment: a pathway to resilient and sustainable cities

Hossein Omrany[1*], Armin Mehdipour[1], Daniel Oteng[1] and Karam M. Al-Obaidi[2]

Abstract

Urban Digital Twin (UDT) technology is increasingly recognised as a promising tool for designing and developing sustainable, resilient urban environments. Nonetheless, the current literature lacks a comprehensive understanding of UDTs' current applications in the built environment. Therefore, this study addresses the identified gap by analysing scholarly literature and industry reports connected to UDT implementations. The results of scientometric analysis revealed five key research fields including: (i) UDT for urban monitoring and controlling, (ii) UDT for smart urban planning, (iii) UDT for environmental management, (iv) UDT for decision-making, and (v) UDT for smart and sustainable cities. Further, this study analysed 10 industry reports on UDT technology to identify practical insights and evaluate industry-driven approaches for implementing UDT solutions in urban environments. Despite promising progress, the findings indicate the absence of a clear, structured process to facilitate consistent implementation, scalability, and interoperability in UDT technology. This further highlights the need for globally recognised guidelines and well-defined KPIs to fully realise its potential in urban environments. The study also presents a new classification model developed from analysing the research flow to elaborate on the main outcomes from five clusters towards UDT pathways. The new proposed model reintroduces the structure of UDT literature with a new flow to interpret and correlate the content identified in previous studies. Based on these insights, the study offers recommendations to support the advancement of UDT technology for building resilient, sustainable cities.

Keywords Digital twin, Smart cities, Urban planning, Sustainability, Industry 4.0, Built environment

1 Background

Urban development in the 21st century faces numerous challenges, driven by rapid urbanisation and a growing population worldwide (Lei et al., 2023; Weil et al., 2023). The United Nations predicts that by 2050, approximately 68% of the global population will reside in urban areas, placing significant strain on infrastructure, housing, and public services (UN-Habitat, 2022). Traditional urban planning approaches, typically developed for simpler urban environments, are increasingly challenged in keeping up with the rapidly changing demands of contemporary cities (Caprari et al., 2022; Schrotter & Hürzeler, 2020). These approaches often lack the flexibility to address the multifaceted nature of today's urban environments, where social, economic, environmental, and technological factors are deeply interconnected. As cities grow larger and more complex, the limitations of conventional planning become more apparent. This underlines the necessity for adopting innovative solutions such as smart cities that employ advanced technologies to manage the intricate and interdependent challenges of urbanisation.

*Correspondence:
Hossein Omrany
Hossein.omrany@adelaide.edu.au
[1] School of Architecture and Civil Engineering, The University of Adelaide, Adelaide, Australia
[2] Sheffield Creative Industries Institute, College of Social Sciences and Arts, Sheffield Hallam University, Sheffield, UK

The concept of smart city has gained significant momentum in recent years due to its capacity to integrate advanced technologies, optimise resource use, and enhance public services (Adreani et al., 2024; Dembski et al., 2020). The notion of smart cities revolves around the integration of information and communication technologies (ICT) with urban infrastructure and services to improve the quality of citizens' lives (Omrany et al., 2024a). Urban studies increasingly emphasize data-driven approaches, leveraging data science and computational urban science to effectively address the complexities of urban environments (Zhang et al., 2024). The computational urbanisation is a new paradigm that allows researchers to investigate sustainable urbanisation challenges using correlations and cause-effect links across many fields of data, as opposed to previous methodologies that are difficult to manage (Chen et al., 2022). It provides new cross-cutting views and factors using geographic big data to understand complicated urban issues (Meerow, 2020). The nature of its interdisciplinary field uses data science methodologies and technologies such as informatisation, spatial positioning techniques, remote sensing, digitalisation and cloud computing, enable us to collect vast quantities of information in real time for the urban development and urbanisation process (Trevisani & Omodeo, 2021). Urban computing is a fundamental component of computational urban science that combines data from urban surroundings with the use of the IoT and AI to optimise city planning (Kumar & Bassill, 2024).

The study of urban data using model-driven decision support systems enables optimal design solutions to enhance urban efficiency, resilience, and sustainability. The use of large-scale data sets, machine learning algorithms and simulations provides useful information about urban dynamics, energy usage, traffic patterns and environmental impacts (Omrany & Al-Obaidi, 2024). Machine learning approaches like logistic regression, random forests, and neural network techniques frequently outperform standard sample statistics in terms of parameter estimation Omrany & Al-Obaidi, 2024). The field has interconnected layers with a platform-based that spans human dynamics, action-oriented, and convergence-driven (Li et al., 2020). Although research into AI and machine learning in urbanisation science is still in its early stages, these are the primary paths for future technical and methodological improvement (Chen et al., 2022). This necessitates an awareness of current advances in computational urban science and data science to create future cities that are equitable, resilient and environmentally sensitive (Liu et al., 2021).

Among the advanced technologies and tools developed to enable the operation of smart cities, the 'digital twin' technology holds grave potential for transforming urban planning by providing precise, real-time data and simulations that enhance decision-making, resource management, and overall urban resilience (Saeed et al., 2022; Yossef Ravid & Aharon-Gutman, 2023). A digital twin model is a virtual replica of a physical entity that leverages real-time data and advanced analytics to simulate, monitor, and optimise urban environments (Grieves & Vickers, 2017; Omrany et al., 2023). This technology facilitates the development of smart cities by merging various technological advancements, such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics, to generate dynamic, interactive models of urban systems (Bibri et al., 2024; Wajid et al., 2024; Wu & Guan, 2024). This capacity enables urban planners to monitor, manage, and predict urban phenomena with enhanced accuracy and efficiency.

Building on such capabilities, Urban Digital Twins (UDTs) extend their application to entire urban environments, offering a more comprehensive framework for urban planning, management, and sustainability. UDTs are defined as digital representations of urban spaces that utilise real-time data to enhance urban planning, management, and decision-making processes (Ferré-Bigorra et al., 2022; Somanath et al., 2024). UDTs target at developing immersive and interactive urban environments for participants by using virtual replicas of real assets, procedures, and systems (Omrany et al., 2025). UDTs facilitate real-time surveillance, analysis, and simulation of complex city systems (Weil et al., 2023). The fundamental difference between a digital model and an UDT lies in their essence, as conventional approaches such as Building Information Modelling (BIM) depict specific elements of a system without inherently capturing its dynamic processes (Deng et al., 2021a, b). BIM models often focus on specific variables and parameters, making them useful for targeted analysis and forecasting; however, they lack the depth and comprehensive system-wide scope offered by UDTs (Omrany & Al-Obaidi, 2024). In this regard, Sepasgozar (2021) stated that virtual models that just depict the physical model and have one-way data flow are called "Digital Shadows," whereas UDTs have the capacity to establish a two-way communication channel between the physical and virtual models.

IBM (2021) also classified UDTs into four types including (1) Component twins or Parts twins, (2) Asset twins, (3) System or Unit twins and (4) Process twins. The differences in these types refer to the complexity of the approach such as the number of components and level of magnification. Studies indicate that UDTs can be categorised into three parts including physical reality, virtual representation and interconnections between the physical and virtual elements (Tuhaise et al., 2023;

VanDerHorn & Mahadevan, 2021). These parts are exemplified by eight features to administrate the UDTs process through data collection, product behaviour, analysis, operational history, maintenance history, learning, collaboration network and exploring opportunities (Javaid et al., 2023). In a recent study, Omrany and Al-Obaidi (2024) presented an UDT consisted of five layers including the Physical Entity component, Digital Representation component, Tools component, Functional Outputs component and Digital Coupling component. These parts and features necessitate specific methods and hierarchical structure in dealing with data collected through UDTs. Several studies classified data collected via digital twin models into four forms generated from the physical entity, virtual model, services and domain knowledge (Omrany & Al-Obaidi, 2024; Zhang et al., 2022). These data will be processed within 7 layers including data gathering, data interaction, data storage, data association, data fusion, data evolution and data servitisation (Zhang et al., 2022). These layers form the foundation for processing and utilising data within UDT frameworks, enabling comprehensive analysis and decision-making capabilities.

1.1 Motivation for this study

Retrospective studies highlight the significant potential of UDTs to enhance urban planning by addressing key challenges such as traffic management, energy consumption, public safety, infrastructure maintenance, building energy efficiency, urban resilience, and urban heat island (UHI) effects (Peldon et al., 2024; Therias & Rafiee, 2023; Weil et al., 2023). Shahat et al. (2021) assert that UDTs have the potential to significantly enhance urban resilience by facilitating real-time monitoring and enabling prompt responses to emergencies. To date, several cities have made promising strides in developing UDTs, with exemplars including Singapore's 'Virtual Singapore' (Walker, 2023), Helsinki's smart city DT (Hämäläinen, 2021), and Zurich's DT initiatives (Schrotter & Hürzeler, 2020). These projects highlight the diverse applications of UDT technology, ranging from improving public service delivery to optimising urban mobility and enhancing environmental monitoring. Despite these advancements, the uptake of UDT technology is still slow, hindered by significant technological, financial, and regulatory challenges (Lei et al., 2023; Omrany et al., 2023).

A plethora of research has been undertaken in recent years to promote the implementation of UDT technology. This rapid expansion of publications has subsequently led to a fragmented body of literature, making it difficult to attain a cohesive understanding of UDTs. To address this issue, several review articles have been developed to consolidate existing knowledge and providing clearer insights into UDT implementation. These studies have generally focused on certain areas, such as investigating the key technologies enabling UDTs (Lehtola et al., 2022; Omrany et al., 2023; Therias & Rafiee, 2023; Weil et al., 2023), understanding the current applications (Peldon et al., 2024), highlighting challenges associated with UDT adoption (Lei et al., 2023; Wang et al., 2023; Weil et al., 2023), or focusing on the theoretical foundations underpinning the UDT technology (Peldon et al., 2024; Shahat et al., 2021; Wu & Guan, 2024). Despite the contributions of retrospective studies, the current body of literature remains fragmented in providing a comprehensive view of UDT technology's current applications and its full potential. Therefore, this paper seeks to fill this gap by analysing both scholarly research and industry reports to offer a nuanced perspective on UDT technology's role in driving sustainable practices and fostering innovation within the built environment.

To achieve this aim, the current paper sets out three primary objectives: (i) to identify key research streams in UDT through a scientometric analysis, and (ii) to examine UDT areas and classify the structure of UDT literature (iii) to highlight challenges associated with UDT application in the built environment and provide recommendations for future development. The outcomes of this research can be of interest to multiple target groups. First, researchers can rely on the findings as a point of reference for future development in the field. Second, urban planners and policymakers can use the insights to inform sustainable urban development strategies and support data-driven decisions in designing resilient, citizen-centred cities.

2 Research methodology

The research methodology in this study follows a multi-step approach, beginning with a comprehensive literature search using scholarly databases and reviewing grey literature from government and industry reports. Literature retrieval was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach, which systematically identifies, screens, and selects relevant studies (Fig. 1). To this end, a comprehensive search syntax was constructed: ("Urban Digital Twin" OR "UDT" OR "City Digital Twin" OR "Digital Twin" OR "DT" OR "Digital Replica" OR "Virtual City" OR "Digital Model" OR "Urban Virtual Twin" OR "Urban Simulation Model") AND ("urban planning" OR "urban development" OR "smart cities" OR "city management"). This syntax was thence applied to the Scopus database, which was chosen for its extensive coverage, advanced search capabilities, and comprehensive indexing of peer-reviewed literature (Scopus, 2024).

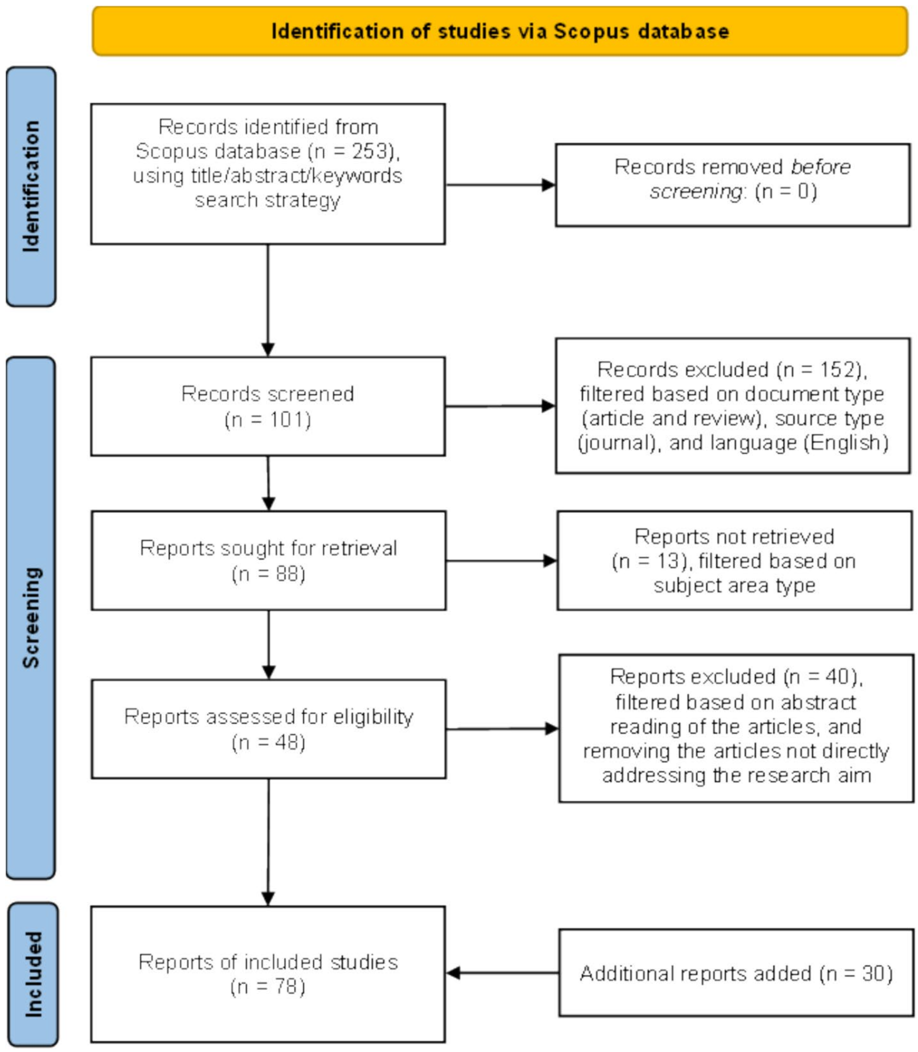


Fig. 1 PRISMA protocol for the study

The initial search process identified 253 documents. Filters were then applied based on document type (articles and reviews), source type (journals), and language (English), which reduced the dataset to 101 papers. In the next phase, 13 documents were excluded due to subject irrelevance, as fields like agriculture, medicine, and biology fell outside the study's scope, resulting in 88 articles for further screening. The abstracts and conclusions of these 88 papers were then reviewed to evaluate the relevance of each source to the core focus of the study. At this stage, materials not directly aligned with the study's objectives were excluded, refining the database to 48 papers. To ensure comprehensive search coverage, the reference lists of these shortlisted articles—particularly review articles—were thoroughly examined to identify any additional relevant materials. This step led to the discovery of 30 more studies, bringing the total number of selected materials to 78. Additionally, to account for sources with potential impact on UDT development that may not yet be published in scholarly outlets, an extensive web search was conducted to find industry reports, government publications, and policy documents on UDTs. The analysis of such documents can contribute valuable practical insights, bridging the gap between academic research and real-world applications of UDT technology. This search yielded 10 reports, which were subsequently included for content analysis to extract key insights on UDTs.

3 Results

3.1 Scientometric analysis

Scientometric analysis is a quantitative method used to map and evaluate the intellectual structure, trends, and evolution of a research domain (Khokhlov, 2020; Zhong et al., 2019). This approach employs bibliometric data from academic publications to uncover relationships, collaboration patterns, and emerging themes within a body of knowledge (Luo et al., 2022a, b; Patel et al., 2022). The use of this technique allows researchers to systematically explore complex datasets and reveal insights that may not be apparent in traditional literature reviews (Khokhlov, 2020; Luo et al., 2022a, b).

At its core, scientometric analysis focuses on mapping scientific knowledge through techniques such as co-citation analysis, co-occurrence analysis, and cluster analysis (Khokhlov, 2020; Omrany et al., 2022; Patel et al., 2022). Among all, keyword co-occurrence analysis is a widely adopted technique that helps identify frequently co-occurring keywords across academic publications (Omrany et al., 2022). This enables researchers to detect key research themes, track their evolution, and understand their interconnections (Patel et al., 2022). Keyword co-occurrence analysis provides a visual map of dominant research areas by clustering related keywords and highlighting their associations, which supports the identification of key research topics and emerging trends (Luo et al., 2022a, b; Zhong et al., 2019).

In this study, keyword co-occurrence analysis was employed to identify key research streams in UDT technology and uncover the intellectual foundations shaping this domain. To this end, VOSviewer software was used—a widely recognised bibliometric tool designed for constructing and visualising bibliometric networks. Thereupon, a keyword co-occurrence analysis was conducted, utilising both author-provided keywords and index keywords (Keywords Plus) to ensure comprehensive coverage of the research landscape (Luo et al., 2022a, b; Patel et al., 2022). In the resulting keyword network, node size corresponds to keyword frequency, node proximity indicates the strength of associations between keywords, and the thickness of connecting lines represents the intensity of these associations (Patel et al., 2022; Zhong et al., 2019). Total link strength represents the cumulative strength of connections a keyword has with other keywords in the network (Van Eck, & Waltman, 2023). It reflects the frequency and intensity of co-occurrences, indicating how strongly a keyword is associated with others within the research domain. The results of this analysis are presented in Fig. 2, which illustrates the keyword co-occurrence network and highlights five

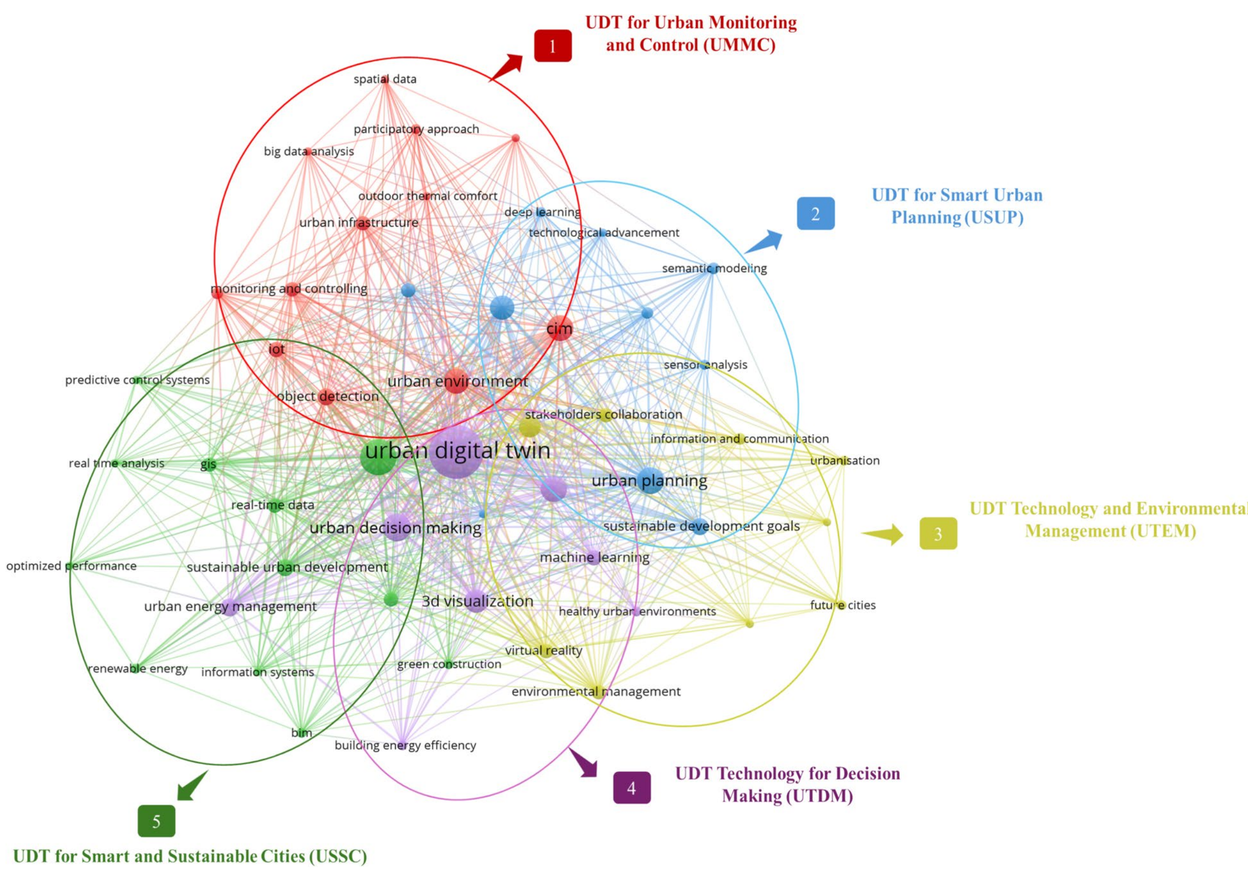


Fig. 2 Keywords analysis of the retrieved articles using science mapping

key thematic clusters. Each cluster represents a distinct area of focus within the field of UDT technology, and their implications are discussed in detail in subsequent sections.

The identification of clusters in this study (see Fig. 2) was carried out using VOSviewer's clustering algorithm, which is designed to detect meaningful groupings within bibliometric networks (Van Eck, & Waltman, 2023). The clustering approach in VOSviewer is based on the modularity optimisation method, where items (keywords, in this case) are grouped to maximise the strength of connections within clusters while minimising connections between clusters (Van Eck, & Waltman, 2023). To ensure a balance between granularity and interpretability, a minimum threshold of 51 keywords was applied, focusing on the most significant associations and excluding infrequent terms that could introduce noise into the clustering process. This threshold was selected to provide a refined dataset that retains sufficient detail to represent dominant thematic structures while avoiding excessive fragmentation.

The resolution parameter, which controls the level of clustering detail, was carefully adjusted to produce a meaningful number of clusters. Too low a resolution would have resulted in overly broad clusters, obscuring thematic nuances, while too high a resolution could have led to excessive fragmentation, making interpretation challenging (Van Eck, & Waltman, 2023). The final clustering output reflects a balance between thematic cohesion and differentiation, with each cluster representing a distinct yet interrelated research stream in UDT technology. It is acknowledged that some conceptual overlaps exist across clusters, as is common in complex interdisciplinary fields like UDT technology. However, these overlaps reflect the interconnected nature of research themes rather than weaknesses in the clustering approach. The characteristics and unique contributions of each cluster are discussed in the following sections, while their thematic boundaries and interconnections are elaborated in the sect. 4.

3.1.1 UDT for Urban Monitoring and Control (UMMC)

The first cluster contains keywords that suggest the underlying technologies of UDT, which enable data collection (e.g., IoT, spatial data, and object detection), data analytics (e.g., big data analysis), and technologies such as 'City Information Modelling' (CIM) used for modelling physical entities, such as urban infrastructure, within urban environments. Figure 3 also illustrates the interrelationships within this cluster and its connections with keywords from other clusters, along with their total link strength and occurrence. This close relationship with the USUP, UTEM, UTDM, and USSC clusters suggests a strong overlap in themes such as efficiency, governance, resilience, and inclusivity, indicating that advancements in this area are interconnected with broader smart city and urban planning efforts. The technologies identified in this cluster can play a significant role in enabling UDT to monitor and manage urban environments for various purposes, such as measuring and minimising Urban Heat Island (UHI) effects (Omrany & Al-Obaidi, 2024), improving outdoor thermal comfort (Liu et al., 2023a, b), and enhancing the resilience of urban infrastructure (Therias & Rafiee, 2023; Ye et al., 2023). For instance, in a recent study, Omrany and Al-Obaidi (2024) introduced a UDT-enabled framework to mitigate UHI effects. Their research showed how UDT technologies can be employed to monitor urban climates in real-time and provide dynamic data for informed decision-making. By integrating diverse data sources, including IoT and spatial data, the framework enables city planners to optimise urban greenery, adjust infrastructure, and implement strategies to reduce UHI impacts.

Table 1 provides a summary of the analysis of several studies' approaches within the UMMC cluster in utilising UDT technology. The presence of keywords like 'participatory approach' indicate the importance of citizen engagement in urban management, where the public actively participates in providing feedback, data, and insights (Ham & Kim, 2020; Luo et al., 2022a, b). This involvement helps inform monitoring and decision-making processes, highlighting the potential impact of collaborative approaches to monitoring and managing urban environments. For instance, Ham and Kim (2020) propose a framework that integrates participatory sensing with UDT technology to enhance risk-informed decision-making in urban environments. The study employed crowdsourced visual data from citizens to update 3D virtual city models with real-time information about physical vulnerabilities, such as structural risks or potential hazards. This approach exemplifies how public involvement through participatory sensing can provide valuable, real-time data that informs decision-making processes, especially in disaster management and infrastructure resilience. In another research, White et al. (2021) devised an UDT of Docklands area of Dublin, Ireland. The model was developed based on integrating citizen feedback to inform urban planning and policy decisions. This publicly available DT enabled residents to interact with a 3D model of the city, report issues, and provide feedback on proposed changes, such as new buildings or green spaces. The study showcased how participatory approaches through DT can enhance urban management by incorporating real-time citizen input into planning, infrastructure development, and environmental monitoring.

Keywords	Urban Environment	CIM	Object detection	Monitoring & Controlling	IoT	Urban Infrastructure	Data analytics	Participatory Approach	Big data analysis	Built environment	Spatial Data	Outdoor Thermal Comfort
Total Link Strength	129	101	72	57	55	48	39	27	21	21	19	19
Occurrences	17	19	9	7	8	7	5	4	3	3	3	3

Fig. 3 An illustration of the keywords within the UMMC cluster and their interrelationships with keywords from other clusters. Note that the original figure has been edited to enhance the legibility of keywords

As shown in Figs. 2 and 3, the keywords within the UMMC cluster have strong associations with keywords from other clusters, highlighting the interconnected nature of UDT technologies. For example, the data collection and analytics processes within UMMC, such as IoT and big data analysis, feed directly into clusters related to urban infrastructure management and resilience planning, suggesting that real-time data informs infrastructure optimisation and mitigation of disaster risks (Henriksen et al., 2022; Macatulad & Biljecki, 2024). The integration of participatory approaches within the UMMC cluster fosters significant collaboration with other clusters, particularly those focused on governance (Haraguchi et al., 2024; Quek et al., 2023; Shan et al., 2024) and social inclusivity (Yossef Ravid & Aharon-Gutman, 2023). This interaction underscores the critical role of public input in shaping urban management strategies. By leveraging participatory sensing and citizen engagement, data collected from the public contributes directly to decision-making processes in governance clusters, where urban policies and planning frameworks are formed. This collaborative approach ensures that urban development is not only data-driven but also reflective of the needs and preferences of the population, promoting social inclusivity. Citizens' feedback on issues such as infrastructure, environmental sustainability, and public spaces feeds into broader urban strategies, which in turns, highlights the importance of aligning governance

Table 1 Analysis of five exemplary studies in UMMC cluster in using UDT technology

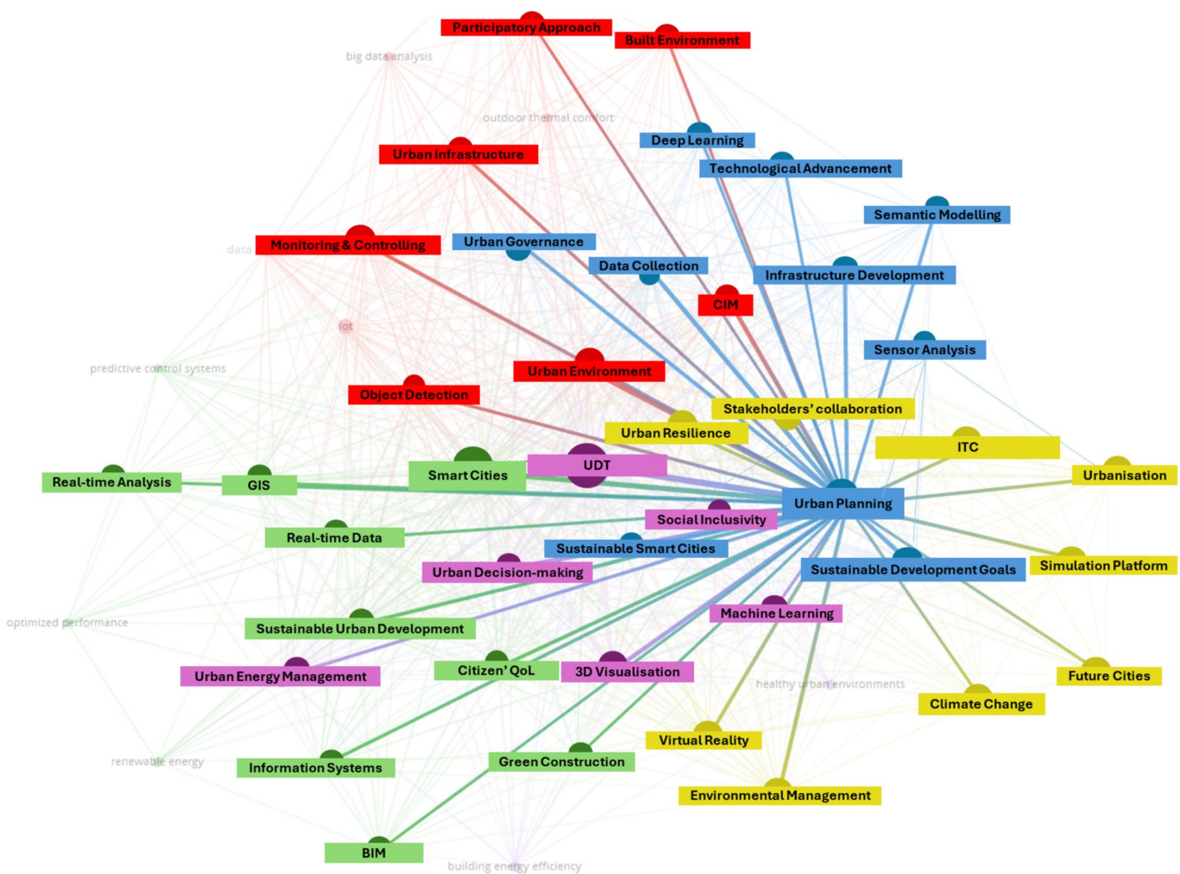
Reference	Purpose of Using DT	Key Enabling Technologies	Key Findings
Ham and Kim (2020)	To improve urban risk management and disaster preparedness through real-time data integration in UDT models	• Participatory sensing (for crowdsourced data collection) • IoT sensors (for real-time monitoring) • 3D virtual city models (for risk simulations)	UDT systems integrating participatory sensing with real-time data provide enhanced visibility of urban vulnerabilities, improving risk-informed decision-making for infrastructure management and disaster scenarios
White et al. (2021)	To integrate citizen feedback into urban planning and policy decisions using UDT	• IoT (for data collection) • 3D city models (for urban simulations) • Public participation platforms (for citizen feedback)	UDT systems incorporate citizen feedback to enhance urban planning decisions by integrating real-time data from IoT devices and enabling participatory simulations for urban development and disaster response
Henriksen et al. (2022)	To improve climate change adaptation, water management, and disaster risk reduction using UDT	• IoT (for real-time monitoring) • Big Data Analysis (for hydrological modelling) • Machine learning (for predictive modelling and downscaling) • DK-model HIP (for real-time data integration)	UDT system enhances climate resilience by integrating real-time data on groundwater, soil moisture, and streamflow, improving water security and disaster preparedness under climate change scenarios
(Omrany & Al-Obaidi, 2024)	To propose a framework for mitigating UHI effects by optimising urban greenery and enhancing urban planning	• IoT (for real-time environmental monitoring) • BIM/CIM (for digital representation and analysis) • Remote sensing (for urban microclimate data collection)	UDTs play a crucial role in monitoring urban heat dynamics and optimising strategies like urban greenery and climate-responsive design, helping cities enhance resilience to heat stress
Dani et al. (2023)	To develop a smart city platform for real-time monitoring and decision-making using UDT	• IoT (for real-time data collection) • 3D models (for urban simulation) • Augmented Reality (for data visualisation) • Unity engine (for integration of real-time data)	UDT-based platform enables real-time monitoring and supports urban decision-making by integrating data from IoT sensors, visualising it in 3D, and facilitating smart city management

decisions with real-time insights gathered from the community. In this way, the participatory elements within UMMC help bridge the gap between technological advancements in urban analytics and the human-centric objectives of urban governance.

All in all, the UMMC cluster shows the foundational role of data-driven technologies in enabling effective urban management, with real-time monitoring and predictive analytics playing a key role in optimising urban infrastructure and enhancing environmental resilience. By integrating these technologies with citizen engagement mechanisms, UMMC not only supports data collection but also ensures that public feedback directly informs decision-making processes, leading to more inclusive and responsive urban governance. Ultimately, the synergy between data analytics and participatory approaches strengthens the ability of urban systems to adapt to dynamic challenges, paving the way for smarter, more resilient cities.

3.1.2 UDT for Smart Urban Planning (USUP)

The keywords in this cluster indicate the application of UDT technology in urban planning as an instrumental tool for achieving sustainability goals in the built environment. This is reflected in Figs. 2 and 4, where keywords such as 'Urban Planning', 'Sustainable Smart Cities', and 'Sustainable Development Goals' demonstrate strong associations with terms from the USUP cluster, as well as with keywords from other clusters. In this research stream, the key aim is to utilise UDT technology to



Keywords	Urban Planning	Data Collection	Sustainable Development Goals	Urban Governance	Infrastructural Development	Semantic Modelling	Deep Learning	Technological Advancement	Sustainable Smart Cities	Sensor Analysis
Total Link Strength	133	107	55	48	39	31	30	26	25	21
Occurrences	20	16	9	7	5	5	4	3	3	4

Fig. 4 An illustration of the keywords within the USUP cluster and their interrelationships with keywords from other clusters. Note that the original figure has been edited to enhance the legibility of keywords

optimise urban development and making sure that cities meet sustainability goals while becoming more resilient and efficient. For instance, Schrotter and Hürzeler (2020) describe how the Digital Twin of Zurich can serve as a critical tool for urban planning, supporting sustainability goals by creating digital replicas of urban environments. This UDT allows for real-time data collection, simulation of urban dynamics, and the visualisation of potential scenarios for decision-making. The integration of 3D spatial data, advanced modelling, and sensor technologies facilitates collaboration between stakeholders, enabling more effective urban governance and planning processes to address issues like climate adaptation, infrastructural development, and urban densification. These capabilities demonstrate the pivotal role of UDTs in optimising urban development and ensuring sustainable city growth. In another study, Caprari et al. (2022) highlight how the UDT of Zurich may play a central role in advancing sustainable urban planning and development. The UDT enables real-time data collection, 3D spatial modelling, and dynamic simulations, allowing city planners to visualise and predict the outcomes of different urban scenarios. These capabilities are essential for addressing challenges such as urban densification, climate adaptation, and land-use competition. They stated that the UDT can provide decision-makers with accurate, data-driven insights that are crucial for synchronising urban development with broader sustainability goals. By linking the physical and digital worlds, the UDT helps optimise resource use, reduce environmental impacts, and enhance resilience, making it a powerful tool for creating sustainable, efficient, and adaptable urban environments.

The analysis also identified additional keywords in this cluster, highlighting the technologies essential for data analysis in UDT models, such as 'Deep Learning,' 'Semantic Modelling,' and 'Sensor Analysis.' Table 2 summarises a number of studies in the USUP cluster, including those that employed advanced analytical tools to process data for urban planning. For instance, Nazim and Joyce (2024) explored how deep learning, and generative urban design can be integrated with UDT models to enhance urban planning processes. Using the Virtual Singapore UDT platform, they implemented a generative design tool that utilises deep learning techniques to produce real-time urban prototypes. This tool, driven by Generative Adversarial Networks (GANs), allows urban planners to generate multiple design options for residential developments based on existing urban context and data. By leveraging deep learning, the study demonstrated how UDT technology can offer predictive planning and facilitate efficient, data-driven decision-making in urban environments. In another study, Austin et al. (2020) explored the integration of semantic modelling with machine learning in UDT systems to enhance smart city planning and operations. The study proposed a digital twin architecture where semantic knowledge representation works in conjunction with machine learning algorithms to process urban data, identify events, and support decision-making. They applied this framework to the analysis of energy usage in buildings in the Chicago Metropolitan Area, demonstrating how semantic modelling can help automate decision-making processes by providing contextual knowledge that complements data-driven insights. This approach enables the UDT to facilitate better planning and management of urban resources.

The results showed that UDT technology holds great promise in enhancing urban planning and sustainability by streamlining resource management and enabling informed, data-driven decision-making. However, significant challenges remain. Although technologies like deep learning and semantic modelling are increasingly being adopted, their integration is often constrained by issues such as inconsistent data standards, limited real-time processing capabilities, and the lack of seamless interoperability across different platforms (Fuller et al., 2020; Omrany et al., 2023). Furthermore, the scalability of UDT solutions poses a concern, particularly for smaller cities with limited financial and technical capacity. To fully leverage the benefits of UDTs in fostering sustainable urban development, it is crucial to address these operational and technological challenges. Additionally, there is a need for stronger collaboration among stakeholders to ensure that UDT technologies are accessible and can be applied across diverse urban contexts.

3.1.3 UDT Technology for Environmental Management (UTEM)

This cluster includes keywords such as 'Environmental Management,' 'Climate Change,' 'Urban Resilience,' 'Urbanisation,' and 'Future Cities,' which collectively indicate the role of UDT technology in enhancing environmental management within the built environment. These keywords suggest a focus on leveraging UDTs to address pressing global challenges by simulating and optimising urban systems to mitigate climate risks, improve resilience, and support sustainable urban growth (Argyroudis et al., 2022; Omrany et al., 2024b). For instance, Roudbari et al. (2024) demonstrated the potential of UDT technology in flood prediction and environmental risk management. Their study utilised graph neural networks combined with real-time environmental data to create a DT simulation for flood forecasting. By simulating flood events in Terrebonne, Canada, they were able to assess flood risks, enabling stakeholders to test mitigation strategies such as flood barriers. The application of DT technology in

Table 2 Analysis of five exemplary studies in USUP cluster in using UDT technology

Reference	Purpose of Using DT	Key Enabling Technologies	Key Findings
Schrotter and Hürzeler (2020)	To support urban planning, manage densification, and simulate urban climate impacts	• 3D spatial data (used for creating digital models and simulations) • GIS (for managing spatial data) • Real-time data (for live updates) • Open Government Data (for public collaboration)	UDT of Zurich enables simulations for urban planning, climate analysis, and land-use optimisation, providing critical insights for sustainable urban development
Caprari et al. (2022)	To support sustainable urban planning and decision-making through simulations and predictive modelling	• Geospatial technologies (GIS for spatial analysis) • IoT sensors (for real-time monitoring) • 3D spatial data (for modelling environments) • AI and Machine Learning (for predictive analysis)	UDTs provide critical data for urban governance, integrating simulations for planning, climate action, and urban resilience, demonstrating the potential for participatory, data-driven urban development
Nazim and Joyce (2024)	To integrate deep learning with UDT for generative urban design and predictive planning	• Generative Adversarial Networks (GANs for design generation) • 3D spatial data (for urban context modelling) • AI and machine learning (for predictive planning)	UDT of Virtual Singapore enables real-time generation of urban prototypes using deep learning techniques, improving planning and decision-making by providing multiple design options
Li et al. (2022a, b)	To enhance data transmission, analysis, and energy efficiency in smart cities using UDT	• IoT (for real-time data collection) • Big Data Analysis (for processing large urban data sets) • Convolutional Neural Networks (used for data analysis) • Multi-hop transmission (for optimised communication)	UDT system with deep learning optimises data processing, improves transmission speed, reduces delays, and enhances prediction accuracy for smart city management
Austin et al. (2020)	To enhance smart city planning and operations through integration of semantic modelling and machine learning in UDT systems	• Semantic modelling (for knowledge representation) • Machine learning (for data analysis and decision support) • IoT (for data collection)	The integration of semantic modelling with machine learning enhances UDT's ability to process urban data, identify events, and automate decision-making, improving urban planning and resource management

this context offers valuable insights into urban resilience and sustainable management of climate risks. In another study, Kwon et al. (2022) demonstrated the use of UDT technology in disaster management by developing a distributed computing framework aimed at improving disaster predictions, particularly for large-scale environmental events such as wildfires. Their study proposed the use of semantic data and convolutional neural networks to accelerate the simulation processes, which enabled real-time predictions and more effective responses to environmental changes. This approach highlights the potential of UDT technology to significantly enhance the resilience of urban areas against climate-related disasters by facilitating faster and more precise predictions and mitigation strategies.

As illustrated in Fig. 5, this cluster is strongly interconnected with other clusters, demonstrating the multifaceted nature of UDT technology in supporting urban systems. A notable example is the strong relationship between 'Urban Resilience', which has the highest occurrence and strongest connections in the network, and keywords like 'Building Energy Efficiency'. This connection underscores the critical role of energy-efficient buildings as a foundational element in enhancing urban resilience, suggesting that energy efficiency at the building scale is not just a component but a pivotal strategy

Keywords	Urban Resilience	Stakeholders Collaboration	Virtual Reality	Environmental Management	ITC	Urbanisation	Climate Change	Future Cities	Simulation Platform
Total Link Strength	94	54	53	51	32	29	25	22	21
Occurrences	14	7	7	7	5	4	3	4	3

Fig. 5 An illustration of the keywords within the UTEM cluster and their interrelationships with keywords from other clusters. Note that the original figure has been edited to enhance the legibility of keywords

for mitigating climate risks and ensuring long-term sustainability in urban environments. This is echoed in the research carried out by Alva et al. (2024) who present a UDT-based solution, the GHG App, designed to help mitigate operational greenhouse gas (GHG) emissions in ageing residential buildings. By combining real-time data with energy models, this UDT offers an interactive platform where decision-makers can simulate building energy use, forecast GHG emissions, and identify priority buildings for low-carbon interventions. In another research, Ohueri et al. (2023) explored the integration of IoT-based DT technology for reducing operational carbon emissions in building retrofits. The study highlighted that IoT-DT can enable continuous real-time monitoring of buildings, optimising systems such as HVAC to reduce energy consumption and carbon footprints in buildings. Mohamad Zaidi et al. (2024) also investigated the potential of UDT technology to mitigate energy consumption and carbon emissions in a tropical residential city in Malaysia. Using the iCL-iCD software, a UDT model of Bertam City was developed to simulate energy consumption and carbon emissions under various scenarios. The study found that implementing energy-efficient measures, such as improving building materials and HVAC systems, could reduce energy consumption and emissions by up to 39.5%. Additionally, integrating solar photovoltaic panels showed a potential 22.3% reduction in carbon emissions. The research highlights the effectiveness of UDT technology in achieving low-carbon city goals, demonstrating its potential as a valuable tool for urban planning in tropical environments.

Table 3 provides an analysis of five studies within this cluster, each demonstrating different approaches to utilising UDT technology. Studies in this group also capture the importance of using renewable energy, utilising UDT technology to assist in the integration and management of renewable energy systems within urban environments (Cao & Zhou, 2024; Li & Tan, 2023; Wang & Wang, 2024; Zhang & Feng, 2024). For instance, Wang and Wang (2024) demonstrated how UDT technology can optimise the placement and management of renewable energy sources in urban environments. Their study integrated solar, wind, and other renewable energy systems into smart city planning, providing real-time simulations to evaluate energy efficiency, environmental impacts, and cost-effectiveness. The UDT model enabled planners to assess various scenarios for minimizing carbon emissions and improving energy resilience, highlighting the technology's potential to support sustainable urban development. Li and Tan (2023) also proposed a framework integrating solar and wind renewable energy sources into smart city microgrids using UDT technology. Their study employed DT-based simulations to assess energy management strategies, including cost reduction and voltage stability, under various scenarios. The UDT model, fed with real-time data from smart meters and weather sensors, enabled accurate simulations of energy flows and optimization strategies. This demonstrated the potential of UDT technology to improve the efficiency and integration of renewable energy in urban power systems.

All in all, the studies in this cluster collectively highlight the transformative potential of UDT technology in enhancing energy efficiency, integrating renewable energy systems, and strengthening urban resilience. The findings demonstrate that UDT technology can play a crucial role in fostering smarter and more sustainable built environments by enabling real-time monitoring, predictive simulations, and advanced data analytics. These technologies not only optimise renewable energy systems' operation but also offer critical insights into mitigating climate change impacts. As UDT applications continue to advance, their role in creating sustainable and resilient urban environments becomes increasingly clear, underlining their potential to help cities achieve net-zero energy goals and improve overall environmental management.

3.1.4 UDT Technology for Decision Making (UTDM)

This cluster contains keywords that underscore the potential of UDT technology in supporting decision-making within the urban built environment. In this category, the term 'UDT' has the highest values for both 'occurrence' and 'link strength,' primarily due to its inclusion in the search syntax used to identify relevant materials. However, this keyword was retained in the analysis to prevent the omission of important terms related to UDT. Figure 6 provides a closer view of the keywords within this cluster, as well as those connected to them from other categories. Interestingly, keywords such as 'Urban Decision-Making,' 'Social Inclusivity,' 'Urban Energy Management,' and 'Healthy Urban Environments' emerged as the most prominent in this cluster. This may imply the significant role of UDT technology in facilitating key decision-making processes, including 'social inclusivity,' 'urban energy management,' and 'healthy urban environments'. The emergence of keywords such as '3D Visualisation' and 'Machine Learning' also highlights the growing reliance on advanced computational tools and immersive technologies in enhancing decision-making processes within urban environments, particularly in optimising resource management and visualising complex urban systems.

Table 4 presents a summary of five studies focused on the three primary research areas identified through scientometric analysis: 'Social Inclusivity,' 'Urban Energy

Table 3 Analysis of five exemplary studies in UTEM cluster in using UDT technology

Reference	Purpose of Using DT	Key Enabling Technologies	Key Findings
Roudbari et al. (2024)	To improve flood prediction and disaster management using UDT simulations	• Graph Neural Networks (for water systems modelling) • Unreal Engine (for UDT simulation) • Hydrometric data (as the source of real-time data) • Real-time monitoring sensors (for continuous updates)	UDT improved flood prediction accuracy and supported decision-making for mitigation strategies in the Greater Montreal Area
Kwon et al. (2022)	To accelerate disaster prediction services using UDT with a distributed computing framework	• Convolutional Neural Networks (for computing load prediction) • Distributed computing (to process large-scale disaster models) • Semantic data (for representing disaster states) • IoT sensors (for real-time data collection)	The UDT framework reduced prediction times by 38.5%, showing significant improvement in large-scale disaster prediction efficiency compared to previous methods
Alva et al. (2024)	To mitigate operational GHG emissions in ageing residential buildings using an UDT	• GHG App (for visualising GHG emissions) • City Energy Analyst (for simulating energy demands) • Multiple-Criteria Decision Analysis (for creating a Potential for Intervention map)	The GHG App enabled decision-makers to prioritize building interventions, improving energy efficiency and reducing carbon emissions in Singapore's residential buildings
Wang and Wang (2024)	To optimise renewable energy landscape design and support smart city net-zero planning using UDT technology	• Genetic Algorithm (for optimising energy source placement) • IoT sensors (for real-time data collection) • Reinforcement Learning (for load demand forecasting)	The UDT model optimised the placement of renewable energy sources, reduced carbon emissions, improved cost efficiency, and supported environmentally sustainable smart city development
Zhang and Feng (2024)	To improve the integration of tidal energy into smart cities through reliable forecasting using UDT technology	• Fuzzy Feature Selection (for extracting relevant features) • Long Short-Term Memory (for predicting tidal currents) • Whale Optimisation Algorithm (for optimising model parameters)	The UDT model accurately predicted tidal currents, optimising tidal energy placement and improving energy reliability in coastal regions, demonstrating its effectiveness in smart city energy planning

Keywords	Urban Digital Twin	Urban Decision Making	Social Inclusivity	3d Visualisation	Urban Energy Management	Machine Learning	Building Energy Efficiency	Healthy Urban Environments
Total Link Strength	329	154	130	99	67	45	26	21
Occurrences	61	21	18	15	10	8	4	4

Fig. 6 An illustration of the keywords within the UTDM cluster and their interrelationships with keywords from other clusters. Note that the original figure has been edited to enhance the legibility of keywords

Management,' and 'Healthy Urban Environments.' Regarding social inclusivity, Haraguchi et al. (2024) developed the CITYSTEPS Maturity Model to assess the governance implications of City-scale Digital Twins (CDTs). Their study explored how CDT technology can enhance urban governance by improving public participation, transparency, and decision-making processes. The proposed model highlights the different stages of CDT development, from basic planning to real-time synchronisation and autonomous decision-making. CDT technology, using AI and dynamic data integration, enables cities to simulate urban phenomena and assess the impacts of policy changes in real-time. Despite its potential, the study emphasised challenges such as the exclusion of marginalized groups from CDT data, privacy concerns, and the need for unbiased data collection to ensure social inclusivity in smart city designs. In another study, Francisco et al. (2020) proposed a DT-enabled energy management platform for real-time urban building energy benchmarking. The study employed smart meter data to develop temporally segmented energy benchmarks, identifying periods of inefficiencies and overperformance. By segmenting energy consumption data into specific time frames, such as occupied and unoccupied periods, the UDT model provided more accurate insights compared to annual benchmarks. This approach enabled cities to prioritize building retrofits and optimise energy management, showcasing the potential of UDT technology to enhance urban energy efficiency through more targeted and dynamic strategies.

Table 4 Analysis of five exemplary studies in UTDM cluster in using UDT technology

Reference	Purpose of Using DT	Key Enabling Technologies	Key Findings
Haraguchi et al. (2024)	To assess governance and social implications of city-scale digital twins using a maturity model	• Data integration for real-time simulations • (OpenStreetMap, Maptionnaire, web-based 3D tools, interactive games in Zurich) • IoT and sensor networks • Machine learning for decision-making processes	The model showed enhanced public participation in urban planning, but challenges persist with social inclusion of marginalised groups, transparency, and data collection biases. Authors recommended unbiased data collection and transparent governance practices
Yossef Ravid and Aharon-Gutman (2023)	To introduce the concept of Social UDT and explore its role in integrating social issues with urban planning	• 3D City Modelling using a Vector-based model (LOD 2.3 from Systematics, based on aerial photographs) • Hyper-realistic 3D model (created by Simplex with a 3 cm per pixel resolution using aerial photography and onboard algorithms) • GIS for social insights • IoT and Data Collection Tools • Algorithmic Analysis for Social Data Integration	The proposed framework emphasised the integration of physical and social elements in urban environments. A Haifa case study showed UDT's potential to address social issues like aging, gentrification, and inequality, with key challenges being ethical data use and enhancing social inclusivity in smart city designs
Francisco et al. (2020)	To assess energy management in smart cities through real-time urban building energy benchmarking using UDT	• Smart meter data integration for real-time energy monitoring • Temporally segmented energy benchmarking • Machine learning for energy efficiency analysis • IoT infrastructure for real-time data collection	UDT-enabled energy management platforms allow real-time monitoring and benchmarking of building energy performance. Temporally segmented benchmarks showed specific periods of inefficiencies or overperformance, leading to more precise retrofit strategies and energy management decisions
Xu and Liu (2024)	To propose an energy management system integrated into an UDT to optimise urban energy management and transition	• Smart meters (used for real-time energy monitoring and two-way communication) • Gray Wolf Optimisation Algorithm (used for optimising load scheduling, reducing power costs, and improving peak-to-average ratios) • Day-ahead pricing methods (used for forecasting energy prices and enabling cost-efficient load scheduling) • Automatic operation machines (operate based on real-time data for optimal energy usage)	Integration of an UDT into urban energy management enabled real-time monitoring, load scheduling, and predictive modelling
EL Azzaoui et al. (2021)	To create a secure and real-time system for managing public health in smart cities using UDT and Blockchain	• UDT for real-time monitoring of individuals and hospitals • Blockchain for secure and immutable data handling • IoT for health data collection	The framework integrates blockchain with UDTs for secure, real-time health monitoring. It helps track disease outbreaks, manage medical resources, and predict health crises in smart cities

This paper has also identified studies that focused on leveraging the potential of UDT technology for creating healthy environment (EL Azzaoui et al., 2021; Gholami et al., 2022; Ramani et al., 2023). For instance, EL Azzaoui et al. (2021) proposed a Blockchain-based Secure UDT Framework aimed at creating smart, healthy cities. Their study utilised UDT technology to monitor real-time health data from individuals and healthcare institutions, enabling the simulation of urban health scenarios and the optimisation of medical resources. The proposed UDT system helped predict disease spread, manage healthcare resources effectively, and provide personalised healthcare strategies. Ramani et al. (2023) developed a dynamic UDT to integrate longitudinal thermal imagery for studying microclimates at the neighbourhood scale. Their UDT model combined thermal images, captured through an infrared observatory, with a virtual 3D model of buildings at the National University of Singapore. This enabled real-time analysis of surface temperatures and their contribution to the UHI effect. The application of UDT technology offers urban planners the potential to design more comfortable and healthier urban environments by identifying and addressing microclimate challenges such as UHI effects effectively.

UDT technology has proven to be a powerful tool for facilitating informed decision-making processes in urban environments. By integrating advanced technologies such as 3D visualisation and machine learning, UDTs allow for the analysis of complex data in real time, helping urban planners address issues related to social inclusivity, energy management, and the creation of healthier urban spaces. However, while the benefits of UDT technology are evident, challenges such as data privacy and equitable access to its benefits remain critical areas for further exploration. Future advancements in this field must focus on addressing these challenges to fully unlock UDT's potential in urban decision-making processes.

3.1.5 UDT for Smart and Sustainable Cities (USSC)

This cluster contains keywords that emphasise the role of UDT technology in enabling smart cities to achieve their sustainability goals. Figure 7 illustrates these keywords, displaying their occurrence and total link strength values. Notably, 'smart cities' stands out with the highest values for both occurrence and association with other terms in this cluster, largely due to its inclusion in the search syntax. Beyond this term, keywords such as 'GIS,' 'BIM,' 'Real-time Data,' 'Real-time Analysis,' and 'Information Systems' indicate the integration of technologies essential for modelling, data analysis, and real-time decision-making within UDT frameworks. These technologies enhance UDT's ability to monitor urban infrastructure, optimise resource management, and support responsive service delivery, thereby contributing to the functionality of smart cities (Omrany & Al-Obaidi, 2024).

Table 5 summarises five exemplary studies in this category, addressing three primary research areas identified through scientometric analysis: 'Citizens' Quality of Life,' 'Green Construction,' and 'Renewable Energy.' The analysis reveals keywords such as 'Citizens' Quality of Life,' indicating the potential of UDT technology to enhance urban living standards. UDTs contribute to enhancing citizens' quality of life through real-time data and predictive analytics, which inform urban planning and resource allocation, making cities more adaptable and responsive to the evolving needs of their residents. For instance, through precise monitoring of air quality, noise levels, and traffic congestion (Jiang et al., 2022; Kumar et al., 2018; Raes et al., 2021; Tancev & Toro, 2022), UDTs can potentially allow city authorities to implement targeted environmental and infrastructural interventions that improve health outcomes and reduce daily stressors for residents. This is reflected in the findings of Raes et al. (2021), who introduced the DUET framework to build interoperable and trusted digital twins for smart cities. The DUET framework integrates real-time data on traffic, air quality, and noise pollution, enabling urban planners to simulate "what-if" scenarios and assess the impacts of policy changes. This data-driven approach provides city authorities with actionable insights, allowing for the implementation of targeted interventions to reduce pollution and improve urban living conditions, thereby contributing to a healthier and more sustainable environment. In another study, Tancev and Toro (2022) proposed a UDT framework designed for air quality monitoring networks in smart cities. Their study integrates low-cost air quality sensors with high-resolution air pollution models based on partial differential equations, enabling continuous monitoring and recalibration of sensors. The UDT model was able to combine real-time measurements with predictive pollution models, allowing urban authorities to manage air quality proactively and make targeted environmental interventions. This approach demonstrated how UDT technology can enhance public health by reducing pollution exposure and enabling responsive, data-driven adjustments to improve urban air quality.

The findings also highlighted significant interest in leveraging UDT-driven approaches to promote green construction within the built environment. For instance, Yevu et al. (2023) demonstrate how DT-based technology supports green construction by optimising material tracking, managing logistics, and monitoring carbon emissions in real time within the prefabrication supply chain. The adoption of this approach can potentially enhance efficiency and reduce environmental impacts

Keywords	Smart Cities	Sustainable Urban Development	Citizens' Quality of Life	Real-time Data	GIS	Information Systems	Real-time Analysis	BIM	Predictive Control Systems	Green Construction	Renewable Energy	Optimised Performance
Total Link Strength	222	70	55	49	48	30	28	27	24	20	18	17
Occurrences	32	9	7	7	7	3	3	4	3	4	4	3

Fig. 7 An illustration of the keywords within the USSC cluster and their interrelationships with keywords from other clusters. Note that the original figure has been edited to enhance the legibility of keywords

in the built environment. Liu et al. (2023a, b) developed a six-dimensional DT model for managing green construction in prefabricated buildings, integrating real-time monitoring and data visualisation to optimise environmental performance. This model captures core green construction elements across physical and virtual spaces, including energy consumption and material usage, and applies an evolution mechanism to adapt the model throughout construction stages. The study demonstrated that using DT for green construction management in prefabricated projects reduces pollution, energy consumption, and waste, underscoring the potential of this technology in advancing sustainable construction practices.

Another research area surfaced in the scientometric analysis was 'renewable energy,' indicating the contribution of UDT technology in supporting the development of low-carbon urban environments. This emphasis on renewable energy suggests that UDT technology can facilitate the integration of sustainable energy sources, such as solar and wind, into urban infrastructure, enabling more efficient energy management and reducing the city's overall carbon footprint (Chen et al., 2024; Liu & Zhang, 2024; Zhao & Zhang, 2024). For instance, Zhao and Zhang (2024) presents a multi-microgrid management framework that integrates UDT technology to support renewable energy usage in urban settings, with a goal of achieving net-zero emissions. By employing advanced algorithms, including Long Short-Term Memory (LSTM) and Covariance Matrix Adaptation (CMA), the framework enables precise energy forecasting and adaptive decision-making. The DT model leverages real-time data from smart meters and Non-Intrusive Load Monitoring (NILM) to optimise demand response and reduce inefficiencies, ultimately enhancing energy efficiency, reliability, and resilience in urban microgrids. Liu and Zhang (2024) also explored the application of UDT for achieving net-zero emissions within smart cities through renewable energy integration. Their model employs techniques like artificial

Table 5 Analysis of five exemplary studies in USSC cluster in using UDT technology

Reference	Purpose of Using DT	Key Enabling Technologies	Key Findings
Raes et al. (2021)	To build an interoperable and trusted UDT framework for smart cities, supporting decision-making for urban planning	• Data Integration APIs (for real-time data from traffic, air quality, and noise sensors) • T-Cell Architecture (for secure, modular data sharing) • Simulation Engines (for "what-if" scenario modelling)	The DUET framework, implemented in cities like Athens and Flanders, supports real-time "what-if" scenario analysis, offering insights for policy adjustments. The framework facilitates targeted interventions to improve air quality, reduce noise, and manage congestion, enhancing urban liveability
Tancev and Toro (2022)	To develop a UDT framework for air quality monitoring, enhancing measurement accuracy and maintenance efficiency in smart cities	• Low-Cost Sensors (for real-time air quality data collection) • Partial Differential Equation Models (for high-resolution air pollution simulations) • Online Calibration Protocol (for continuous sensor recalibration based on DT data)	The UDT framework enables dynamic recalibration of air quality sensors and improves pollution monitoring accuracy, supporting proactive urban environmental management
Liu et al. (2023a, b)	To develop a six-dimensional UDT model for managing green construction in prefabricated buildings, focusing on reducing pollution, energy consumption, and waste	• RFID and QR Codes (for material tracking) • Sensors (for real-time monitoring of energy use, pollution, and material status) • HuiZhu-BIM Platform (for data integration and visualisation)	The DT model promotes sustainable construction by monitoring resources, reducing waste, and optimising logistics in real time, with continuous updates enhancing green practices throughout project phases
Zhao and Zhang (2024)	To develop a multi-microgrid management framework using DT to support renewable energy integration and achieve net-zero emissions in urban areas	• Long Short-Term Memory (LSTM) (for energy forecasting) • Covariance Matrix Adaptation (CMA) (for adaptive decision-making) • Smart Meters and NILM (for real-time data collection)	The UDT framework enhances energy efficiency and resilience in urban microgrids by optimising demand response, minimising inefficiencies, and supporting renewable energy usage, contributing to net-zero goals
Liu and Zhang (2024)	To develop a short-term load forecasting model within a UDT framework to support renewable energy integration in smart cities	• (for relevant data filtering) • Modified Flower Pollination Algorithm (MFPA) (for error reduction) • ANNs (for rapid and accurate load forecasting)	The UDT model achieved a high accuracy rate of 99.5% and reduced runtime by 52.38%, optimising load forecasting and enhancing renewable energy integration in smart city infrastructures

neural networks (ANNs) and modified flower pollination algorithms (MFPA) to enhance short-term load forecasting (STLF) for renewable energy management. The study demonstrates the UDT model's capability to optimise energy predictions with 99.5% accuracy and reduce runtime by over 50%, promoting more efficient and sustainable energy use across urban infrastructures.

In summary, the findings highlight UDT technology's promising potential to foster healthier urban environments that improve quality of life, advance green construction practices, and support the planning of low-carbon urban landscapes. With capabilities in real-time monitoring and informed decision-making, UDT stands out as a crucial tool for building sustainable, resilient cities.

3.2 Content analysis of industry reports

The comparative analysis of various reports on UDT technologies showcases promising advancements in urban planning, sustainability, and infrastructure management, demonstrating the transformative potential of DTs in enhancing city operations (Table 6). However, a notable gap remains in the absence of a standardised guideline or unified framework for developing and deploying UDTs across different urban contexts. Despite numerous studies and frameworks proposed—each with distinct models for integration, governance, and application—there is no universally accepted pathway to guide cities in building efficient and scalable UDTs. For example, while reports such as those from World Economic Forum (2022) and Price Waterhouse Coopers (2022) offer models for urban planning and smart city management, they vary greatly in their technological approaches and data governance strategies, often leading to inconsistent performance and scalability. This fragmentation poses a serious hurdle to the broader adoption of UDTs, as the lack of standardisation leads to inefficiencies in cross-sector collaboration and data sharing. Without a clear, structured process—akin to a recipe that guarantees accuracy when followed—future advancements in UDTs technology risk being slowed by inconsistent implementations and misaligned objectives. Therefore, a globally recognised guideline or protocol for UDT development, coupled with well-defined key performance indicators (KPIs) to measure performance, scalability, and efficiency, is essential to ensure that diverse implementations are interoperable and capable of driving the full potential of UDTs in urban environments.

A closer look into the implementation of UDT technologies, as presented in Table 6, reveals that most applications have been carried out in smaller cities. This trend may stem from the fact that smaller and medium-sized cities (SMCs) often serve as more manageable environments for piloting and testing new technologies. As indicated by Anschütz et al. (2024), SMCs may have populations ranging from 5,000 to < 100,000, and their urban systems are generally less complex compared to larger cities with populations exceeding 100,000. This simplicity allows for easier implementation, monitoring, and evaluation of UDT technologies. Furthermore, SMCs often face unique development challenges, such as limited funding and urban growth constraints, which can be addressed through the adoption of smart technologies (Iammarino et al., 2019; Weck & Beißwenger, 2014). By integrating UDT solutions, SMCs can modernise infrastructure, stimulate economic growth, and enhance their appeal to residents and businesses (Anthopoulos et al., 2019). In this way, SMCs striving to become smart cities are better positioned to manage urban populations and foster stronger links between citizens, governments, and economies. Anschütz et al. (2022) highlighted that successful smart cities should target at integrating six key domains: people, government, economy, mobility, living, and environment, all of which can benefit significantly from UDT applications.

On the other hand, the focus and popularity of UDTs in smaller cities may align with the concept of the 15-min city. This concept envisions urban environments where residents can meet six essential needs—living, commerce, work, education, healthcare, and entertainment—within a 15-min walk or bike ride from their homes (Moreno et al., 2021). It offers an appealing alternative by recognising fundamental urban principles and advocating for a return to proximity-based living (Moreno et al., 2021). To achieve this, the 15-min city emphasises four key elements: density, proximity, digitalisation, and diversity (Teixeira, et al. 2024; Moreno et al., 2021). By promoting urban accessibility, sustainable mobility, and liveability, the 15-min city has gained significant traction in public discourse. It has inspired a movement of advocates who support the development of small, human-scaled, walkable, and diverse urban forms, reducing reliance on motorised transportation and private cars (Mouratidis, 2024).

Further, Moreno et al. (2021) argued that digitalisation can facilitate the application of these principles by enabling remote work, enhancing citizen participation through digital tools, and supporting the development of innovative sustainable transportation options such as shared mobility. However, the successful implementation of the 15-min city concept largely depends on contextual factors, including demographics, urban morphology, local socio-economic structures, and institutional frameworks (Teixeira, et al. 2024; Moreno et al., 2021). In recent years, nearly a hundred cities have expressed interest in adopting the 15-min city model, with cities

Table 6 Analysis of ten industry reports on UDTs

Ref	Key focus areas	Technological approach	Data governance and interoperability	Primary applications	Gaps/limitations
Industry (2021)	Sustainability via virtual twins: circular economy, carbon reduction, operational efficiency	Real-time digital twins integrating AI, IoT, cloud computing for lifecycle optimisation and resource efficiency	Focus on secure, transparent data continuity across lifecycles to enhance material recovery and operational performance	Urban planning, building efficiency, traffic optimization, energy management (e.g., Virtual Singapore)	Challenges in measuring return on investment (ROI); lack of leadership for large-scale implementation; scalability challenges; privacy and ethical concerns
Griffith and Truelove M. (2021)	Federated ecosystem of spatially enabled UDTs for urban planning and infrastructure management	Spatially enabled UDTs using real-time data, IoT integration, and a federated model to allow cross-sector data sharing without centralised storage	Emphasis on secure, federated data sharing with role-based access and data standards. Supports both open and closed data sharing models	Urban planning, infrastructure management, city-wide integration of UDT data, enabling interoperability across government, industry, and research sectors	Limited focus on privacy challenges, unclear real-time implementation strategies, and lacking in-depth guidance for smaller jurisdictions with fewer resources
Capgemini Research Institute (2022)	Enhancing sustainability, operational efficiency, and business models through DTs	Real-time UDTs using IoT, AI, and cloud integration. Focus on lifecycle optimisation, predictive maintenance, and scenario modelling	Emphasises the need for data continuity and integration across systems. Highlights challenges in API integration and cloud infrastructure deployment	Traffic optimisation, energy efficiency, and sustainability, especially in urban planning and industrial systems (e.g., Virtual Singapore and NTU in Singapore)	Limited global scalability insights, with a strong focus on case studies in specific regions. Lack of detail on real-time privacy and data security challenges
ARUP (2019)	Dynamic UDTs for urban planning, transport, energy, and water management	Real-time data, AI, IoT, and machine learning. Proposes a UDT maturity model	Focus on data interoperability and governance for urban sectors	Infrastructure, energy, transport, and water management	Lacks metrics for implementation in smaller cities, limited focus on privacy and ethics
Price Waterhouse Coopers (2022)	Smart city development through UDTs, focusing on urban planning, operations, and sustainability	Real-time data integration, AI, IoT, and simulations to enhance city management and sustainability	Stresses the need for robust data governance, privacy, and regulatory frameworks. Emphasises data-sharing and collaboration across sectors	Urban planning, traffic optimisation, infrastructure management, and reducing carbon emissions	Lacks focus on privacy concerns, limited practical guidance for scaling in diverse urban contexts
World Bank Group (2022)	Institutionalising smart cities through legal frameworks, innovation ecosystems, and platforms in Korea	Focus on ICT, data infrastructure, AI, IoT, and UDT integration for urban management	Strong emphasis on data governance, privacy, and security regulations, enabling open data and cross-platform interoperability	Urban planning, transportation, energy efficiency, and disaster management	Limited insights on challenges of scaling for smaller cities, with little attention to real-time data privacy and ethical concerns
IEC (2021)	Integration of CIM and UDTs to improve urban planning, management, and sustainability	Use of CIM and UDT for data processing, urban analysis, and simulation. Integration of real-time data, IoT, GIS, and AI for smart urban decision-making	Emphasis on open standards, multi-scale data integration, and cross-sector collaboration to ensure interoperability and data governance	Urban planning, infrastructure management, spatial analysis, and decision-making. Case studies from Nanjing and NSW on UDTs for city management	Lack of specific metrics for smaller cities, limited guidance on data privacy and governance challenges across diverse regions
ANZLIC (2019)	Establishing principles for spatially enabled UDTs to improve urban and environmental planning, focusing on interoperability and collaboration	Use of 3D/4D spatial data, IoT, and AI to integrate real-time data with DTs for enhanced urban and environmental management	Emphasises open data, federated models, role-based access, and secure data sharing across industries and government	Urban planning, infrastructure management, environmental monitoring, and smart city initiatives	Limited focus on privacy challenges and real-time dynamic scaling for smaller municipalities

Table 6 (continued)

Ref	Key focus areas	Technological approach	Data governance and interoperability	Primary applications	Gaps/limitations
World Economic Forum (2023)	Development of UDT cities through multistakeholder collaboration, urban sustainability, and smart city governance	SODPA model: strategy, operations, data, platform, and applications. Integration of IoT, AI, and 3D modelling for real-time urban management	Emphasis on privacy, data quality, and cross-platform data sharing for city-wide applications. Advocates for strong public–private partnerships	Urban planning, infrastructure management, public services, and transportation optimisation	Limited practical insights on scaling for smaller cities and addressing real-time privacy issues in smart city data management
World Economic Forum (2022)	Framework for developing UDTs focused on urban management, sustainability, and enhancing city services	Integration of IoT, AI, BIM, and 3D modelling for real-time urban management and decision-making through a 4 + 5 model framework (infrastructure, data, platform)	Emphasis on open standards, data-sharing protocols, and privacy protection to enable cross-sector collaboration in city management	Urban planning, infrastructure management, energy optimisation, and emergency response (e.g., Xiong'an, Shenzhen, New South Wales)	Limited attention to challenges in scaling for smaller cities and insufficient discussion on real-time privacy concerns and implementation hurdles

like Edinburgh, Milan, and Paris making notable progress in turning their plans into reality. These examples highlight the relevance of UDTs' focus on smaller cities, aligning with their potential to support the principles of the 15-min city.

4 Discussions

The findings identified overlaps among topics, reflecting the interconnected nature of UDT applications and shared goals in addressing urban challenges. These overlaps highlight the need for further discussion to clarify the unique contributions of each research cluster. Across all clusters, technology—both digital and physical—emerged as a central theme, with studies and reports consistently focusing on four key areas: monitoring, management, planning, and decision-making. These areas are closely tied to Sustainable Development Goal (SDG) 11, which promotes resilient, inclusive, and sustainable cities. Integrating insights from research clusters was identified as a way to advance holistic solutions for smart cities. However, industry reports highlighted challenges such as inconsistencies in focus areas, the lack of specific metrics, scalability issues for smaller cities, and concerns over data privacy. The analysis of these issues was conducted by examining the core content of each topic and evaluating the factors discussed earlier. Figure 8 illustrates the research process developed to clarify the distinctions among the five clusters. This process follows a structured three-stage approach: (1) *Stage 1* – Bibliometric analysis, using keyword co-occurrence analysis to map research trends; (2) *Stage 2* – Assessment through systematic analysis to evaluate the scope and interconnections of the identified topics; and (3) *Stage 3* – Classification via content analysis to categorise and refine key themes. This structured methodology provides a comprehensive framework for identifying UDT pathways and understanding their broader implications.

In *Stage 1*, the research identified five clusters within UDT, highlighting complex intersections, as illustrated in Figs. 3, 4, and 5. These overlaps suggest a lack of clarity in distinguishing the defining characteristics of UDT. To address this, *Stage 2* systematically analysed each cluster, categorising research based on the purpose of using DT, key enabling technologies, and key findings (as detailed in Tables 1, 2, 3, 4 and 5). Additionally, Table 6 summarises major aspects from industry reports, focusing on key areas, technological approaches, and primary applications. The findings revealed a shared technological approach across studies, yet complexities arose due to overlapping uses of DT and its primary applications. Consequently, *Stage 3* was developed to classify the content of each cluster and examine their integration in advancing effective UDT applications, as presented in Fig. 9. This stage systematically categorises six key areas and their attributes: *Monitoring and Controlling* (11 attributes), *Urban Planning* (13 attributes), *Environmental Management* (11 attributes), *Decision-Making* (9 attributes), *Technologies* (13 attributes), and *Integrated Models for Sustainable and Smart Cities* (12 attributes).

The proposed model restructures UDT literature by introducing a new framework to interpret and correlate the identified content. Figure 9 highlights the critical attributes present in the literature that shape the organisation and development of UDTs, guiding their role in fostering resilient and sustainable cities. This model provides a structured approach to identifying challenges, including existing limitations and key areas for future research.

5 Challenges and recommendations for future development of UDTs

Urban environments are becoming increasingly complex, and UDT can distinguish itself as a vital tool for helping decision-makers optimise urban development. Despite considerable progress in the development and application of UDTs, substantial gaps remain that should be addressed to fully realise their potential. This section highlights several key directions for future development in the field.

- *Data management*: Several research applications were proposed to amplify the power of data that include designing with the data-mechanism-fused (DMF) to overcome issues by integrating BIM, data mining, and physical mechanisms in digital twin (Wang et al., 2024). Device recognition assistants were developed as a data management method for Digital Twins to structure the communicated raw data based on time series classifiers (Dittmann et al., 2024). However, several research gaps are identified including limitations with data management in DT such as relying on a two-dimensional excavation mechanical model. More research and optimisation are required to address the algorithms' accuracy on test data. Precision of semantic interaction norms is especially difficult due to the complexity of the urban system (Austin et al., 2020). Data heterogeneity between scales varies in accuracy and detail level (Scalas et al., 2022). Addressing challenges in data privacy and security is crucial, given the sensitive nature of urban data (Papyshev & Yarime, 2021). Additionally, improving the accuracy and quality of data, especially from IoT sensors is limited. Inconsistencies and gaps in data collection and analysis can undermine the effectiveness of UDTs, and addressing these issues will be key to building reliable systems

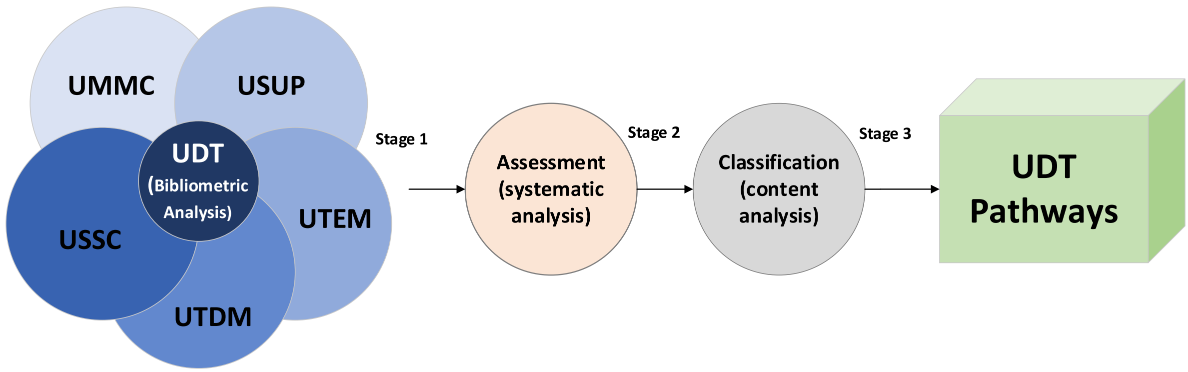


Fig. 8 Developed research process to identify UDT pathways

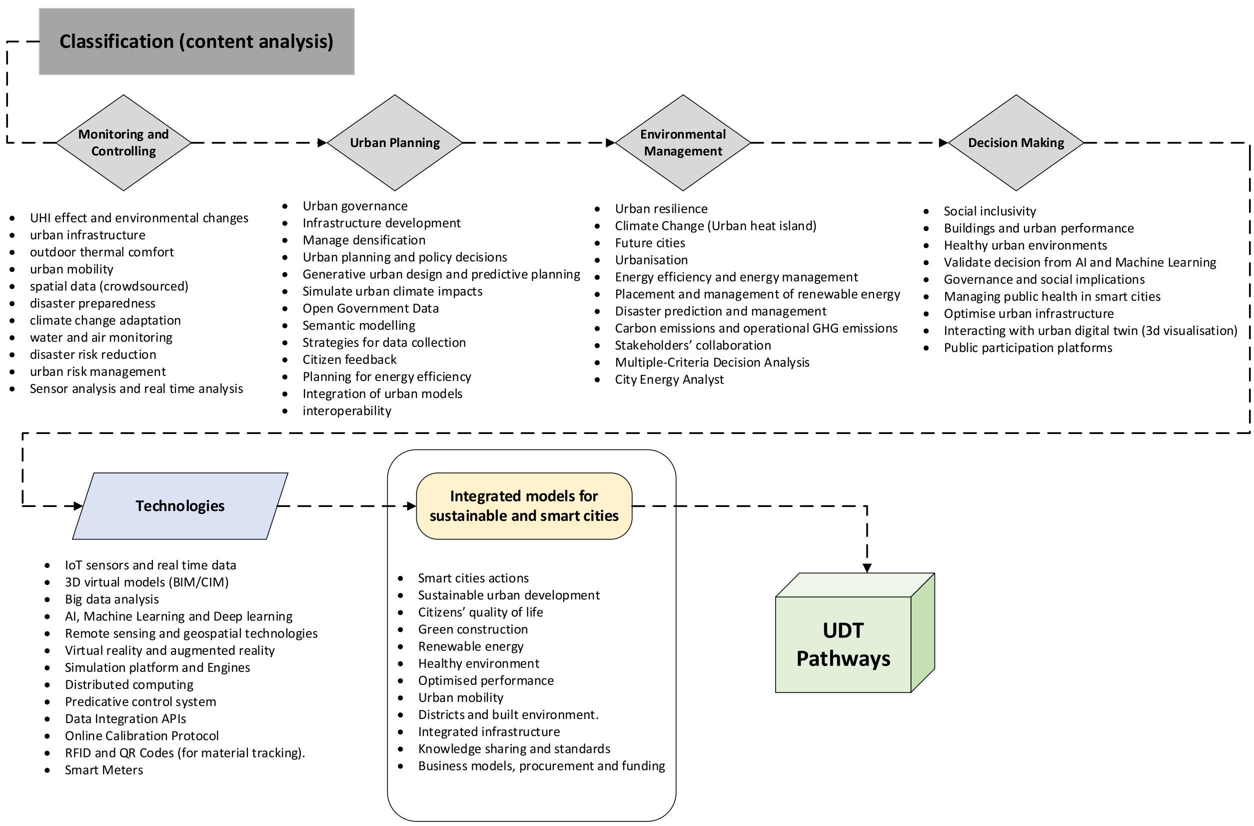


Fig. 9 Classifications of research outcomes towards UDT pathways

(Masoumi et al., 2023; Omrany et al., 2024b). Therefore, future development of UDTs should prioritise robust data management systems that can integrate and ensure interoperability across diverse platforms, such as BIM (Cureton & Hartley, 2023), GIS (Masoumi et al., 2023), and other digital platforms. Seamless interoperability should be a key focus moving forward, as it will enable comprehensive management of complex urban systems. Thus, future research should focus on strengthening cybersecurity frameworks and advancing privacy-preserving analytics to maximise data utility while safeguarding individual rights.

- *Technology integration*: Esri UK (Esri UK, 2024) a pioneer in solving urban problems using GIS, indicated that current solutions in DT technologies include advanced data integration, dynamic modelling and an immersive environment. Current technologies cover interactive models in the form of 3D with accuracy positions that transform collaboration and problem-solving. These technologies simulate and predict outcomes and make complex systems easier to comprehend. However, several research gaps are detected such as the use of AI and ML in predictive analytics and decision-making in urban planning is increasingly becoming popular, still its potential is yet to be harnessed (Bibri et al., 2024; Wajid et al., 2024). Visual tools are still in an early stage to allow planners to make informed decisions that improve city resilience. Leveraging advancements in AI, IoT, and distributed computing architectures—such as edge and fog computing is limited in research that could assist in improving the real-time processing and responsiveness of UDTs (Omrany et al., 2024b). Therefore, enabling more efficient management of urban environments and fostering innovation. The expansion and accuracy of IoT and sensor networks will be essential for comprehensive urban monitoring, enabling cities to gather real-time data on various aspects, such as traffic flow and environmental conditions (Abdeen et al., 2023; Deng et al., 2021a, b). Exploring simulation and modelling tools, particularly those that offer enhanced 3D modelling and real-time simulations, will be vital for visualising potential urban developments and emergency scenarios (Scalas et al., 2022).

- *Governance and policy involvement*: Several studies conducted on creating a framework for evaluating UDTs' involvement in city governance. Diaz-Sarachaga (2025) evaluated the impact of urban digital twins on city government, the study created a novel scoring system. A recent study introduced CITYSTEP Maturity model as a new maturity framework for city-scale digital twins. The proposed framework was developed for improving public involvement in urban planning and tackling important issues with smart cities, like transparency and accountability (Haraguchi et al., 2024). However, several research gaps are found such as ethical considerations that are central to governance, especially in balancing the needs for public safety and urban security with individual privacy rights. Transparent governance models are required to foster public trust, ensuring that UDT data is used responsibly and fairly. Equitable access to the benefits of UDTs should be guaranteed, with policies that prevent digital divides and ensure that all urban communities—regardless of socioeconomic status—can benefit from the transformative potential of UDTs. UDT-specific regulations should be developed to ensure smooth integration across different sectors while safeguarding intellectual property rights, promoting innovation, and avoiding exploitation of proprietary technologies (Papyshev & Yarime, 2021). Therefore, potential areas for future research cover developing legal and regulatory frameworks to address the unique challenges these technologies present, such as data ownership, cross-border data sharing, and liability issues arising from the use of UDTs in urban management (Lei et al., 2023). Additionally, Create models of Transparent and governance and Equitable access. Exploring the Involvement of policymakers, urban planners, and community stakeholders in the governance process will be crucial to establishing frameworks that are both inclusive and adaptable to the fast-evolving nature of UDT technology.
- *Social and cultural integration*: The review identified limited research in this area that particularly were conducted on the integrations of social and cultural aspects in digital twin. For example, Yossef Ravid & Aharon-Gutman., (2023) stated that to create a social turn in the realm of smart cities and urban innovation, developing a UDT with a social focus requires interdisciplinary expertise from the domains of sociology, anthropology, planning, and ethics studies. The study explored the Social Urban Digital Twin through the application of technology instruments from the progressive development field that integrates critical theory and applied practice to advance social policy. Ye et al. (2023) found that public involvement also enhances the collective knowledge base, allowing urban planners to draw on the lived experiences and insights of residents, which can lead to more effective and context-sensitive urban solutions. However, several research gaps are identified including UDT design requires an understanding of local values, norms, and practices to ensure that UDTs are not only technically effective but also socially meaningful. adapting UDTs to different urban environments—whether in densely populated metropolitan areas or rural settings—is critical for ensuring their wide applicability. In rural contexts, for instance, UDTs may need to focus on different priorities, such as agricultural management or basic infrastructure development, while in urban centres, the focus may shift towards congestion management, minimising UHI effects or optimising energy efficiency. As such, ensuring UDTs are flexible enough to operate effectively across these diverse settings will be key to their long-term success and adoption. Therefore, potential areas for future research cover options to engage the public in the creation and utilisation of UDTs to ensure their success and relevance in urban environments (Yossef Ravid & Aharon-Gutman, 2023). Explore active public participation to

align UDT initiatives with the needs and priorities of local communities, improving acceptance and fostering a sense of ownership among citizens.

- *Sustainability and resilience*: Several studies examined the concept of UDT towards Sustainable Development Goals. Patel et al. (2024) reviewed the DT for sustainable urban development. The results point to important issues that prevent broad adoption, such as data integration, cross-sector cooperation, and governance impediments. The study also establishes connections between the advantages, difficulties, and implications of different Digital Twin Technology applications. For example, by facilitating better decision-making, data integration advancements not only increase operational effectiveness but also fortify urban resilience. Omrany et al. (2024a) investigated the use of DT technology in supporting social sustainability by exploring 17 UN Sustainable Development Goals (SDGs). The findings indicated a significant emphasis on SDG11 (77 publications), followed by SDG3 (58 studies) and SDG9 (48 research). Although UDT design, installation, and maintenance require a wide range of technical skills (Ferré-Bigorra et al., 2022), developers and systems engineers are scarce in the infrastructure and construction sectors. Additionally, when teams hire individuals from different disciplines for digital twin projects, collaborations suffer from a lack of literacy and understanding between disciplines (Broo et al., 2022). However, several research gaps are identified including a technology-focused development that requires both organisational learning (collaboration) and individual skills (upskilling) (Nochta et al., 2021). Concerns about the shortage of skilled human resources frequently result in the outsourcing of information technology (IT) services, which has drawbacks (reliance on outside companies, lack of technical know-how in local governments, open standards not followed in practice, etc.). There is limited consideration of sustainable dimensions for ensuring the long-term success of UDTs, particularly in addressing the pressing challenges of climate change and resource management (Therias & Rafiee, 2023). There is a gap in providing data-driven insights into emergency preparedness, UDTs significantly bolster urban resilience, helping cities better anticipate and respond to potential threats (Ford and Wolf, 2020). Specific models of simulations enable urban planners to visualise potential climate risks, such as rising sea levels or heatwaves, and implement mitigation efforts tailored to local vulnerabilities (Argyroudis et al., 2022; Henriksen et al., 2022; Therias & Rafiee, 2023). Therefore, potential areas for future research cover developing optimisation models of UDTs to optimise the management of key resources, including energy and water, by modelling consumption patterns and integrating renewable energy sources, contributing to more sustainable urban living. Further examination and empirical analysis of UDT sustainability ramifications is necessary, especially for equality, economic growth, and community well-being. Additionally, to understand the resilience of UDT in urban contexts, it is necessary to look at governance structures, business models, and regulatory frameworks.
- *Economic and financial considerations*: Promoting and gaining acceptance of the most effective UDT systems and equipment is challenging due to their higher initial investment costs and more technological complexity compared to current standard procedures (Ferré-Bigorra et al., 2022). In addition, the cost of system maintenance and exploitation is significant (Nochta et al., 2021). The findings from the literature indicated that many studies focused on the electricity consumption from UDT processes, especially for computing, as data-driven models require a lot of calculations (Ding & Ho, 2022). Therefore, several gaps are highlighted such as economic and financial considerations are critical to ensuring the financial sustainability and scalability of UDT projects (Dembski et al., 2020; Quek et al., 2023). Comprehensive cost–benefit analyses are essential for justifying the substantial initial investments required for UDT development, as well as the ongoing maintenance and operational costs. Scalable and adaptable business models are found to be crucial for extending UDT benefits across multiple cities and facilitating widespread adoption (Omrany et al., 2023). As a result, potential areas for future research cover the exploration of cost–benefit analyses to demonstrate the long-term value of UDTs by quantifying potential returns in areas such as reduced operational costs, resource efficiency, and improved urban management outcomes. Exploring innovative business models, such as public–private partnerships, can unlock new financial resources and reduce the financial burden on local governments (Shan et al., 2024). Exploring the acceleration of partnerships enable cities to leverage private sector investment and expertise for implementing of UDTs.
- *UDTs in Urban Planning*. Urban planning remains one of the most prominent applications of UDTs, with studies leveraging Machine Learning, Deep Learning, and AI to develop models for transport and mobility management. These approaches have led to platforms that simulate and optimise traffic flow and public transit systems, helping cities reduce conges-

tion, improve commute times, and enhance overall urban mobility (Xia et al., 2022). However, several gaps remain, including the early-stage exploration of computational urban science, computational limitations that often require data or model simplifications (Nochta et al., 2021), data quality concerns (Ferré-Bigorra et al., 2022), and challenges in multi-scale model integration (Wu et al., 2021). Current models are still unable to fully capture the complexity of urban systems. Future research should focus on developing clear frameworks for integrating UDTs into smart city initiatives, using real-time data to foster collaboration among urban planners, policymakers, and private sector stakeholders (Ye et al., 2023). Additionally, expanding UDT applications to predictive infrastructure maintenance could prevent costly failures, extend asset lifespans, and reduce long-term capital expenditures.

- *UDTs and advanced visualisation technologies*: Studies have shown that UDT technologies enhance urban development projects by providing 3D visualisations that simulate the impact of new infrastructure, traffic patterns, and environmental changes (Kuru, 2023; Merlo & Lavoratti, 2024). Various plugins and engines, such as Unity Engine, Unreal Engine, and Simulation Engines, have been introduced to support these applications (Dani et al., 2023; Raes et al., 2021; Roudbari et al., 2024). However, several research gaps remain, particularly in the integration of AR and VR. When these visualisation technologies are used to communicate large-scale quantitative data, such as spatial and parametric information, performance issues arise, including lagging and slow response times (Beil et al., 2020), particularly in multi-scale (Park & Yang, 2020) and multi-dimensional (Wu et al., 2021) contexts. Future research should focus on developing integrated models and transformative tools that enhance the adaptability of immersive visualisation technologies to evolving UDT innovations. Additionally, new methods should be explored to improve real-time monitoring and stakeholder engagement, ensuring that visualisation platforms can effectively handle the complexity of urban data.

6 Conclusion

Notwithstanding the growing number of research, the current body of literature remained fragmented when it came to providing a holistic understanding of UDT technology, and its current applications in the built environment. Correspondingly, this paper approached the literature by adopting a comprehensive systematic approach to unveil the dominating research areas in the field. To this end, the current study identified 78 scholarly materials and analysed them using a scientometric method to understand the key research areas in the field. This resulted in identifying five primary application domains for UDTs, i.e. urban monitoring and control, smart urban planning, environmental management, decision-making, and the development of smart, sustainable cities. The findings showed the promising potential of UDTs to enhance urban governance, optimise resource management, and inform data-driven decision-making, which can subsequently promote fostering innovative solutions to tackle multilayered challenges within urban environments. The findings also indicated that UDTs can support designing and creating healthier urban environments by facilitating better air quality management, noise reduction, and green space planning. This can directly contribute to enhancing the wellbeing of citizens.

Further, this study analysed 10 industry reports on UDT technology to identify practical insights and evaluate industry-driven approaches for implementing UDT solutions in urban environments. The findings revealed notable progress in applying this technology to urban planning and infrastructure management. However, the absence of a standardised framework across the reviewed reports presents challenges to consistent implementation, scalability, and cross-sector collaboration. This highlights the need for unified guidelines to support broader UDT adoption in the built environment. Future research can focus on developing standardised protocols that guide UDT development while accommodating the unique requirements of varied urban settings. Without such guidelines, UDT adoption may remain limited by fragmented solutions and constrained cross-sector collaboration.

This study introduces a new classification model derived from analysing research flows, offering a refined interpretation of key outcomes across five clusters in UDT pathways. The proposed model redefines the structure of UDT literature, providing a systematic framework to interpret and correlate findings from previous studies. In addition to this, the study identified a range of challenges that future research should address to unlock the full potential of UDT technology in urban development. Effective data management is highlighted as a critical area, essential for establishing interoperable systems that integrate platforms such as BIM and GIS. Advancing technology integration through AI, IoT, and edge computing is also recommended to enhance real-time processing capabilities critical for responsive UDTs. Furthermore, governance frameworks must address data ownership and privacy concerns to build public trust and accountability. Finally, the study emphasises the importance of prioritising social and cultural integration by adapting UDTs to diverse urban and rural contexts, thereby increasing public engagement and ensuring alignment with community needs.

Further, this study recommends that UDTs incorporate adaptive resource management and climate response functions to support long-term urban resilience and foster sustainability in the built environment. Economic and financial sustainability should also be prioritized, including cost–benefit analyses and innovative funding models, such as public–private partnerships, to make UDTs accessible for cities of all sizes. This approach can aid in the widespread adoption of UDTs, enabling cities to achieve resilient, sustainable development goals effectively and inclusively. As urban planning remains a core application, UDTs provide data-driven insights to optimise infrastructure, enhance mobility, and support predictive maintenance. Additionally, integrating advanced visualisation technologies like AR and VR allows planners, stakeholders, and the public to interact with UDT models, enhancing transparency and collaborative decision-making. By addressing these interconnected challenges, UDT technology can play a transformative role in creating resilient, inclusive, and sustainable cities.

Acknowledgements
Not applicable.

Authors' contributions
Dr. Hossein Omrany: conceptualisation; data collection and analysis; original writing and editing. Dr. Armin Mehdipour: contributed to conceptualisation; writing and editing. Dr. Daniel Oteng: contributed to conceptualisation; writing and editing. Dr. Karam M. Al-Obaidi: contributed to conceptualisation and revision of the paper.

Funding
The first author acknowledges the financial support provided by the School of Architecture and Civil Engineering at the University of Adelaide through the Start-Up Funding Scheme and the School Research Growth Scheme.

Data availability
The data used in this study are available upon request from the corresponding author.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 29 October 2024 Revised: 3 February 2025 Accepted: 24 March 2025
Published online: 16 April 2025

References

Abdeen, F. N., Shirowzhan, S., & Sepasgozar, S. M. (2023). Citizen-centric digital twin development with machine learning and interfaces for maintaining urban infrastructure. *Telematics and Informatics, 84*, 102032.

Adreani, L., Bellini, P., Fanfani, M., Nesi, P., & Pantaleo, G. (2024). Smart city digital twin framework for real-time multi-data integration and wide public distribution. *IEEE Access, 12*, 76277–76303.

Alva, P., Mosteiro-Romero, M., Miller, C., & Stouffs, R. (2024). Mitigating operational greenhouse gas emissions in ageing residential buildings using an Urban Digital Twin dashboard. *Energy and Buildings, 322*, 114681.

Anschütz, C., Ebner, K., & Smolnik, S. (2022). Free ride in rush-hour traffic–designing gamified smart mobility systems for sustainable use. *ICIS 2022 Proceedings*. 6. Available on https://aisel.aisnet.org/icis2022/user_behaivor/user_behaivor/6. Accessed 28 Jan 2025.

Anschütz, C., Ebner, K., & Smolnik, S. (2024). Size does matter: A maturity model for the special needs of small and medium-sized smart cities. *Cities, 150*, 104998.

Anthopoulos, L., Janssen, M., & Weerakkody, V. (2019). A Unified Smart City Model (USCM) for smart city conceptualization and benchmarking. In *Smart cities and smart spaces: Concepts, methodologies, tools, and applications* (pp. 247–264).

ANZLIC. (2019). *Principles for spatially enabled digital twins of the built and natural environment in Australia*. Retrieved 24/09/2024, from https://www.anzlic.gov.au/sites/default/files/files/principles_for_spatially_enabled_digital_twins_of_the_built_and_natural_.pdf

Argyroudis, S. A., Mitoulis, S. A., Chatzi, E., Baker, J. W., Brilakis, I., Gkoumas, K., ... & Linkov, I. (2022). Digital technologies can enhance climate resilience of critical infrastructure. *Climate Risk Management*, *35*, 100387.

ARUP. (2019). *Digital twin: Towards a meaningful framework*. Retrieved 24/09/2024, from https://www.arup.com/globalassets/downloads/insights/digital-twin-towards-a-meaningful-framework.pdf

Austin, M., Delgoshaei, P., Coelho, M., & Heidarinejad, M. (2020). Architecting smart city digital twins: Combined semantic model and machine learning approach. *Journal of Management in Engineering, 36*(4), 04020026.

Beil, C., Ruhdorfer, R., Coduro, T., & Kolbe, T. H. (2020). Detailed streetspace modelling for multiple applications: Discussions on the proposed CityGML 3.0 transportation model. *ISPRS International Journal of Geo-Information, 9*(10), 603.

Bibri, S. E., Huang, J., Jagatheesaperumal, S. K., & Krogstie, J. (2024). The synergistic interplay of artificial intelligence and digital twin in environmentally planning sustainable smart cities: A comprehensive systematic review. *Environmental Science and Ecotechnology*, *20,* 100433.

Broo, D. G., Bravo-Haro, M., & Schooling, J. (2022). Design and implementation of a smart infrastructure digital twin. *Automation in Construction, 136*, 104171.

Cao, W., & Zhou, L. (2024). Resilient microgrid modeling in digital twin considering demand response and landscape design of renewable energy. *Sustainable Energy Technologies and Assessments, 64*, 103628.

Capgemini Research Institute. (2022). *Digital twins: Adding intelligence to the real world*. Retrieved 24/09/2024, from https://www.capgemini.com/gb-en/wp-content/uploads/sites/5/2022/11/DigitalTwins_adding-intelligence-to-the-real-world.pdf

Caprari, G., Castelli, G., Montuori, M., Camardelli, M., & Malvezzi, R. (2022). Digital twin for urban planning in the green deal era: A state of the art and future perspectives. *Sustainability, 14*(10), 6263.

Chen, L., Li, X., & Zhu, J. (2024). Carbon peak control for achieving net-zero renewable-based smart cities: Digital twin modeling and simulation. *Sustainable Energy Technologies and Assessments, 65*, 103792.

Chen, M., Chen, L., Li, Y., & Xian, Y. (2022). Developing computable sustainable urbanization science: Interdisciplinary perspective. *Computational Urban Science, 2*(1), 17.

Cureton, P., & Hartley, E. (2023). City information models (CIMs) as precursors for urban digital twins (UDTs): A case study of lancaster. *Frontiers in Built Environment, 9*, 1048510.

Dani, A. A. H., Supangkat, S. H., Lubis, F. F., Nugraha, I. G. B. B., Kinanda, R., & Rizkia, I. (2023). Development of a smart city platform based on digital twin technology for monitoring and supporting decision-making. *Sustainability, 15*(18), 14002.

Dembski, F., Wössner, U., Letzgus, M., Ruddat, M., & Yamu, C. (2020). Urban digital twins for smart cities and citizens: The case study of Herrenberg, Germany. *Sustainability, 12*(6), 2307.

Deng, M., Menassa, C. C., & Kamat, V. R. (2021a). From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry. *Journal of Information Technology in Construction*, *26*, 58–83.

Deng, T., Zhang, K., & Shen, Z. J. M. (2021b). A systematic review of a digital twin city: A new pattern of urban governance toward smart cities. *Journal of Management Science and Engineering, 6*(2), 125–134.

Diaz-Sarachaga, J. M. (2025). Developing an assessment governance framework for urban digital twins: Insights from smart cities. *Cities, 156*, 105558.

Ding, C., & Ho, I. W. H. (2022). Digital-twin-enabled city-model-aware deep learning for dynamic channel estimation in urban vehicular environments. *IEEE Transactions on Green Communications and Networking, 6*(3), 1604–1612.

Dittmann, S., Mathieu, M. P., Zhang, P., Glodde, A., & Dietrich, F. (2024). Device recognition assistants as additional data management method for digital twins. *CIRP Journal of Manufacturing Science and Technology, 51*, 73–90.

EL Azzaoui, A., Kim, T. W., Loia, V., Park, J. H. (2021). Blockchain-based secure digital twin framework for smart healthy city. In *Advanced multimedia and ubiquitous engineering: MUE-FutureTech 2020* (pp. 107–113). Springer.

Esri UK. (2024). https://www.esriuk.com/en-gb/digital-twin/overview?gad_source=1&gclid=EAIaIQobChMIx77aqJaPiwMVPZdQBh05CBFjEAAYAiAAEgI0cfD_BwE#the-university-of-warwick. Accessed 26 Jan 2025.

Ferré-Bigorra, J., Casals, M., & Gangolells, M. (2022). The adoption of urban digital twins. *Cities, 131*, 103905.

Ford, D. N., & Wolf, C. M. (2020). Smart cities with digital twin systems for disaster management. *Journal of Management in Engineering, 36*(4), 04020027.

Francisco, A., Mohammadi, N., & Taylor, J. E. (2020). Smart city digital twin–enabled energy management: Toward real-time urban building energy benchmarking. *Journal of Management in Engineering, 36*(2), 04019045.

Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: Enabling technologies, challenges and open research. *IEEE Access, 8*, 108952–108971.

Gholami, M., Torreggiani, D., Tassinari, P., & Barbaresi, A. (2022). Developing a 3D city digital twin: Enhancing walkability through a green pedestrian network (GPN) in the city of Imola, Italy. *Land, 11*(11), 1917.

Grieves, M., & Vickers J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In *Transdisciplinary perspectives on complex systems: New findings and approaches* (pp. 85–113).

Griffith, C., & Truelove, M. (2021). *Framework for spatially enabled digital twins: Information paper*. Retrieved 24/09/2024, from https://www.anzlic.gov.au/sites/default/files/files/Data61%20Digital%20Twin%20Framework%20Information%20Paper%20-%20February%202021.pdf

Ham, Y., & Kim, J. (2020). Participatory sensing and digital twin city: Updating virtual city models for enhanced risk-informed decision-making. *Journal of Management in Engineering, 36*(3), 04020005.

Hämäläinen, M. (2021). Urban development with dynamic digital twins in Helsinki city. *IET Smart Cities, 3*(4), 201–210.

Haraguchi, M., Funahashi, T., & Biljecki, F. (2024). Assessing governance implications of city digital twin technology: A maturity model approach. *Technological Forecasting and Social Change, 204*, 123409.

Henriksen, H. J., Schneider, R., Koch, J., Ondracek, M., Troldborg, L., Seidenfaden, I. K., ... & Stisen, S. (2022). A new digital twin for climate change adaptation, water management, and disaster risk reduction (HIP digital twin). *Water*,*15*(1), 25.

Iammarino, S., Rodriguez-Pose, A., & Storper, M. (2019). Regional inequality in Europe: Evidence, theory and policy implications. *Journal of Economic Geography, 19*(2), 273–298.

IBM. (2021). *What is a digital twin?*. https://www.ibm.com/think/topics/what-is-a-digital-twin. Accessed 25 Jan 2025.

IEC. (2021). *Technical report: City information modelling and urban digital twins*. Retrieved 24/09/2024, from https://www.iec.ch/system/files/2024-04/iec_tec_cim_udt_en.pdf

Industry, A. (2021). *Designing disruption: The critical role of virtual twins in accelerating sustainability*. Retrieved 24/09/2024, from https://www.accenture.com/content/dam/accenture/final/a-com-migration/r3-3/pdf/pdf-147/accenture-virtual-twin-and-sustainability.pdf

Javaid, M., Haleem, A., & Suman, R. (2023). Digital twin applications toward industry 4.0: A review. *Cognitive Robotics, 3*, 71–92.

Jiang, F., Ma, L., Broyd, T., Chen, W., & Luo, H. (2022). Digital twin enabled sustainable urban road planning. *Sustainable Cities and Society, 78*, 103645.

Khokhlov, A. N. (2020). How scientometrics became the most important science for researchers of all specialties. *Moscow University Biological Sciences Bulletin, 75*, 159–163.

Kumar, D., & Bassill, N. P. (2024). Analysing trends of computational urban science and data science approaches for sustainable development. *Computational Urban Science, 4*(1), 1–27.

Kumar, S. A., Madhumathi, R., Chelliah, P. R., Tao, L., & Wang, S. (2018). A novel digital twin-centric approach for driver intention prediction and traffic congestion avoidance. *Journal of Reliable Intelligent Environments, 4*(4), 199–209.

Kuru, K. (2023). Metaomnicity: Toward immersive urban metaverse cyberspaces using smart city digital twins. *IEEE Access, 11*, 43844–43868.

Kwon, J. W., Yun, S. J., & Kim, W. T. (2022). A semantic data-based distributed computing framework to accelerate digital twin services for large-scale disasters. *Sensors, 22*(18), 6749.

Lehtola, V. V., Koeva, M., Elberink, S. O., Raposo, P., Virtanen, J. P., Vahdatikhaki, F., & Borsci, S. (2022). Digital twin of a city: Review of technology serving city needs. *International Journal of Applied Earth Observation and Geoinformation, 114*, 102915.

Lei, B., Janssen, P., Stoter, J., & Biljecki, F. (2023). Challenges of urban digital twins: A systematic review and a Delphi expert survey. *Automation in Construction, 147*, 104716.

Li, B., & Tan, W. (2023). A novel framework for integrating solar renewable source into smart cities through digital twin simulations. *Solar Energy, 262*, 111869.

Li, X., Liu, H., Wang, W., Zheng, Y., Lv, H., & Lv, Z. (2022a). Big data analysis of the internet of things in the digital twins of smart city based on deep learning. *Future Generation Computer Systems, 128*, 167–177.

Li, X., Luo, J., Li, Y., Wang, W., Hong, W., Liu, M., ... & Lv, Z. (2022b). Application of effective water-energy management based on digital twins technology in sustainable cities construction. *Sustainable Cities and Society*, *87*, 104241.

Li, Y., den Hartog, H., Liu, T., & Cheng, Y. (2020). Research progress in thermal comfort assessment of urban green spaces based on scientific knowledge mapping technology. In *2020 International Conference on Innovation Design and Digital Technology (ICIDDT)* (pp. 306–311). IEEE.

Liu, M., Ma, H., & Bai, Y. (2021). Understanding the drivers of land surface temperature based on multisource data: A spatial econometric perspective. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 14*, 12263–12272.

Liu, M., & Zhang, K. (2024). Smart city landscape design for achieving net-zero emissions: Digital twin modeling. *Sustainable Energy Technologies and Assessments, 63*, 103659.

Liu, P., Zhao, T., Luo, J., Lei, B., Frei, M., Miller, C., & Biljecki, F. (2023a). Towards human-centric digital twins: Leveraging computer vision and graph models to predict outdoor comfort. *Sustainable Cities and Society, 93*, 104480.

Liu, Z., Zhu, Z., Sun, Z., Li, A., & Ni, S. (2023b). A digital twin-based green construction management method for prefabricated buildings. *Digital Twin, 3*, 8.

Luo, J., Liu, P., & Cao, L. (2022a). Coupling a physical replica with a digital twin: A comparison of participatory decision-making methods in an urban park environment. *ISPRS International Journal of Geo-Information, 11*(8), 452.

Luo, W., Sandanayake, M., Hou, L., Tan, Y., & Zhang, G. (2022b). A systematic review of green construction research using scientometrics methods. *Journal of Cleaner Production, 366*, 132710.

Macatulad, E. & Biljecki, F. (2024). Continuing from the Sendai framework midterm: Opportunities for urban digital twins in disaster risk management. *International Journal of Disaster Risk Reduction*, *102,* 104310.

Masoumi, H., Shirowzhan, S., Eskandarpour, P., & Pettit, C. J. (2023). City digital twins: Their maturity level and differentiation from 3D city models. *Big Earth Data, 7*(1), 1–36.

Meerow, S. (2020). The politics of multifunctional green infrastructure planning in New York City. *Cities, 100*, 102621.

Merlo, A., & Lavoratti, G. (2024). Documenting urban morphology: From 2d representations to metaverse. *Land, 13*(2), 136.

Mohamad Zaidi, N. H., Lim, C. H., & Razali, H. (2024). Mitigating the energy consumption and carbon emissions of a residential area in a tropical city using digital twin technology: A Case study of Bertam, Penang. *Buildings, 14*(3), 638.

Moreno, C., Allam, Z., Chabaud, D., Gall, C., & Pratlong, F. (2021). Introducing the "15-minute city": Sustainability, resilience and place identity in future post-pandemic cities. *Smart Cities, 4*(1), 93–111.

Mouratidis, K. (2024). Time to challenge the 15-minute city: Seven pitfalls for sustainability, equity, livability, and spatial analysis. *Cities, 153*, 105274.
Nazim, I., & Joyce, S. C. (2024). Urban analytics and generative deep learning for context responsive design in digital twins. In *Proceedings of the 29th International Conference of the Association for Computer Aided Architectural Design Research in Asia (CAADRIA) 2024, Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, vol. 2* (pp. 495–504).
Nochta, T., Wan, L., Schooling, J. M., & Parlikad, A. K. (2021). A socio-technical perspective on urban analytics: The case of city-scale digital twins. *Journal of Urban Technology, 28*(1–2), 263–287.
Ohueri, C. C., Masrom, M. A. N., Habil, H., & Ambashe, M. S. (2023). IoT-based digital twin best practices for reducing operational carbon in building retrofitting: a mixed-method approach. *Engineering, Construction and Architectural Management,* 32(3), 2044–2065.
Omrany, H., & Al-Obaidi, K. M. (2024). Application of digital twin technology for Urban Heat Island mitigation: Review and conceptual framework. *Smart and Sustainable Built Environment IN PRESS*. https://doi.org/10.1108/SASBE-05-2024-0189
Omrany, H., Al-Obaidi, K. M., Ghaffarianhoseini, A., Chang, R. D., Park, C., & Rahimian, F. (2025). Digital twin technology for education, training and learning in construction industry: implications for research and practice. *Engineering, Construction and Architectural Management*, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/ECAM-10-2024-1376
Omrany, H., Al-Obaidi, K. M., Hossain, M., Alduais, N. A., Al-Duais, H. S., & Ghaffarianhoseini, A. (2024a). IoT-enabled smart cities: A hybrid systematic analysis of key research areas, challenges, and recommendations for future direction. *Discover Cities, 1*(1), 2. https://doi.org/10.1007/s44327-024-00002-w
Omrany, H., Al-Obaidi, K. M., Husain, A., & Ghaffarianhoseini, A. (2023). Digital twins in the construction industry: A comprehensive review of current implementations, enabling technologies, and future directions. *Sustainability, 15*(14), 10908. https://doi.org/10.3390/su151410908
Omrany, H., Chang, R., Soebarto, V., Zhang, Y., Ghaffarianhoseini, A., & Zuo, J. (2022). A bibliometric review of net zero energy building research 1995–2022. *Energy and Buildings, 262*, 111996. https://doi.org/10.1016/j.enbuild.2022.111996
Omrany, H., Mehdipour, A., & Oteng, D. (2024b). Digital twin technology and social sustainability: Implications for the construction industry. *Sustainability, 16*(19), 8663. https://doi.org/10.3390/su16198663
Papyshev, G., & Yarime, M. (2021). Exploring city digital twins as policy tools: A task-based approach to generating synthetic data on urban mobility. *Data & Policy, 3*, e16.
Park, J., & Yang, B. (2020). GIS-enabled digital twin system for sustainable evaluation of carbon emissions: A case study of Jeonju city, south Korea. *Sustainability, 12*(21), 9186.
Patel, T., Guo, B. H., & Zou, Y. (2022). A scientometric review of construction progress monitoring studies. *Engineering, Construction and Architectural Management, 29*(9), 3237–3266.
Patel, U. R., Ghaffarianhoseini, A., Ghaffarianhoseini, A., & Burgess, A. (2024). Digital twin technology for sustainable urban development: A review of its potential impact on SDG 11 in New Zealand. *Cities, 155*, 105484.
Peldon, D., Banihashemi, S., LeNguyen, K., & Derrible, S. (2024). Navigating urban complexity: The transformative role of digital twins in smart city development. *Sustainable Cities and Society, 111*, 105583.
Price Waterhouse Coopers. (2022). *How digital twins can make smart cities better*. Retrieved 24/09/2024, from https://www.pwc.com/m1/en/publications/documents/how-digital-twins-can-make-smart-cities-better.pdf
Quek, H. Y., Sielker, F., Akroyd, J., Bhave, A. N., von Richthofen, A., Herthogs, P., ... & Kraft, M. (2023). The conundrum in smart city governance: Interoperability and compatibility in an ever-growing ecosystem of digital twins. *Data and Policy*, *5*, e6.
Raes, L., Michiels, P., Adolphi, T., Tampere, C., Dalianis, A., McAleer, S., & Kogut, P. (2021). DUET: A framework for building interoperable and trusted digital twins of smart cities. *IEEE Internet Computing, 26*(3), 43–50.
Ramani, V., Ignatius, M., Lim, J., Biljecki F., & Miller, C. (2023). A dynamic urban digital twin integrating longitudinal thermal imagery for microclimate studies. In *Proceedings of the 10th ACM international conference on systems for energy-efficient buildings, cities, and transportation* (pp. 421–428).
Roudbari, N. S., Punekar, S. R., Patterson, Z., Eicker, U., & Poullis, C. (2024). From data to action in flood forecasting leveraging graph neural networks and digital twin visualization. *Scientific Reports, 14*(1), 18571.
Saeed, Z. O., Mancini, F., Glusac, T., & Izadpanahi, P. (2022). Artificial intelligence and optimization methods in construction industry. *Buildings, 12*, 685.
Scalas, A., Cabiddu, D., Mortara, M., & Spagnuolo, M. (2022). Potential of the geometric layer in urban digital twins. *ISPRS International Journal of Geo-Information, 11*(6), 343.
Schrotter, G., & Hürzeler, C. (2020). The digital twin of the city of Zurich for urban planning. *PFG–Journal of Photogrammetry, Remote Sensing and Geoinformation Science, 88*(1), 99–112.
Scopus. (2024). *Scopus: Comprehensive, multidisciplinary, trusted abstract and citation database*. Retrieved 24/09/2024, from https://www.elsevier.com/products/scopus
Sepasgozar, S. M. (2021). Differentiating digital twin from digital shadow: Elucidating a paradigm shift to expedite a smart, sustainable built environment. *Buildings, 11*(4), 151.
Shahat, E., Hyun, C. T., & Yeom, C. (2021). City digital twin potentials: A review and research agenda. *Sustainability, 13*(6), 3386.
Shan, S., Song, Y., Wang, C., & Ji, W. (2024). Influencing factors and action paths for public crisis governance performance improvement in digital twin cities. *Library Hi Tech, ahead of print.*
Somanath, S., Naserentin, V., Eleftheriou, O., Sjölie, D., Wästberg, B. S., & Logg, A. (2024). Towards urban digital twins: A workflow for procedural visualization using geospatial data. *Remote Sensing, 16*(11), 1939.
Tancev, G., & Toro, F. G. (2022). Towards a digital twin for air quality monitoring networks in smart cities. In *2022 IEEE International Smart Cities Conference (ISC2)* (pp. 1–4). IEEE
Teixeira, J. F., Silva, C., Seisenberger, S., Büttner, B., McCormick, B., Papa, E., & Cao, M. (2024). Classifying 15-minute cities: A review of worldwide practices. *Transportation Research Part A: Policy and Practice, 189*, 104234.
Therias, A., & Rafiee, A. (2023). City digital twins for urban resilience. *International Journal of Digital Earth, 16*(2), 4164–4190.
Trevisani, S., & Omodeo, P. D. (2021). Earth scientists and sustainable development: Geocomputing, new technologies, and the humanities. *Land, 10*(3), 294.
Tuhaise, V. V., Tah, J. H. M., & Abanda, F. H. (2023). Technologies for digital twin applications in construction. *Automation in Construction, 152*, 104931.
UN-Habitat. (2022). *Envisaging the future of cities, world city report 2022*. from https://unhabitat.org/sites/default/files/2022/06/wcr_2022.pdf
Van Eck, N. J., & Waltman, L. (2023). VOSviewer manual. In *Manual for VOSviewer version 1.6.20*. Available on: https://www.vosviewer.com/documentation/Manual_VOSviewer_1.6.20.pdf. Accessed 6/01/2025.
VanDerHorn, E., & Mahadevan, S. (2021). Digital twin: Generalization, characterization and implementation. *Decision Support Systems, 145*, 113524.
Wajid, M. S., Terashima-Marin, H., Najafirad, P., Pablos, S. E. C., & Wajid, M. A. (2024). DTwin-TEC: An AI-based TEC district digital twin and emulating security events by leveraging knowledge graph. *Journal of Open Innovation: Technology, Market, and Complexity, 10*(2), 100297.
Walker, A. (2023). Singapore's digital twin—from science fiction to Hi-Tech reality. In *Infrastructure Global.* Available on: https://infra.global/singapores-digital-twin-from-science-fiction-to-hi-tech-reality/. Accessed 4 Jan 2025.
Wang, H., Chen, X., Jia, F., & Cheng, X. (2023). Digital twin-supported smart city: Status, challenges and future research directions. *Expert Systems with Applications, 217*, 119531.
Wang, H., & Wang, Y. (2024). Smart cities net zero planning considering renewable energy landscape design in digital twin. *Sustainable Energy Technologies and Assessments, 63*, 103629.
Wang, X., Pan, Y., & Chen, J. (2024). Digital twin with data-mechanism-fused model for smart excavation management. *Automation in Construction, 168*, 105749.
Weck, S., & Beißwenger, S. (2014). Coping with peripheralization: Governance response in two German small cities. *European Planning Studies, 22*(10), 2156–2171.
Weil, C., Bibri, S. E., Longchamp, R., Golay, F., & Alahi, A. (2023). A systemic review of urban digital twin challenges, and perspectives for sustainable smart cities. *Sustainable Cities and Society, 99*, 104862.

White, G., Zink, A., Codecá, L., & Clarke, S. (2021). A digital twin smart city for citizen feedback. *Cities, 110*, 103064.

World Bank Group. (2022). *Smart cities in the Republic of Korea*. Retrieved 24/09/2024, from https://documents1.worldbank.org/curated/en/099501509212220541/pdf/IDU09bc4586900d9a047080a9de0afa91af324a9.pdf

World Economic Forum. (2022). *Digital twin cities: Framework and global practices*. Retrieved 24/09/2024, from https://www3.weforum.org/docs/WEF_Global_Digital_Twin_Cities_Framework_and_Practice_2022.pdf

World Economic Forum. (2023). *Digital twin cities: Key insights and recommendations*. Retrieved 24/09/2024, from https://www3.weforum.org/docs/WEF_Digital_Twin_Cities_2023.pdf

Wu, T. G., & Guan, C. (2024). Advancing intra and inter-city urban digital twins: An updated review. *Journal of Planning Education and Research*, 0739456X241260887.

Wu, Y., Zhang, K., & Zhang, Y. (2021). Digital twin networks: A survey. *IEEE Internet of Things Journal, 8*(18), 13789–13804.

Xia, H., Liu, Z., Efremochkina, M., Liu, X., & Lin, C. (2022). Study on city digital twin technologies for sustainable smart city design: A review and bibliometric analysis of geographic information system and building information modeling integration. *Sustainable Cities and Society, 84*, 104009.

Xu, W., & Liu, S. (2024). Novel economic models for advancing urban energy management and transition: Simulation of urban energy system in digital twin. *Sustainable Cities and Society, 101*, 105154.

Ye, X., Du, J., Han, Y., Newman, G., Retchless, D., Zou, L., ... , & Cai Z. (2023). Developing human-centered urban digital twins for community infrastructure resilience: A research agenda. *Journal of Planning Literature*, *38*(2), 187–199.

Yevu, S. K., Owusu, E. K., Chan, A. P., Sepasgozar, S. M., & Kamat, V. R. (2023). Digital twin-enabled prefabrication supply chain for smart construction and carbon emissions evaluation in building projects. *Journal of Building Engineering, 78*, 107598.

Yossef Ravid, B., & Aharon-Gutman, M. (2023). The social digital twin: The social turn in the field of smart cities. *Environment and Planning b: Urban Analytics and City Science, 50*(6), 1455–1470.

Zhang, G., Cheng, S., & Gao, Y. (2024). A visibility-based approach to manage the vertical urban development and maintain visual sustainability of urban mountain landscapes: A case of Mufu Mountain in Nanjing, China. *Environment and Planning B: Urban Analytics and City Science, 51*(2), 384–400.

Zhang, H., & Feng, X. (2024). Reliability improvement and landscape planning for renewable energy integration in smart cities: A case study by digital twin. *Sustainable Energy Technologies and Assessments, 64*, 103714.

Zhang, M., Tao, F., Huang, B., Liu, A., Wang, L., Anwer, N., & Nee, A. Y. C. (2022). Digital twin data: Methods and key technologies. *Digital Twin, 1*, 2.

Zhao, X., & Zhang, Y. (2024). Integrated management of urban resources toward net-zero smart cities considering renewable energies uncertainty and modeling in digital twin. *Sustainable Energy Technologies and Assessments, 64*, 103656.

Zhong, B., Wu, H., Li, H., Sepasgozar, S., Luo, H., & He, L. (2019). A scientometric analysis and critical review of construction related ontology research. *Automation in Construction, 101*, 17–31.

Publisher's Note